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Abel Ortego Bielsa

Thermodynamic assessment of raw material use in passenger vehicles

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Tesis Doctoral

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PhD Dissertation

Thermodynamic assessment of raw material use in passenger vehicles

Abel Ortego Bielsa

Supervised by:

Alicia Valero Delgado and Antonio Valero Capilla

November 2018

Informe del director de Tesis

Dr. Antonio Valero Capilla, catedrático del Área de Máquinas y Motores Térmicos de la Universidad de Zaragoza y director del Instituto Universitario de Investigación Mixto CIRCE – Universidad de Zaragoza.

Y

Dra. Alicia Valero Delgado, profesora Ayudante Doctor del Área de Máquinas y Motores Térmicos de la Universidad de Zaragoza y Directora del Grupo de Investigación de Ecología Industrial del Instituto Universitario de Investigación Mixto CIRCE – Universidad de Zaragoza.

CERTIFICAN

Que la presente memoria de Tesis Doctoral titulada:

Thermodynamic assessment of raw material use in passenger vehicles

Ha sido realizada por Don Abel Ortego Bielsa bajo nuestra dirección en el Instituto Universitario de Investigación Mixto CIRCE dentro del programa de Doctorado de Energías Renovables y Eficiencia energética y **AUTORIZAN** su presentación como compendio de publicaciones.

Zaragoza, a 9 de noviembre de 2018

Fdo: Dr. D. Antonio Valero Capilla

Fdo: Dr. Dña. Alicia Valero Delgado

Publicaciones

La presente tesis doctoral está realizada por un compendio de trabajos de investigación que han sido previamente publicados en revistas científicas. A continuación se presentan las referencias bibliográficas que forman la tesis:

I. Valero, Al. Valero, A. Calvo, G. **Ortego, A.** Material bottlenecks in the future development of green technologies. *Renewable and Sustainable Energy Reviews.* October 2018. Vol 93, pp 178-200. https://doi.org/10.1016/j.rser.2018.05.041.

Factor de impacto: 9.18 (Journal Citation Reports 2017)

II. **Ortego, A.** Valero, Al. Valero, A. Restrepo, E. Vehicles and Critical Raw Materials. A Sustainability Assessment using Thermodynamic Rarity. *Industrial Ecology.* Vol 22. Nº5. March 2018. https://doi.org/10.1111/jiec.12737

Factor de impacto: 4.35 (Journal Citation Reports 2017)

III. **Ortego. A**, Valero. Al, Valero. A, Calvo. G, Villacampa. M, Iglesias. M. Strategic metals ranking in the automobile sector. *13th Sustainable Development Energy Water and Environmental Systems Conference. Palermo, Italy.* 4th October 2018.

Factor de impacto: No tiene factor de impacto pero está indexado a Scopus. Ha sido seleccionado para ser publicado en el Journal of Environmental Management.

IV. **Ortego, A**. Valero, Al. Valero, A. Iglesias, M. Downcycling in automobile recycling process: A thermodynamic assessment. *Resources, Conservation and Recycling.* Vol 136, pp 24-32. September 2018. https://doi.org/10.1016/j.resconrec.2018.04.006

Factor de impacto: 5.12 (Journal Citation Reports 2017)

V. **Ortego, A.** Valero, Al. Valero, A. Iglesias, M. Towards material efficiency vehicles. Eco-design recommendations based on metal sustainability assessments. *SAE International Journal of Materials and Manufacturing.* Vol 11. Issue 3. September 2018. https://doi.10.4271/05-11-03-0021

Factor de impacto: 0.43 (Scimago Journal and Country Rank). El impacto a nivel científico no es muy elevado, pero es una de las revistas con mayor impacto a nivel industrial en el sector del automóvil.

Además de las citadas publicaciones, sobre las cuales se desarrolla la presente Tesis doctoral, a lo largo del proceso de investigación realizado en el doctorado, se han hecho también los siguientes trabajos que han contribuido a avanzar en la investigación presentada.

- **Ortego, A.** Valero, Al. Valero, A. What is the stock in use of urban mobility? An exergy approach. *Life Cycle assessment and other assessment tools for waste management and resource optimization.* Calabria. Italy. 5-10 June 2016.
- Valero, A. Valero, Al. **Ortego, A.** Calvo, G. Material constraints in the future development of Green technologies. *International Symposium on Industrial Ecology*. Chicago, USA. Jun 25-29 2017.
- Valero, Al. **Ortego, A.** Iglesias, M. EXCITE – Exergy approach to encourage Circular economy pracTices in vEhicles. *SEAT Mobility Days*. Martorell. 8 nov 2017.
- **Ortego, A.** Iglesias, M. Metal downcycling in automobile shredding processes: A thermodynamic assessment. *Symposium on Urban mobility challenges.* Escuela de Caminos Universidad Politécnica de Barcelona. 13 nov 2017.
- Iglesias, M. **Ortego, A.** Thermodynamic Rarity as a raw material sustainablity indicator to identify ecodesign measures in vehicles. *Symposium on Urban mobility challenges*. Escuela de Caminos Universidad Politécnica de Barcelona. 13 nov 2017.
- Valero, Al. Valero, A. Calvo, G. **Ortego. A,** Ascaso. S, Palacios, J. Global material requirements for the energy transition. An exergy flow analysis. *Energy.* September 2018. https://doi.org/10.1016/j.energy.2018.06.149
- Gonzalez, E. **Ortego, A**. Topham, E. Valero, Al. Is the future development of wind Energy compromised by the availability of raw materials? Journal of Physics: Conf. Series. 1102 (2018). https://doi:10.10881742-6596/1102/1/02 2028

Appended publications

The work presented in this thesis is based on the following publications, referred to in the text using the assigned Roman numerals.

I. Valero, Al. Valero, A. Calvo, G. **Ortego, A.** Material bottlenecks in the future development of green technologies. *Renewable and Sustainable Energy Reviews.* October 2018. Vol 93, pp 178-200. https://doi.org/10.1016/j.rser.2018.05.041.

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Impact factor: It has no impact factor but it is indexed in Scopus. It has been selected for publication in the journal of Environmental Management.

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Impact factor: 5.12 (Journal Citation Reports 2017)

V. **Ortego, A.** Valero, Al. Valero, A. Iglesias, M. Towards material efficiency vehicles. Eco-design recommendations based on metal sustainability assessments. *SAE International Journal of Materials and Manufacturing.* Vol 11. Issue 3. September 2018. https://doi.10.4271/05-11-03-0021

Impact factor: 0.43 (Scimago Journal and Country Rank). **The scientific impact is not very high, but it is one of the most relevant journals in the automobile industry.**

In addition to the aforementioned publications, during the research process, the following works have also been published. Although they are not included inside the Thesis, their contributions have also been valuable to advance in the research line.

- **Ortego, A.** Valero, Al. Valero, A. What is the stock in use of urban mobility? An exergy approach. *Life Cycle assessment and other assessment tools for waste management and resource optimization.* Calabria. Italy. 5-10 June 2016.
- Valero, A. Valero, Al. **Ortego, A.** Calvo, G. Material constraints in the future development of Green technologies. *International Symposium on Industrial Ecology*. Chicago, USA. Jun 25-29 2017.
- Valero, Al. **Ortego, A.** Iglesias, M. EXCITE – Exergy approach to encourage Circular economy pracTices in vEhicles. *SEAT Mobility Days*. Martorell. 8 nov 2017.
- **Ortego, A.** Iglesias, M. Metal downcycling in automobile shredding processes: A thermodynamic assessment. *Symposium on Urban mobility challenges.* Escuela de Caminos Universidad Politécnica de Barcelona. 13 nov 2017.
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- Valero, Al. Valero, A. Calvo, G. **Ortego. A,** Ascaso. S, Palacios, J. Global material requirements for the energy transition. An exergy flow analysis. *Energy.* September 2018. https://doi.org/10.1016/j.energy.2018.06.149
- Gonzalez, E. **Ortego, A**. Topham, E. Valero, Al. Is the future development of wind Energy compromised by the availability of raw materials? Journal of Physics: Conf. Series. 1102 (2018). https://doi:10.10881742-6596/1102/1/02 2028

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Después de mucho tiempo, llega el momento de escribir la página más emocionante y una de las más importantes de esta Tesis. Durante varios años he tenido este sueño y he luchado por alcanzarlo. En el camino he encontrado obstáculos, pero gracias a vuestra ayuda me ha sido más fácil superarlos.

En primer lugar tengo que agradecer a los que me habéis aguantado desde casa día a día. A Patricia por estar a mi lado en todas las decisiones profesionales que he tomado. Cuando decidí comenzar con la Tesis sabíamos que iba a ser un camino largo, que iba a suponer una gran dedicación por mi parte, sin embargo estuviste ahí apoyándome y comprendiendo que era un desafío tanto profesional como personal que si no realizaba, nunca me podría perdonar. En este punto también me acuerdo de ti Manuel, aunque no entiendes muy bien a lo que me dedico, has tenido que soportar durante estos años que una gran parte de mis pensamientos hayan estado ocupados con la Tesis Doctoral. Un día comprenderás que en la vida este tipo de sacrificios acaban mereciendo la pena. Antes de que llegue ese día tendrás que aprender a leer así que tranquilo, aún queda lejos, de momento me conformo con verte feliz.

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Para finalizar no sería justo que terminara esta sección sin expresar mi gratitud a todos los autores e instituciones que he referenciado en esta Tesis. A comienzos de la Tesis cree una carpeta en mi gestor de referencias llamada “Tesis”. Hoy contiene más de 800 archivos, de entre ellos 221 han sido empleados como referencias en este trabajo. Gracias al esfuerzo y trabajo previo desarrollado por todos ellos pude identificar con claridad los objetivos de la Tesis y desarrollar mi investigación adecuadamente.

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After a long time it is the moment to write the most exciting and maybe one of the most important pages of this Thesis from the personal perspective. I had a dream over several years and I have fought to achieve it. Along this trip I have found several difficulties but thanks to your support it has been easier to overcome them.

First of all I have to thank to those that support me every day from home. To Patricia for being at my side in all professional decisions that I have taken. When I began with my research we realized that the trip would be difficult. Nevertheless, you were supporting me and understanding that I needed to face this challenge. At this point I also remember my son Manuel. Although you don´t quite understand my job you have had to endure that a part of my thoughts had been busy with the Thesis. One day you will understand that this kind of efforts are worth it, although you will have to learn reading before this day comes.

I can´t either forget my parents. You have worked very hard to make possible that Juan and I could study in the University. From a nearer perspective I would like to thank my mother for encouraging me to study beyond high school. On the other hand, I would like to thank my father for transmitting me the passion for engines, vehicles and mechanics in general. On your side I have learnt a lot of lessons in our home garage. All of them have been very valuable to make this report because they transformed my hands in one of my fundamental tools as researcher.

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Moreover, I would like to thank all my colleagues from CIRCE, family and friends that have supported me at some stage during the last years. Especial thanks are owed to Juan José Alba, Juan Manuel Ortego and Victor Carreras. Your words of support and sincere interest have been very important to overcome some moments of loneliness and incomprehension to which researchers are exposed.

Finally, it would be unfair that I finish the acknowledgements without expressing my gratitude to all authors that I have cited in this report. At the beginning of the Thesis I created a folder named “Thesis” in my reference manager. Today there are more than 800 files in this folder, from them 221 have been used as references in this Thesis. Thanks to this revision I was able to identify clearly what should be the Thesis objectives and so to align my efforts along the research process properly.

Thank you very much

A Patricia
Por respetar y comprender mi decisión
de emprender este apasionante viaje

To Patricia
For respecting and understanding my decision
to undertake this exciting journey

Resumen

Conseguir una economía mundial libre de carbono es de vital importancia para evitar el aumento de las temperaturas del planeta y sus fatales consecuencias para la humanidad. Para lograr ese objetivo se están llevando a cabo grandes avances en el desarrollo tanto de energías renovables como de vehículos más limpios. En el caso de los vehículos esos avances se están centrando principalmente en mejorar la eficiencia de los motores combustión, reducir la emisión tanto de gases de efecto invernadero como de otros perjudiciales para la salud y en el desarrollo de vehículos libres de emisiones directas, como los vehículos eléctricos.

Estos avances hacía la obtención de automóviles más limpios está provocando un cambio en la actual flota de vehículos y se espera que en las próximas décadas habrá una renovación total de la misma. La nueva generación de vehículos reducirá en gran parte su dependencia con relación a los combustibles fósiles, sin embargo a cambio demandará una gran cantidad de recursos naturales, tan valiosos e incluso más escasos en ocasiones que el petróleo. Algunos de estos recursos serán: Co, Ni, Mn o Li para fabricar baterías; Ga, Ge, Y para hacer sistemas de iluminación tipo LEDs; Nd, Dy, Pr para construir imanes permanentes de motores eléctricos; Pt, Pd, Zr para hacer catalizadores que reduzcan la contaminación; Au, Ag, Sn, Ta, Yb para fabricar unidades electrónica; Ce, Tb, Se, La para hacer sensores o Nb, Mo, Cr, Ti, V, Sc, W para hacer aleaciones de acero de alta resistencia. Lamentablemente, estos recursos son finitos y algunos de ellos incluso ya son considerados como críticos por la Comisión Europea y otras instituciones internacionales.

Una de las soluciones para mejorar la sostenibilidad en la fabricación de vehículos desde el punto de vista de los materiales que se emplean es el reciclaje. Sin embargo hay dos grandes problemas en torno al mismo. Por un lado los ratios de reciclaje no están avanzando tan rápidamente como la demanda de materiales y por otro lado las políticas de reciclaje no incentivan la recuperación de metales escasos. En la actualidad, los objetivos de reciclaje de vehículos se fijan en alcanzar un porcentaje de reciclabilidad sobre la masa total del vehículo. Para conseguir esas cuotas de reciclaje se llevan a cabo convencionalmente procesos mecánicos de separación de materiales. Estos procesos son de baja intensidad energética y a la vez muy eficaces para recuperar los metales que se emplean en mayores cantidades (acero, aluminio o cobre) pero resultan ineficaces para recuperar metales empleados en pequeñas proporciones (metales críticos o escasos). Como consecuencia, los metales críticos terminan subciclados en los procesos de fabricación de aleaciones de acero o aluminio y en el peor de los casos dispersos en un vertedero.

Esta tesis se desarrolla con el objetivo principal de mejorar la eficiencia en el uso de los recursos necesarios para la fabricación de automóviles. Para conseguir dicho propósito se presenta una metodología que mide la eficiencia en el uso de los recursos e identifica posibles restricciones de suministro de metales.

La metodología desarrollada se basa en la aplicación de la segunda ley termodinámica y el concepto de rareza termodinámica. Este enfoque cuantifica el valor real físico de todos los metales empleados y destaca en especial la aportación de aquellos cuya contribución al peso total del vehículo es pequeña, pero cuya escasez y por tanto su valor para el planeta es elevada. Este método evalúa la calidad de los materiales en función de su abundancia en la naturaleza y la energía útil (exergía) requerida tanto para extraerlos como para procesarlos y ponerlos a disposición de las industrias.

Además del enfoque termodinámico, en esta Tesis se analizan las posibles restricciones de metales que puedan surgir en las próximas décadas. Para ello se aplica un modelo que considera la disponibilidad geológica de materiales (reservas y recursos), la capacidad de producción anual de los metales, la demanda anual estimada de cada metal, la demanda acumulada hasta 2050, la evolución de las cuotas de reciclaje y el impacto de la demanda de materiales de otros sectores.

Los métodos desarrollados se aplican a diferentes tipos de vehículos (ICEV[1], PHEV[2] y BEV[3]) y han permitido alcanzar entre otros los siguientes resultados principales: (1) Desde el punto de vista del valor mineral de los recursos empleados, un vehículo eléctrico demanda 2.2 veces más recursos que un vehículo de combustión; (2) Hay 31componentes críticos en un vehículo convencional desde la perspectiva de los materiales que emplean; (3) Se han definido recomendaciones de ecodiseño para esos componentes basadas en reducir la demanda de metales escasos y mejorar tanto su reciclabilidad como su reusabilidad; (4) En los actuales procesos de reciclaje de vehículos un 27 % del valor mineral de los metales no se recicla funcionalmente; (5) Se han propuesto recomendaciones para la reducción de dichas pérdidas; (6) Se ha definido un ranking de los metales más estratégicos para el sector de la fabricación de vehículos siendo los 10 más estratégicos los siguientes: Ni, Li, Tb, Co, Dy, Sb, Nd, Pt, Au y Ag.

Las contribuciones de esta Tesis son de gran valor para mejorar la sostenibilidad del sector de la fabricación de vehículos desde la perspectiva de los materiales que se emplean y están principalmente dirigidas a los siguientes grupos de interés: (1) Los diseñadores de vehículos, porque les ayudará a identificar propuestas de ecodiseño desde la perspectiva de los materiales; (2) Los responsables de desarrollar políticas en torno a la eficiencia en el uso de los recursos, ya que demuestra la debilidad de las políticas actuales basadas en el peso de los materiales y ofrece como alternativa un método que evalúa tanto la cantidad como la calidad de los materiales; (3) Los ejecutivos de las empresas, porque les presenta la dependencia y vulnerabilidad de la tecnología sobre ciertos materiales y les ayudará a planificar con antelación líneas de I+D+i basadas en la eficiencia en el uso de los recursos.

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[1] Vehículo de combustión interna (en versiones diésel y gasolina)

[2] Vehículo híbrido

[3] Vehículo eléctrico

Abstract

Decarbonizing world economies is necessary to avoid the continuous increase of global temperature and its negative consequences for humanity. To get this ambitious target new advances in the fields of power generation with renewables and mobility with cleaner vehicles are being made. In the case of vehicles, these advances are being mainly focused on improving the performance of combustion engines, to reduce greenhouse and polluting emissions and the development of free direct emission vehicles like the electric ones.

Advances towards cleaner vehicles are encouraging the continuous renovation of vehicle fleet so it is expected that in the following decades a complete renovation will take place. This new generation of vehicles will significantly reduce its fossil dependency. But in contrast, it will demand a huge quantity of other kinds of natural resources being some of them even scarcer than oil. Some of these resources will be necessary to manufacture the following components: batteries (Co, Ni, Mn or Li); LEDs for lighting (Ga, Ge, Y); permanent magnets for motors (Nd, Dy, Pr); catalytic converters (Pt, Pd, Zr); electronic units (Au, Ag, Sn, Ta, Yb), different kinds of sensors (Ce, Tb, Se, La), infotainment screens (In); automotive high performance steel or aluminum alloys (Nb, Mo, Cr, Ti, V, Sc, W) or injectors (Tb). Unfortunately these resources are finite and some of them are very scarce being even considered as critical for the European Commission and other institutions from several perspectives such as vulnerability, economic importance, supply, or ecological risks.

One of the solutions to improve resource efficiency in vehicles is to recycle these valuable metals. Nevertheless, there are two main problems around the recycling situation. On one hand, recycling rates are not growing up as faster as metal demand. On the other hand, current recycling policies define targets based on mass weight approaches, and even if they are ambitious, they fail in enhancing the recycling of minor but critical metals. The legislation compliance is achieved by means of applying mechanical separation techniques. These processes are effective to recycle those metals with the highest contribution in the vehicle weight (steel, aluminum and copper) but they are not effective for the recovery of minor metals like those that are scarce and/or critical. Consequently, minor metals end downcycled during steel or aluminum smelting or in the worst case they finish dispersed in landfills.

This Thesis is presented with the main aim to improve the resource efficiency in the vehicle manufacturing sector. To accomplish with this aim, a novel method for measuring the resource efficiency and to identify possible shortages in the supply of metals is presented.

The resource efficiency is analyzed through the second law of Thermodynamics through the concept of thermodynamic rarity. This method takes into account the quality of mineral commodities as a function of their relative abundance in Nature and the energy intensity required to extract and process them. The application of the thermodynamic approach allows not only to recognize the physical value of materials with a low weight contribution but also to identify those components that use them.

As it has been mentioned before this Thesis also assesses possible metal shortages. This activity is made by means of an own method which combines geological data (reserves and resources), annual capacity production, annual expected demand, cumulative expected demand to 2050, recycling rates evolutions and future resource demand of other technologies.

The methodology is applied to different types of vehicles (ICEV[4], PHEV[5] and BEV[6]) and it has been useful to achieve the following main results: (1) From a thermodynamic point of view an electric vehicle demands 2.2 times more quality resources than a combustion one; (2) 31 critical components were identified in a conventional vehicle from the perspective of the materials used to manufacture them; (3) Eco-design recommendations for these components have been defined. These recommendations are based on: reducing the demand of scarce metals and to increase both the recyclability and the reusability; (4) In current End of Life Vehicle (ELV) processes 27 % of the mineral capital (measured in rarity terms) is not functionally recycled; (5) Recommendations to reduce these losses have been proposed; (6) A strategic metal ranking for the automobile sector has been produced, being the top 10 most strategic metals the following: Ni, Li, Tb, Co, Dy, Sb, Nd, Pt, Au and Ag.

The contributions of this Thesis are valuable to improve the sustainability of the vehicle manufacturing sector from the raw materials point of view. These contributions are mainly valuable for the following stakeholders: (1) Designers because it helps them to apply eco-design proposals from a raw materials point of view; (2) Policy makers because it evidences the weakness of mass based approach recycling policies and it proposes an alternative method that takes into considerations not only quantity but also quality; (3) Company's executives because it confronts them with the metal dependency and vulnerability of technology and it helps them to plan with enough time R+D+i lines based on resource efficiency.

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[4] Internal combustion engine vehicle (in diesel and petrol versions)

[5] Plug hybrid engine vehicle

[6] Battery electric vehicle

Nomenclature

A	Automobile manufacturing sector demand of each metal with respect to the total production[1] (-)
A	Vehicle part[2] (-)
B	Available reserves with respect to cumulative demand from 2018 to 2050 (-)
b	Exergy (kJ/kg)
C	Metal known resources with respect to cumulative demand from 2018 to 2050 (-)
D	Production capacity and annual demand ratio for each metal from 2018 to 2050[1] (-)
D	Downcycling[2] (kJ)
D	Cumulative material demand[3] (t)
d	Material demand (t)
E	Economic Importance (-)
ERC	Exergy Replacement Cost (kJ/kg)
F	Supply Risk (-)
i	Metal assessed (-)
k	Unit exergy cost (-)
m	Mass (g)
m	Studied technologies[3]
N	Manufactured units (-)
p	Production (t)
R	Thermodynamic Rarity (kJ/kg)
r	Material share from recycling (%)
R	Resources or Reserves[3] (t)
R	Universal gas constant (kJ/kgK)
Re	Recycling quote (%)
T	Temperature (K)
t	Year (-)
x	Mineral concentration (-)

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[1] This nomenclature is used in Paper III.

[2] This nomenclature is used in Paper IV.

[3] This nomenclature is used in Paper I.

Greek letters

α	Weighting coefficient of variable A[4] (-)
β	Weighting coefficient of variable B[4] (-)
γ	Weighting coefficient of variable C[4] (-)
δ	Weighting coefficient of variable D[4] (-)
ε	Weighting coefficient of variable E[4] (-)
ζ	Weighting coefficient of variable F[4] (-)
Δ	Difference (-)

Subscripts and superscripts

$_0$	Reference conditions
$_a$	commodity
$_{ave\_metal\_scrap}$	Car part manufactured with average metal scrap
$_c$	Earth´s crust
$_i$	Substance
$_m$	Mineral deposit
$_{ngt}$	Green technologies manufactured
$_{ns}$	New units added to the global market
$_{ori\_metal\_comp}$	Car part manufactured with the original metal composition
$_r$	Commercial grade
$_{rgt}$	Green technologies to renew older installations
$_{rn}$	Vehicle sales to replace older ones

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[4] This nomenclature is used in Paper III.

Abbreviations

AMS	Automobile sector
ASR	Automotive Shredding Residue
ATS	Advance Technologies Scenario
BAU	Business As Usual
BEV	Battery Electric Vehicle
BP	British Petroleum
B2DS	Beyond 2º Scenario
CCS	Carbon capture storage
CdTe	Cadmium telluride solar cell
CIGS	Copper indium gallium diselenide solar cell
CRM	Critical Raw Materials
CRS	Central Receiver System
ECU	Electronic Control Unit
EIA	Energy Information Administration
ELV	End of Life Vehicle
EoL	End of Life
Equi	Equitative
EV	Electric Vehicle
Exp	Experts
FU	Functional Unit
GEO	Geological
GHG	Greenhouse gas
ICEV	Internal Combustion Engine Vehicle
IDIS	International Dismantling Information System
IEA	International Energy Agency
IEEEJ	Institute of Energy Economics Japan
LCA	Life Cycle Assessment
LDV	Light Duty Vehicle
LED	Light Emitting Diode
LFP/C	Lithium Iron Phosphate ($LiFePO_4$)
LIS	Lithium ion-sieve technology
Li/air	Lithium air battery
Li/S	Lithium-sulfur battery

MDBAU	Business As Usual Development Model
MDH	Hubbert peak Development Model
MDP	Population Development Model
NCA/C	Lithium Nickel Cobalt Aluminum Oxide ($LiNiCoAlO_2$)
NMC/C	Lithium Nickel Cobalt Manganese Oxide ($LiNicoMnO_2$)
NGO	Non-governmental organizations
NiMH	Nickel metal hydride
PGM	Platinum Group Metal
PHEV	Plug Hybrid Electric Vehicle
PT	Parabolic Through
PV	Photovoltaics
REE	Rare Earth Elements
RES	Resources
RSV	Reserves
RTS	Reference Technology Scenario
SMI	Strategic Metal Index
SUV	Sport Utility Vehicle
UHSS	Ultra-High Strength Steel
USGS	United States Geological Survey
WEC	World Energy Council
WEEE	Waste Electrical Electronic Equipment
WWF	World Wildlife Fund
2DS	IEA 2º Scenario

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Chapter 1. Introduction.

1.1. Objectives

The general objective of this Thesis is to understand and provide tools to improve the resource efficiency in the vehicle manufacturing sector from a metals point of view. Overall, this research aims at identifying current weaknesses and define recommendations for improving the sustainability of the sector.

Specifically, the thesis has the following goals:

- To develop a method for assessing the resource efficiency in passenger vehicles from a physical point of view.
- To identify the most critical metals demanded to manufacture vehicles from a physical point of view.
- To identify the most critical components used in a vehicle from the raw materials point of view.
- To analyze the role of future vehicles such as Battery Electric Vehicles (BEV) in the energy transition and the availability of resources to be manufactured.
- To identify possible future metal shortages (bottlenecks) affecting the manufacture of vehicles.
- To estimate functional recycling rates of each metal to avoid such identified metal bottlenecks.
- To compare three types of vehicles (internal combustion engine ICEV, plug hybrid electric vehicle PHEV and BEV) from the point of view of the raw materials demanded.
- To build a vehicle metal ranking based on a holistic vision where both physical and non-physical variables are taken into consideration.
- To quantify the mineral capital that is lost associated to the wastes appearing in current ELV recycling processes as a consequence of downcycling.
- To propose recommendations from a thermodynamics perspective to reduce the downcycling degree in automobile recycling processes.
- To define eco design recommendations to improve the resource efficiency in vehicles.
- To give recommendations for policy makers to reduce the weaknesses concerning weight based approach regulations. Current approaches do not incentivize the recycling of minor but scarce metals.
- To define future research lines to face future challenges concerning resource efficiency in the automobile sector.

1.2. Thesis Structure

This Thesis is presented as a compilation of **five scientific publications**. These works were published following a research line which was mainly focused on analyzing the resource efficiency of the use of metals in passenger vehicles.

A revision about the state of the art has been undertaken with the aim to put into scientific context the main contributions of this Thesis with respect to other authors. This activity is presented in Chapter 2, where previous scientific contributions concerning resource efficiency in vehicles are presented, including shortcomings in End of Life Vehicle (ELV) legislation, possible resources shortages or eco-design methodologies. Subsequently, the methodological fundamentals applied in this Thesis are presented in Chapter 3. The fundamentals are divided into two main sections: The method used for the identification of future shortages or bottlenecks (applied in **Papers I and III**) and the thermodynamic approach used to measure resource efficiency (applied in **Papers II, IV and V**).

Subsequently in Chapter 4, different vehicle metal compositions used in the Thesis are shown. This work has been done by means of a scientific review of previous publications and an own research using internal IT Systems that belong to SEAT S.A.

The research line itself, which is based on the papers compilation begins in Chapter 5. This is addressed by means of giving first an overview about how resource demand will evolve as a consequence of the energy transition to a low carbon economy. As will be seen, a rapid deployment of renewables and electric vehicles will be key to meet Paris commitments, i.e. limiting global warming to well below 2°C. Chapter 5 is thus devoted to analyze the availability of resources to guarantee the required development of green technologies, with special emphasis on vehicles. This overview points to the important demand of metals that will be faced in the coming years in the vehicle manufacturing sector and the reason why this Thesis deeply analyzes this challenge.

Accordingly, in Chapter 6, the resource efficiency of three different types of vehicles (ICEV, PHEV and BEV) is studied through a methodology based on thermodynamics that also allows to identify the most critical car subsystems from a raw materials point of view. The results serve to show some weaknesses regarding current weight-based approaches used in recycling and reuse regulations for the car industry and about the electric vehicle sustainability.

As it has been mentioned, Chapter 6 gives a physical (thermodynamic) approach to identify the most critical metals and components in a vehicle. However, there are also some relevant non-physical variables that makes a metal critical (or strategic) for a given industry. For example: supply risks, sector dependency or economic importance. This is why in Chapter 7, a holistic view to identify the most strategic metals for the automobile sector is presented. As main contribution, a so-called Strategic Metal Ranking is developed, which classifies all metals demanded to manufacture vehicles according to their global strategic value to the sector. This classification takes into consideration both physical like non-physical variables and it serves to demonstrate the reliability of the results offered by the thermodynamic method previously presented in Chapter 6.

As is well known, recycling is considered one of the solutions to guarantee the sustainability of raw materials. Yet, as will be seen in Chapter 8, there are no specific recycling processes for minor metals like Co, Au, Sn or Ta in ELV and as a consequence they end downcycled in steel or aluminum recovery processes, thereby losing their functional use for which they were originally produced. Chapter 8 addresses this issue and quantifies the loss of these materials at the End of Life (EoL) of vehicles along with several recommendations to reduce these losses.

The effectiveness of reuse and recycling processes increases dramatically when products are properly eco-designed considering the EoL. Chapter 9 presents a method to identify the most critical components where valuable metals are lost after common recycling processes. Subsequently, it provides eco-design recommendations classified into the following categories: Facilitate the disassembly; Substitutability; Retrofitting; New approaches. Finally, Chapter 10 summarizes the main contributions of the Thesis and presents the future research lines that have been identified after this work. This chapter is also presented in Spanish according to the University of Zaragoza requirements.

Chapter 2. Resource efficiency in the automobile sector. State of the art.

2.1. Introduction to the chapter

For a better understanding about the novelty and scientific context of this Thesis, a review about the state of the art concerning resource efficiency in the automobile sector has been carried out. This chapter presents this revision with the following structure: (1) Possible bottlenecks in metals demanded in the energy transition; (2) Global situation and outlook about vehicle sustainability from a raw materials point of view; (3) Shortcomings in vehicle recycling processes and (4) Eco-design of vehicles from a raw materials point of view.

2.2. Possible bottlenecks in metals demanded in the energy transition

In the 21st United Nations Framework convention on Climate Change celebrated in December 2015 in Paris, it was agreed to hold the increase in the global average temperature to well below 2ºC above pre-industrial levels. Besides, it was proposed that global peaking of greenhouse gas emissions (GHG) should be reached as soon as possible [1]. In this respect, the European Commission, via the Joint Research Centre (JRC), is exploring the most effective way to make the European economy more climate friendly. As it was published by the European low carbon economy roadmap, GHG emissions must be cut to at least 80% below 1990 levels and to accomplish this goal, all sectors must contribute [2].

Both the electric generation and transport sectors have a great potential to achieve the European targets. According to the European Commission, the electricity power generation sector has actually the biggest potential for cutting emissions and it could almost totally eliminate CO_2 emissions by 2050 [3]. On the other hand and considering the European white paper of transport, the transport sector, and especially private mobility, could reduce its CO_2 emissions by up to 60% in the same time frame [4]. These changes will imply a renovation in the energy sector towards using renewable sources and zero direct emission transport technologies such as electric vehicles.

During this transition period, green technologies like wind power, solar photovoltaic or electrical vehicles will grow. According to International Energy Agency projections [5], in 2050, wind power and solar power technologies[5] will have more than 2,400 GW and 4,500 GW of installed power, respectively. Yet this transition must be carefully accomplished as huge amounts of raw materials are going to be required, increasing the pressure on raw material availability.

As Alonso et al. [6] and Elshkaki and Graedel [7] published, wind power will demand important amounts of rare earth elements (REE) like neodymium and dysprosium to build permanent magnets for electric generators. Additionally as it was published by Grandell et al. [8];

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[5] Solar power technologies include solar photovoltaic and solar thermal power.

Ravikumar. and Malghan [9] and Elshkaki and Graedel [10] solar photovoltaics demands high quantities of silver for electricity connections, and other materials like cadmium, tellurium, or indium for manufacturing p-n junctions in solar cells used in thin film technologies like CIGS or CdTe. As in the case of Solar Thermal Power (STP), Pihl et al. [11] demonstrated that it requires silver for manufacturing reflectors or nickel and molybdenum for manufacturing high strength steel alloys needed in structures.

In the field of mobility, Light Duty Vehicles (LDV) based on polluting internal combustion engines, will be progressively replaced by vehicles based on electro mobility. Regarding the concern about the future impact that large capacity batteries required by electric vehicles will have, Miedema and Moll [12] and Mohr, Mudd and Giurco [13] researched the case of lithium and possible constraints to manufacture electric vehicles.

It is well known that one of the solutions to guarantee a sustainable raw material supply is recycling. However, the current situation of recycling has a lot of improving potential. As Redlinger, Eggert and Woodhouse [14] demonstrated, current recycling rates of some of these materials are almost negligible because sometimes recycling processes are more expensive than primary raw material costs, as it happens with the use of indium, gallium, cadmium and tellurium in solar modules. This argument can be also extracted from Ayres, Villalba and Talens [15] which indicate that many metals are used in very small amounts in each individual product. Indeed, and even if it has been demonstrated that recycling has a huge improving potential by including pre-recycling processes to recover the metals, Wang, Gaustad and Babbit [16] affirm that current recycling rates are still very low. For instance, Vikström, Davidsson and Höök [17] demonstrated that less than 3 % of the lithium contained in a battery is currently recycled and Richa et al. [18] that only 42 % of the total battery waste mass can be recycled with current available technology.

As a result, the concern regarding the impact of green technologies on raw material availability is becoming an important issue for countries with the aim to guarantee their sustainability and many authors and institutions such as Grandell et al. [8]; Silberglitt et al. [19]; The U.S Department of Energy [20]; Moss et al. [21] and Graedel et al. [22] among others are researching this issue.

The importance of some rare materials for the future development has caused that some of them are considered as critical. Nevertheless, there is a discussion related to the definition of raw material criticality. The criticality of materials has been extensively studied using different points of view. According to Alonso et al. [23]; Achzet et al. [24]; The European Commission [25] and Kamei [26], the assessment includes several dimensions related to vulnerability, economic importance, supply or ecological risks. But most of these factors are very influenced by geopolitical and socioeconomic elements, what makes that critical raw materials (CRM) lists must be frequently updated. This is why the term critical evolves so fast and it is difficult to have a clear long-term perspective about criticality. An example about this situation is the case of the critical raw material list developed by the European Commission. This list was published for the first time in 2011 where 14 raw materials were considered as critical. In 2014 this list was updated identifying up to 20 critical raw materials. Finally the last updating of this list appeared in 2017 and included the following 27 CRMs [27]: antimony, fluorspar, LREEs, phosphorus, barite, gallium, magnesium, scandium, beryllium, germanium, natural graphite, silicon metal, bismuth, hafnium, natural rubber, tantalum, borate, helium, niobium, tungsten, cobalt, HREEs, PGMs, vanadium, coking coal, indium, phosphate rock.

As it was proposed by Calvo, Valero and Valero [28] the term criticality should include an additional dimension to economic importance or supply risks. They proposed to include a third dimension named thermodynamic rarity, which accounted for the scarcity in the crust of the given raw material and the energy intensity associated with extracting and refining the material. As main result they proposed to update the 2014 critical raw material list published by the European Commission including also: Li, Ta, Te, V, and Mo. In this regard, it is worth mentioning that in the last update of the European CRM list published in 2017 (which again only considered economic importance and supply risks) with the exception of Mo, all additional CRM proposed by Calvo, Valero and Valero [28] were included. So the economic importance and the supply risks (which are non-physical characteristics) of the commodities have also, at least in the medium to long term, a relationship with the thermodynamic value of metals which only depends on physical characteristics and can be useful to predict future vulnerabilities of some technologies or nations. It is the thermodynamic rarity approach the one mainly used in this Thesis to assign a value to the metals contained in a car.

In addition to the definition of metal criticality, an important issue is the identification of bottlenecks for the development of a given technology. According to Moss et al. [29] and Elshkaki and Graedel [30], material constraints can be assessed by comparing future demand with current production capacity. In contrast, Sohn [31] suggests that this should be done by comparing reserves with production capacity. These approaches consider that production is static and that it does not change over time, a trend that has been proven wrong over the years. Moreover, as reserves are dynamic because they actually depend on demand, exploration efforts and technological progress, all of which very related to economic interest of the commodities, reserve-based approaches also present a high level of incertitude. Thus, even if they constitute a valuable first approach, the analysis must incorporate a dynamic behavior to provide more realistic values.

For instance, in the case of the energy sector, models that provide dynamic data, like TIMES-MARKAL[6] or LEAP[7] can be used to assess the impacts on fossil fuel supply, emissions and encourage the development of energy policies. Such models were applied by Grandell et al. [8]; Emodi et al. [32]; Kuldna, Peterson and Kukhi-Thalfeldt [33] and Nadejda, Nichols and Balash. [34], among others.

As for non-fossil fuels, Sverdrup, Ragnarsdottir and Koca [35–37] have developed several dynamic models for specific minerals (copper, lithium, aluminum, etc.) that rely on information regarding ore grade, production rates or market prices among other factors to make future predictions. It should be stated that these models need very specific data and definition of variables and functions to estimate future projections, which partly need to be based on important assumptions. Indeed, creating a model that estimates future raw material production is a challenge. That said, in the case of fossil fuels, the Hubbert peak methodology, proposed by Marion King Hubbert [38] in the fifties to estimate oil production behaviour in the US, was addmitted by many different authors such as Murray and King [39]; Capellan-Perez et al. [40] and Chapman [41] among others, as a useful and reliable model to predict production peaks. This approach considers that production evolution follows an exponential behaviour until it reaches a peak which is constrained by the available reserves, therefore production is not considered as a constant. This model was applied by Calvo, Valero and Valero [42] to predict future capacity production of different commodities. Obviously the model has weaknesses related with data availability and to unpredictable changes in future production, as it relies on a business as usual scenario. That said, the reliability of its output is greater than of those models which consider yearly production as constant.

For this reason, in the identification of possible bottlenecks for the energy transition and in particular in the vehicle manufacturing sector, the constraints will be identified in this Thesis by combining expected demand with the expected annual capacity production based on a Hubbert-like behaviour.

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[6] Model developed by the IEA. More information: https://iea-etsap.org/index.php/etsap-tools/model-generators/times

[7] Model developed by the Stockholm Environment Institute. More information: https://www.energycommunity.org/default.asp?action=introduction

2.3. Global situation and outlook about vehicle sustainability from a raw materials point of view

The vehicle manufacturing sector is one of the most intensive in raw materials use (Wells [43]). Indeed, vehicles constitute a very significant stock in use of materials. Considering USGS data, steel and aluminum stock in US vehicles amount to 4,070 Mt (5.3 % over the total steel stock in that country) [44] and 19.1 Mt (13.8 % over the total Al stock) [45], respectively. This is partly due to the increasing amount of vehicles being sold. As published by the International Organization of Motor Vehicle Manufacturers [46], global car sales have more than doubled over the past thirty years, from about 29 million in 1980 to 65 million in 2014. This is why Arda et al.. [47] state that a stable supply of raw materials is crucial for the transition to a sustainable and circular economy. For Simic and Dimitrijevic [48] this becomes even more important considering that, by 2030, up to 1.85 billion vehicles are expected to be added to the current fleet, what will undoubtedly require massive amounts of raw materials, as stated by Hernandez et al. [49].

Yet the number of vehicles is not only increasing, but also the models are continuously changing and so the raw materials incorporated in cars. These changes are made because new requirements are constantly demanded by users. According to Schipper [50], this evolution has caused that from mid-1980´s vehicles have become heavier. This weight increment was mainly caused by the increase of power and the inclusion of technical progresses towards energy-efficiency in engines and safety standards in the body in white, as it was demonstrated by Zachariadis [51].

On the other hand, more equipment and environmental requirements are being demanded and accordingly the need of materials to manufacture catalyst converters, glass, flat panel displays, electronic equipment, electrical motors, batteries, super alloys or communication technologies, is rapidly increasing. Specific reasons for the changes in vehicle material composition over time from different author opinions include among others the following:

- The replacement of Fe by Al alloys for parts such as the head cylinder or gearbox case, body-in-white, and wheels. Hatayama al [52]; Lovik, Modaresi and Müller [53] and Van Schaik et al. [54].
- The increase in the use of plastics for the interior of the car. Juska [55].
- The use of hybrid-electric or fully electric powertrains. Eurostat [56].
- The evolution from manual to automated control of vehicle functions owing to an increased number of car electronics. Restrepo et al. [57].

As consequence of this evolution, current vehicles require more electrical and electronic devices that demand an increasing amount of different metals such as Li, Co, Mn, Ni, and different rare earths to manufacture batteries (Simon, Ziemann and Weil [58]); Nd, Pr, and Dy to build permanent magnets (Riba et al. [59]) or Ag, In, Ta, or La to manufacture electronic components

(Andersson et al. [60]). So as demonstrated by Ortego et al. [61] a conventional vehicle demands more than 50 different types of metals.

Steel can be used as an example of how its use in cars evolved. In the past, the primary attributes required from automotive steel were strength and corrosion resistance. However, and as stated by Kawaguchi [62], now steel grades have to satisfy also other requirements such as fuel efficiency or safety performance. For instance, Belanger, Walps and Milititsky [63] demonstrated that only in the body in white 9 different steel grades, including high strength and ultra-high strength steels are used.

On top of this, as stated in the previous section, for achieving European greenhouse gas emissions targets, a change in vehicle powertrains is expected. The use of electric vehicles is one of the proposed solutions to reduce transport environmental impacts. As it is established by the Transport White Paper, internal combustion engine vehicles (ICEV) fleet must be reduced by at least 50 % before 2030 and must be avoided by 2050. This leads to a strong increase in electric vehicle sales. According to sales projections by type of vehicle published by different entities (European Commission [5], European environmental Agency [61], International energy Agency [62] and Spanish Automobile Manufacturers Association [63]) by 2029 PHEV world sales will overpass ICEV sales and by 2038 BEV world sales will also overpass ICEV sales. As a consequence, ICEV world sales share will presumably decrease from 2018 in favor of PHEV. BEV share sales will mainly grow from 2025 onwards and in 2045 they will be even greater than PHEV sales.

Considering these forecasts, PHEV and BEV share in world fleet will be even greater than ICEV in 2045. This new generation of vehicles based on electromobility will require more electrical and electronic devices, which will need materials to manufacture batteries, permanent magnets and electronic components.

Focusing only on the situation of critical metals, according to Cullbrand and Magnusson [67], in a conventional diesel hybrid vehicle, 31 CRM can be found. Yet according to Andersson et al. [68], only 1 % of the vehicle mass includes more than 25 metals, being the most part of them critical as stated by Alonso et al. [69].

As it has been mentioned in the previous section, the term critical has different definitions, however the term in itself has become a topic of concern in the automobile sector independently of the approach used. As demonstrated by Du et al. [70] and Modaresi and Müller [71], critical metals in passenger vehicles are mainly found in the embedded electrical and electronic devices. Moreover, Lovik, Modaresi and Müller [53] affirmed that critical metals are also used as alloying elements in aluminum and steel alloys constituting the body-in-white and powertrain of the vehicle. According to Modaresi and Muller [68], the number of embedded electrical and electronic devices and the alloy types depend on different characteristics such as vehicle equipment, power source, and model, which define the vehicle type. Moreover, and according to some authors like Kushnir and Sanden [69], Scrosati and Garche [70] and Grosjean et al. [71], the future widespread adoption of electrical powertrains will encourage the development of large-capacity batteries which will also increase the demand of some critical metals such as lithium (Schmidt, Buchert and Schebek [72]) or cobalt (Väyrynen and Salminen [73]).

A raw material assessment of passenger vehicles is thus a key topic to understand the sustainability of the sector and as a consequence it has been already studied by different authors. Batista, Freire and Silva [77] presented an overview of different methodologies to calculate the environmental rating of a vehicle, but no identification of critical materials was made. In the field of using critical raw materials Alonso et al. [69] made an assessment of different types of vehicles (ICEV, PHEV and BEV) and the use of REE contained in them to compare REE´s vehicle demand with REE´s reserves values. Du et al. [70] assessed the distribution of critical metals in conventional LDV. This study was made by combining input and output driven approaches. A revision of previous studies was made and in total 57 elements were analyzed. Cullbrand and Magnusson [67] made an assessment of potentially critical materials in passenger cars. The approach used a top-down methodology using manufacturer´s databases from the International Material Data System (IMDS). The study assessed 31 critical materials in 4 different car models with different equipment level and powertrain. The selection of these materials was made according to geological availability or supply risk information. Du and Graedel [78] assessed the global demand of REE (including automobile sector) and quantified the amount of Ce, Nd, La, Pr, Y, Gd, Sm, Tb and Eu stock in use in vehicles.

Beyond providing the raw material composition of vehicles, this Thesis proposes to apply a quality weighting factor to each material used in vehicles. Such weighting factor is based on a novel indicator called thermodynamic rarity, as used by Calvo, Valero and Valero [28] to define thermodynamic criticality of metals. The advantage of doing so is that minor but scarce materials even if used in low quantities in the car, will obtain a much greater relative weight, when measured in rarity terms. This will allow to identify those car parts where the most valuable metals are placed.

2.4. Shortcomings in vehicle recycling processes

According to the European Automobile Manufacturers Association [79] in 2014 the European passenger car fleet amounted to 250 million of units, of which around 45 % were more than 10 years old. Andersson, Ljunggren and Sanden [68] stated that the size and the age of the European fleet makes that each year around 7 million of end of life vehicles must be treated and as a consequence between 8 and 9 million tons of wastes are generated.

To get a global vision about the impact of ELV the following data must be taken into consideration:

- According to European Commission data [80], ELV account for up to 10 % of the total amount of hazardous wastes that each year are generated in Europe.
- According to Zorpas and Inglezakis [81], the vehicle sector generates approximately 5% of the world’s industrial waste.

In this respect, Simic and Dimitrijevic [82] indicate that the treatment of ELV and the impact of discarding their residues are subject of worldwide concern. To encourage the recycling of materials and to prevent waste generation from ELV, the European Commission published the EU Directive 2000/53/EC. This regulation established that from January 2006, the recovering and reusing rate of all end of life vehicles should be as minimum as 85 % and reusing and recycling rate must be 80 % per vehicle and year. Moreover, from January 2015 these targets were increased to 95 % and 85 %, respectively [83]. In that respect, Millet, Yvars and Tonnelier [84] proposed a methodology based on impact of module recycling rate to set the a reference vehicle and so demonstrate the feasibility of the compliance of the EU ELV recycling Directive. This methodology considered the material composition of vehicles and component´s recyclability approaches to identify the reference vehicle. Meanwhile, the impact of ELV legislation was analyzed by Inghels et al. [85], who published a method based on system dynamic models and applied it to the case of Belgium. This assessment was focused on the potential of plastics to be reused and recycled to meet ELV legislation targets.

Focusing on ELV recycling processes, Andersson, Ljunggren and Sanden [60] consider that they are typically aimed at isolating hazardous content, selling spare parts, recovering and recycling some regulated parts such as batteries, tires, or catalytic converters, and recycling the metallic compounds existing in the largest quantities such as steel and aluminum alloys.

For metals contained in ELVs, recycling plants (shredders) are mainly designed to separate ferrous (steel) and non-ferrous (aluminum, copper and zinc) fractions, which are subsequently sent to smelters as secondary sources. According to Ohno et al. [86], these operations entail the loss of most alloy elements either because they are downcycled or because they end up in the automobile shredder residue (ASR), ultimately becoming landfilled.

The concept of downcycling is understood as *"to recycle something in such a way that the resulting product is of a lower value than the original item"* [87]. Metal downcycling in ELV processes is a topic of concern; as demonstrated by Andersson, Ljunggren and Sanden [60] from a total of 17 metals investigated, only Pt from catalytic converters is functionally recycled.

Moreover, as demonstrated by Ohno et al. [88], approximately 60% of Ni, Cr, and Mo contained in light duty vehicles unintentionally end up as the metal source in steel-making process. As a result, Amini et al. [89] demonstrated that these metals are lost during smelting; dissolved in the molten metal during smelting; or diluted as contaminants when they exceed the maximum content allowed for a specific alloy. According to Nickel Institute data [90] only 40% of the automobile content is reused for its nickel content in steel plate rolls; another 40% is downcycled into other metals and becomes unavailable to the nickel recycling loop and finally around a 20% ends up in landfills. According to Maurice, Niero and Bey [91], this fact happens because metals are recycled in open/cascade recycling loops where dilution and quality losses occur.

Similarly, Andersson, Ljunggren and Sanden [60], based on an analysis of Swedish ELV concluded that only Pt was functionally recycled in its main application and for other 16 metals (Y, Li, Au, Dy, Er, Ga, Gd, Pr, Rh, Sm, Tb, Yb, Co, Nd, La and Ta) functional recycling was absent. For their part, Pan and Li [92] studied the case of ELV in China. They used emergy[8] as an indicator for measuring the efficiency of ELV processes and identified that the most important non-renewable input are raw materials (93.98 % over the total) and the most important output waste is the battery (42.56 % over the total waste). This method demonstrated that other kinds of approaches could be used for measuring resource efficiency instead of weight.

In summary, there is a huge improving potential in ELV recycling processes. As Hatayama et al. [52] stated for the case of aluminum, an appropriate scrap sorting in the future could mitigate the generation of unrecyclable scrap and reduce the consumption of primary aluminum by up to 15–25%. For their part, Ohno et al. [93] assessed alternative processes to recover alloying steel elements (Mn, Cr, Ni and Co) from ELV. The important gap that exists between steel producers and ELV recyclers is the main reason why proper recovery of such valuable elements is hindered in practical terms.

With respect to specific car components, Belboom et al. [94] focused on the recycling of hybrid vehicles in which different scenarios were compared according to the treatment of specific vehicle parts like batteries, Electronic Control Unit (ECU) and big plastics. From their point of view the dismantling of these components before shredding was not significant benefits from LCA

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[8] Emergy is defined as *"the amount of direct and indirect solar energy needed to produce any product or service"* Odum [142].

perspective. In this respect, Tian and Chen [95] proposed several disassembly processes for encouraging the dismantling of vehicles at the end of life. The method was applied to a dashboard and plastic polymer used layers.

Dismantling and appropriate material sorting is so important because, as demonstrated by van Schaik and Reuter [96], commercial recycling systems never achieves 100 % material recovery during physical separation, high temperature metal production or thermal processing. According to several authors such as Ignatenko, van Schaik and Reuter [93], Gutowski and Dahmus [94–95], Nakajima et al. [96] and Valero and Valero [97], these losses are intrinsic to any process and many of them are unavoidable as stated by the second law of thermodynamics. The physical limitations posed by the combination of materials, together with the intrinsic efficiency of the current recycling technologies have been previously analyzed by Reuter et al. [98], Ignatenko, van Schaik and Reuter [99] or Castro et al. [100–101]. According to Reuter [106], one of the key drivers of a true circular economy is metallurgy and the understanding of entropy in each of its facets is essential.

In depth recyclability assessments of vehicles have been performed by van Schaik et al. [54,96,107], who developed dynamic and fuzzy rule models to predict the liberation behavior and therefore the quality of e.g. recycles as a function of design choices. This in turn provides a technology based feedback to the designer on the consequences of material combinations, connections and joints as defined in the design stage of the product. A useful software to undertake such analyses is HSC Sim 9 simulator [108], which also allows to quantify the environmental impact via Life Cycle Assessments as well as through exergy.

It should be stressed that recyclability assessments are intricate and work intensive because as it was published by van Schaik et al. [103] and Mesker et al. [104] products are complex combinations of materials changing rapidly and continuously over time and have an effect on the metals and other materials obtained after their recycling. This is why, considering that a car is made up of over 1,000 different car parts, it is advisable to rank them according to the intrinsic value of the materials contained in the given component, as proposed in this Thesis. Once ranked, recyclability assessments can be subsequently performed to those car parts selected as more valuable from a material point of view and so find ways to improve the eco-design of the product.

2.5. Eco-design of vehicles from a raw materials point of view

The development of products with improved environmental performance is regarded as a crucial component of companies' commitment towards sustainable development (Rodrigues, Pigosso and McAloone [110]). This is why in recent decades the sustainability concept has acquired growing importance and a large number of methodologies, tools, standards and regulations have been developed to promote the implementation of its principles inside industrial companies (Plouffe et al. [111]).

In this respect and as demonstrated by Luttropp and Lagerstedt [112] acting in the design phase is the most important moment inside a product lifetime. As van Schaik and Reuter [96] state, during this phase not only the specifications are set, but also the quality of recycling, which is conditioned by the liberation of materials during shredding which in turn strongly depends on the design. In the industrial field, eco-design can be defined as an approach to consider and integrate environmental aspects in the product development process through the application of strategies aimed at reducing the negative environmental impact along the product lifetime (Rossi, Germani and Zamagni [113]). According to Hollander, Bakker and Hultink [114] and Luttropp and Lagerstedt [112] eco-design provides product designers with a range of guiding principles, strategies and methods and encourages better environmental product performance by means of: closing resource loops, minimizing resource consumption, promoting repair and upgrading, product long life and recycling.

In Europe, eco-design requirements are defined by the European Directive 2009/125/EC, but this legislation applies to all products related to energy with the exception of vehicles [115]. For the latter, eco-design approaches are focused on ensuring that the requirements established by the ELV EU Directive [116] and polluted emissions EU regulations [117] are met. In addition to complying with these requirements, vehicle manufacturers can also implement in their products eco-design approaches according to ISO 14006, as has been the case of some vehicle companies like SEAT S.A [118]. According to Aran-Landin and Heras-Saizarbitoria [119], ISO 14006 has as main aim to reduce the environmental impact of companies along the following phases: product design, manufacturing, transport, operation, maintenance and EoL.

In the light of the increasing environmental impacts and raw material pressure of the vehicle sector, it becomes crucial to apply eco-design approaches and so increase the resource efficiency throughout a car's life cycle. Common methods used by different authors such as Hernandez et al. [84], Lee et al. [124], Mayyas, Mayyas and Omar [125], Delegu et al. [126], Ozbilen, Dincer, and Hosseini [127] and Viñoles-Cebolla, Bastante-Ceca and Capuz-Rizo [128] for the eco-design of vehicle components is through Life Cycle Assessment (LCA). They are aimed at assessing products impacts from a cradle to grave perspective, considering material production, product production, product use and product End of Life (EoL). LCA also serve to assess the environmental performance of products. This way, for instance, Tagliaferri et al. [125] undertook a Life Cycle Assessment (LCA) with Ecoinvent [126] data and compared an ICEV and a BEV. Meanwhile, Domingues et al. [127] applied a multi-criteria decision and a LCA methodology to classify different LDV (ICEV, PHEV, BEV) according to their environmental impacts. Similarly, Bauer et al. [128] made an evaluation of the environmental performance of current and future LDV, assessing four types of vehicles: ICEV, PHEV, BEV and fuel cell vehicles (FCV).

In the case of the material production phase, Song and Lee [129] state that common methods are based on assessing the impacts related to the acquisition of natural resources and their later processing by means of using specific LCA tools such as GaBi or SimaPro [130]. Yet according to Amini et al. [89] there is an open debate whether these methods reflect well the depletion of natural resources. In this respect, this thesis proposes an alternative method based on the second law of thermodynamics through rarity indicator to identify critical components and so advise for eco-design approaches.

2.6. Conclusions

After an analysis of the state of the art of resource efficiency in the automobile sector the following conclusions serve as arguments to develop this Thesis:

- In the literature, there are already assessments of raw material use in vehicles. Yet these are still very coarse and in any case they do not provide information regarding where these materials are found in the car. This is why, to the author's knowledge, this Thesis provides the most detailed analysis of metals and components used in vehicles (Chapter 4).
- There is a concern about the availability of raw materials for the next decades and some studies have addressed the issue of possible supply shortages for certain technologies. That said, an in-depth assessment about how will be the vehicle sector affected by metal shortages is missing. This Thesis addresses this gap, Chapter 5 and Chapter 7 possible bottlenecks and the most strategic metals for the automobile sector until 2050 are presented.
- The common approach for measuring resource efficiency in the literature is through weight, thereby ignoring the quality of raw materials. For this reason, in this Thesis (Chapter 6) an alternative unit of measure called thermodynamic rarity (explained in Chapter 3) is used to assess the resource efficiency of vehicles. This method takes into account not only the quantity but also the quality of any material and it allows to measure the resource efficiency of vehicle components or vehicles as a whole.
- From the literature review it has become evident that current recycling processes do not incentivize the recycling of scarce metals. Yet an assessment of what is the loss of the mineral capital due to the downcycling of these metals is missing. This is why in this Thesis (Chapter 8) an analysis of the most downcycled metals and components in a car is done, giving a global vision about the huge amount of valuable raw materials that become lost. Some recommendations to reduce such losses are also provided.
- Eco-design of vehicles is key to improve their sustainability. That said, if resource efficiency does not consider the quality of all raw materials used, eco-design cannot be properly done. So in this Thesis (Chapter 9) eco-design recommendations are proposed for the most critical components identified in the vehicle using a thermodynamic approach.

Chapter 3. Fundamentals.

3.1. Introduction to the chapter

Chapter *Fundamentals* presents some basic principles required to obtain a global vision about the methods applied in each Paper. For this endeavor, this Chapter is divided into the followings two main sections:

- **Bottlenecks identification:** This section will be useful to understand the method to assess the possible raw material bottlenecks in the vehicle manufacturing sector until 2050.
- **Exergy approach and reference state to quantify the physical value of metals:** This section will explain how resource efficiency can be assessed from a physical and universal point of view by means of thermodynamics.

3.2. Bottlenecks identification

One of the most important contributions of this Thesis is the possibility to identify possible metal shortages for the future vehicle manufacturing sector. This method has been applied in **Paper I** and **Paper III** to identify possible bottlenecks for the development of green technologies[9] and to create a metal strategic ranking, respectively. The identification of bottlenecks has been done using a combination of bottom-up and top-down approaches, as defined as follows:

- **Bottom-up approach:** assessment, on a global basis, of reserves, resources and estimated production trends from 2016 to 2050 (assuming a Hubbert-like production trend) for each commodity.
- **Top-down approach:** assessment of material requirements in the 2016-2050 time period for 1) manufacturing green technologies, assuming state of the art developments and for 2) manufacturing products for the rest of economic sectors.

3.2.1.Resources and Reserves

As extraction is ultimately limited by the amount of minerals present in the crust with sufficient concentration, it is important to know raw material availability in terms of reserves and resources. Resources (RES) are concentrations of naturally occurring materials on the Earth’s crust in such a way that economic extraction is feasible, currently or at some future time. Reserves (RSV) in turn are the portion of resources which can be economically extracted or produced at the time of determination. Reserves are thus lower than resources and more dynamic, since identified resources can be reclassified as reserves when commodity prices rise or a decrease in production costs takes place. Different sources have been compared and those considered more accurate have

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[9] In this Thesis the term Green technologies refers to: wind power, solar photovoltaics, solar thermal power and electric vehicles.

been used for the methodology in this Thesis: USGS [131]; Sverdrup and Ragnarsdottir [132]; Emsley [133]; Frenzel et al. [134] and Frenzel, Ketris and Gutzmer [135]. Information regarding reserves and resources of rare earth elements (REE) comes from Haque et al. [136] and USGS [131].

3.2.2. Annual capacity production

As annual production rates need to be synchronized with the rising demand of materials, projections regarding future raw material production are equally required. To accomplish this task it is assumed that material production will follow the Hubbert peak model. Hubbert [38,137] showed that trends in fossil fuels production always followed the same pattern. The curve of production started slowly before rising steeply and tending towards an exponential increase over time.

This trend goes on until reaching an inflection point, upon which the curve starts to decrease, generating a bell-shaped curve of normal distribution. The area below the curve depends on the combination of the available reserves or resources and the historic production data of the commodity. Production of commodity a (p_a) in year t is given by Equation 1:

$$p_a(t) = \frac{R}{b_0\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{t-t_0}{b_0}\right)^2} \tag{1}$$

Where R are the reserves (RSV) or resources (RES) of the commodity and the parameters b_0 and t_0 are the unknowns. The function's maximum is given by parameter t_0, and it verifies that:

$$p_a(t_0) = \frac{R}{b_0\sqrt{2\pi}} \tag{2}$$

With this approach, the maximum production peak of the commodity can be obtained, meaning the year when production starts to decrease. Additionally, future yearly projections of production can be obtained using a business-as-usual scenario. It is presumed that production will continue rising with an exponential trend, as it has been the case for most commodities. Yet geological availability in form of reserves or resources prevents at some point this continuing growth.

The model has uncertainty, for this reason the coefficient of determination (R2) for each metal production capacity has been calculated. This coefficient is used to correct the value of the lineal interpolation always extending the maximum capacity year and thus keeping the criteria of a best case scenario.

3.2.3. Material demand

Metal demand must be calculated to identify future metal shortages. This was done by assessing the metal composition to manufacture different green technologies through data compilation published in the literature in the case of green technologies (**Paper I**) and by means of direct data from a car manufacturer in the case of vehicles (**Paper III**).

It was considered that a certain amount of raw materials comes from secondary sources (recycling processes). As the available information on recycling rates is usually very aggregated or general, recycling rates used in this study come from a global assessment published by the United Nations Environmental Program [138]. Eq. 3 shows how material demand in the studied technologies is calculated for a given year for each commodity:

$$d_{a\_tt} = [N * M * (1 - r)] \tag{3}$$

Where d_{a_tt} is the quantity of primary material a demanded for the analyzed type of technology (tt) during a given year; N is the number of yearly manufactured units of each type of technology; M is the quantity of material a demanded by each type of technology to manufacture one functional unit - FU (FU=1 vehicle or FU=1 MW in the cases of vehicles and renewables, respectively); r is the share of material which comes from recycling. The impact of recycling on primary production is assumed as one to one displacement because reprocessing does not change material properties. It should be stated though that as Geyer, Kuczenski, Zink et al. [139] demonstrated, this approach is not a rule because rebound effects in demand could appear, so robust models to predict the impact of recycling on primary demand must be yet developed. As the projections used in **Papers I and III** go until 2050 and the technology lifetime is lower, material demand from fleet renovation and repowering effects was considered. This effect is taken into consideration using Equation 4.

$$N = N_{ngt} + N_{rgt} \tag{4}$$

Where N_{ngt} is the number of new green technologies manufactured which are added to the global fleet and N_{rgt} is the number of green technologies to renew old ones. Nevertheless, it must be also considered that these technologies (renewables and the automobile manufacturing industry) will need to compete for materials with many sectors, such as construction, chemicals, metal industry or electronics. Unfortunately, in the case of the rest of the sectors, the information on material consumption is scattered and in many cases unavailable. This is why it is assumed that material demand for other sectors (d_{a_os}) will be kept constant until 2050 and equal to the difference between total material production in 2018 $(P_a)_{2018}$ and material demand for green technologies for the same year $(d_{a\_gt})_{2018}$ (Eq. 5). Obviously, this is a very conservative assumption as historically material demand for other sectors has usually increased year by year. That said, this assumption allows us to identify the lower bound for potential material constraints regarding material competition of green technologies with other sectors.

$$d_{a\_os} = (P_a)_{2018} - (d_{a\_gt})_{2018} \tag{5}$$

Accordingly, total demand for a given commodity *a* in year *t* (d_{a_T}) is calculated by means of Eq. 6, whereas the total cumulative material demand for commodity a (D_{a_T}) from 2018 to 2050 is obtained through Eq. 7.

$$(d_{a\_T})_t = (d_{a\_gt})_t + (d_{a\_os})_t \tag{6}$$

$$D_{a\_T} = \sum_{t=2018}^{t=2050} \left[(d_{a\_T})_t\right] \tag{7}$$

3.2.4. Recycling improvements

How can one avoid a potential bottleneck? This is one of the main questions when a bottleneck has been identified. Certainly, there are many ways to overcome them. In addition of increasing material supply (i.e. investment in exploration efforts to increase reserves and eventually resources), from the demand side, change of technologies, improving material efficiency or substitution of materials for a given application or technology (i.e. bio-based materials for metals) are some possible options. It should be though not forgotten that substitution can in some cases reduce product performance or even increase the price, as it was demonstrated by Graedel et al. [22].

In this Thesis, we focus on one of the possible solutions, increase functional recycling. To that end, the objective is to calculate the annual recycling growth that should be achieved to avoid the given bottleneck. This is than with equation 8.

$$Re_f = Re_i * \left(1 + \frac{r}{100}\right)^{f-i} \tag{8}$$

Where *Re* is the recycling quote of a given metal in a year, *f* and *i* are final and initial years of the assessment period and *r* is the annual growth recycling rate (%) with respect to the previous year. It should be stated that in reality, a combination of all above mentioned options will likely take place. That said, this method gives an indication of where to enhance recycling efforts.

3.3. Exergy approach and reference state to quantify the physical value of metals

Once the method to identify possible bottlenecks has been explained, the present section shows the thermodynamic approach used in this Thesis. But before that, it is important to understand why it was decided to use thermodynamics. As it has been explained in Section 1.1 (Objectives) one of the main aims of this work is to identify the most critical metals and components used in a vehicle from a raw materials point of view. The most obvious approach to account for resources is through their weight (i.e. a mass-based approach). This is straightforward and is always required. Yet if one stays at this level and compares different types of resources, we need to face the problem of mixing apples with oranges. Beyond this mass-based approach, one could evaluate resources through prices. However the monetary value of resources is very volatile and depends on many factors alien to the physical reality of the resource. As stated by Oers and Guinée [140], prices are influenced by particular economic markets, national social conditions reflected in labor costs, the power of mining companies with a monopoly, the costs of identifying new reserves. Moreover, money is subject to speculation, devaluation, geopolitical interests, trust in an economy, etc. On top of this, it is not a universal numeraire, and a dollar might change its value with respect to a euro or to a yen at a given time. So the challenge is to find a universal numeraire that serves to account and measure resource efficiency of products.

Other physical-based indicators that could eventually come into play are "the ecological footprint", which consists of converting equivalent global hectares to the direct and indirect consumption of resources (Wackernagel and Rees [141]) or *"emergy",* expressing the amount of direct and indirect solar energy needed to produce any product or service Odum [142]. The problem with the first is that the environmental impact on mining is hardly measurable with biologically productive area and is consequently insensitive to depletion problems. The use of emergy in turn is questionable for mineral resource assessment, as the sun has not played a central role in their creation.

In this respect, thermodynamics might have a better answer to the challenge of mineral resource accounting. Thermodynamics can be used to quantify the value of a natural resource through a property called exergy. Exergy can be defined as the minimum amount of work necessary to produce a given resource with a specific structure and concentration from common materials in the environment (Stanek et al. [143]). Accordingly, this property is a measure about the usefulness of a system with respect to its surrounding environment. This usefulness is due to being at a different state than the environment that surrounds it. The fact of being in non-equilibrium with the environment makes it distinguishable and consequently useful and valuable. Thus, the exergy of a system gives an idea of its evolution potential for not being in thermodynamic equilibrium or "dead state" with the reference environment. At the dead state, a system is at the temperature and pressure of its surroundings; it has no kinetic or potential energy and it does not react with the surroundings. All substances have a definable and calculable exergy content, with respect to a defined external environment. Once the environment is specified, exergy can be regarded as a property of the system.

Taking into consideration this statement a a mineral deposit can be considered a natural resource with an exergy content (Valero, Valero and Vieillard [144]). This exergy content is attributed to the chemical composition, cohesion degree and concentration (ore grade) which is different from its environment surroundings. Certainly, the own fact of having minerals concentrated in mines instead of being dispersed throughout the crust makes them especially valuable (Valero and Valero [145]), because this saves huge amounts of energy when compared if one would need to extract and concentrate minerals from much lower ore grades or in the limit, from barerock.

To quantify the physical value in exergy terms of any substance, it is necessary to define the reference environment, i.e. the starting baseline with respect to which any system can be compared. For mineral resources, Valero, Valero and Gómez [146] proposed a reference environment of minimum exergy, called Thanatia, representing a mineral exhausted Earth. Thanatia was defined as *"a hypothetical state of the Earth where all minerals are dispersed along the crust and all fossil fuels have been burned"* (Valero and Valero [101]).

In Thanatia, there are no high grade deposits and the mineralogical composition is constant throughout the entire crust and is approximately equal to the current planetary average upper crust. Consequently, all the elements of the periodic table are dispersed in the form of minerals at very small concentrations.

The starting point to develop the model was the mineralogical composition proposed by Grigor´ev [147], which was further improved considering the chemical composition in terms of elements proposed by Rudnick and Gao [148]. Accordingly, Thanatia's crust incorporates information regarding composition and crustal concentration of the nearly 300 most abundant minerals in the upper crust. With Thanatia as the reference environment, one can now calculate the exergy of a given mineral, by means of the concentration exergy (bci) as expressed in Eq.9 (Faber and Proost [149]):

$$b_{ci} = -\bar{R}T^0 \left[ln x_i + \frac{(1-x_i)}{x_i} ln(1-x_i)\right] \tag{9}$$

Being R the universal gas constant (*8.314 kJ/kmolK*), T_0 is the temperature of the reference environment (*298.15 K)* and x_i is the concentration of substance i. The difference of the concentration exergy obtained with x_i being the ore grade of a given mine and with x_i being Thanatia's concentration of the mineral is called "*replacement exergy*" and represents the minimum energy (exergy) required to form the mineral from the concentration in the Earth's crust (x_c) to the concentration in the mineral deposits (x_m). In this way, the average exergy of different substances was obtained, considering global average ore grades (x_m), mainly derived from Cox and Singer [150].

3.3.1. Exergy Replacement Cost

It should be noted that exergy only provides minimum values which are far removed from societal perception of value. This is because as per definition, it considers that all involved processes are reversible. Yet man-made processes are very irreversible and in reality, one would need k-times the minimum exergy (Eq. 10):

$$b_{ci}^{*} = k \cdot b_{ci} \qquad (10)$$

Accordingly, instead of replacement exergy, we need to resort to exergy replacement costs, which are defined as the exergy required to concentrate a given mineral from Thanatia's dispersed conditions to the current concentration found in the mines with prevailing technology. Variable k is a constant called unit exergy cost. It is the ratio between a) the real cumulative exergy required to accomplish the real process to concentrate the mineral from the ore grade x_m to the commercial grade x_r and b) the minimum thermodynamic exergy required to accomplish the same process. An implicit assumption in the methodology is thus that the same technology applies for concentrating a mineral from x_m to x_r than from $_{xc}$ to x_m.

Exergy replacement costs can be seen as an avoided cost or "bonus" that Nature provides for free for having minerals concentrated in mines and not dispersed throughout the crust. This bonus is related to mineral scarcity in Nature. Note that scarcity is here referred as the relative low concentration of the given mineral in the crust, in contrast to the more anthropogenic definition by Oers and Guineé [140] where a specific mineral is scarce if "the amount available for use is, or will soon be, insufficient".

3.3.2.Embodied Exergy

It should be stated that exergy replacement costs are an important part of the physical value of a substance but not the only one. A mineral resource from which useful materials are obtained can be regarded as valuable from a physical point of view when 1) It is scarce in Nature and/or 2) It is costly to obtain.

The second part refers to the energy associated to extract, beneficiate and refine the mineral to produce the useful element or commodity. In other words, the embodied exergy cost incurred by companies in mining and metallurgical processes. These costs increase as ore grades decline and so the Earth approaches to Thanatia.

From a Life Cycle Assessment (LCA) point of view, this part corresponds to a cradle to gate approach, whereas exergy replacement costs to a grave to cradle approach as it is related to the exergy required to restore natural mines from the grave, i.e. Thanatia [151]. Using embodied exergy and not embodied energy as commonly done in conventional LCA has an additional advantage: cost allocation among simultaneously produced materials or energy flows is carried out according to the quality of the streams, i.e. through exergy and not through tonnage or monetary costs.

Moreover, as demonstrated by Valero and Valero [152], exergy allocation brings the advantages of monetary allocation (resulting costs are close to societal perception of value) and those of tonnage allocation (stable and absolute value independent of market fluctuations).

3.3.3.Thermodynamic Rarity

The sum of exergy replacement cost and embodied exergies is what Valero and Valero [101] named *thermodynamic rarity* of minerals. Thermodynamic rarity can be thus defined as the amount of exergy resources needed to obtain a mineral commodity from ordinary rock (Thanatia), using the prevailing technology. Hence, it allows taking Nature into account as it apprehends both ideas: 1) conservation, because it advices to preserve those minerals that are scarce through exergy replacement costs and 2) efficiency, because embodied exergies indicate real energy expenditures that should be decreased in order to be cost-effective. Thermodynamic rarity varies from mineral to mineral, as a function of absolute scarcity in Nature and the state of technological development (see Figure 1).

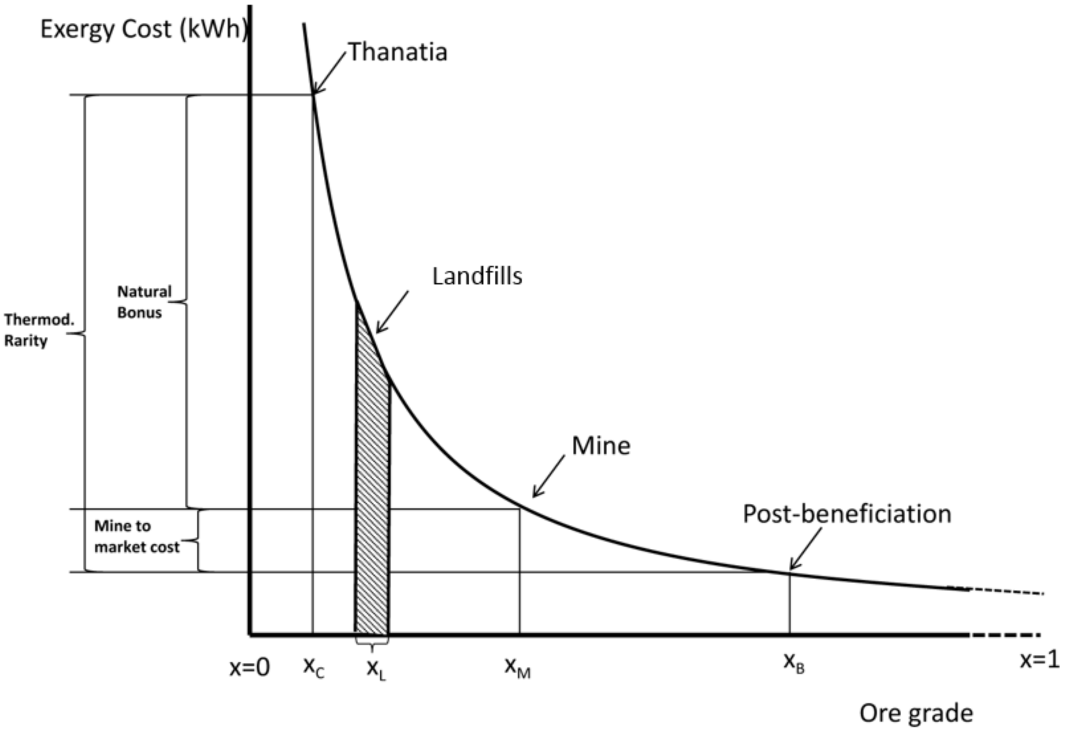

Figure 1: Thermodynamic rarity represents the exergy cost (kWh) needed for producing a given mineral commodity from bare rock to market, i.e., from Thanatia to the mine and then to post beneficiation. Source Valero and Valero [153].

Note that if technology does not change, rarity can be assumed to be constant. Before effective mining appeared, mineral deposits were abundant and highly concentrated (the natural bonus was high and so the exergy replacement costs). In turn, it was very easy to mine and beneficiate minerals (embodied exergy costs were low). Throughout history, the low hanging fruits have been already mined, steadily resulting in exploitation of lower ore grade mines. Nowadays, the mining industry needs to go deeper, further and more energy intensively than before (the natural bonus has been decreased), i.e. exergy replacement costs have been converted into embodied exergies. In some cases, technology improvements could partially offset decreasing ore grades (Swart and Dewulf [154]). Yet, as demonstrated by Calvo et al. [155] for the case of copper, ore grades have generally declined throughout history leading to greater energy costs.

In short, this Thesis proposes to evaluate resource efficiency in vehicles through the thermodynamic rarity indicator. It should be mentioned that measuring resource efficiency of products would be impossible with other criticality assessments such as the one defined by the European Commission, based on supply risk or economic importance, since both indicators are dimensionless. This is why Calvo, Valero and Valero [28] proposed rarity as a new dimension in the criticality assessment of minerals. Thermodynamic rarity values used in this Thesis are shown in Table 1.

Table 1: Embodied Exergy, Exergy Replacement Cost and Thermodynamic Rarity values of different metals. Valero and Valero [101]

Metal	**Embodied Exergy**	**Exergy Replacement Cost**	**Thermodynamic Rarity**
Ag	1,566	7,371	8,937
As	28	399.84	427.84
Au	108,626	546,057	654,683
Ba	1	38.34	39.34
Be	457.20	252.73	709.93
Bi	56.40	489.22	545.62
Cd	542.40	5,898	6,440.40
Ce	523	97	620
Co	138	10,872	11,010
Cr	36.40	4.50	40.90
Cu	56.70	291.70	348.40
Dy	384	348	732
Er	384	348	732
Eu	384	348	732
Ga	610,000	144,828	754,828
Gd	3,607	478	4,085
Ge	498	23,749	24,247
Hf	0	32,364.36	32,364.36
Hg	409	28,298	28,707
In	3,320	360,598	363,918
Ir	2,870,013.09		2,870,013.09
La	297	39	336
Li	432	546	978
Mg	0	145.73	145.73
Mn	57	16	73

Mo	148	908	1,056
Nb	360	4,422	4,782
Nd	592	78	670
Ni	234	524	758
Pb	4	37	41
Pd	2,870,013.09		2,870,013.09
Pr	296	577	873
Pt	2,870,013.09		2,870,013.09
Rh	156	102,931	103,087
Ru	2,870,013.09		2,870,013.09
Sb	13.40	474.49	487.89
Sm	384	348	732
Sn	26.60	426.35	452.95
Ta	3,083	482,828	485,911
Tb	384	348	732
Te	589,405.30	2,235,699	2,825,104.30
Ti	196.45	6.67	203.12
U	188.80	901.40	1,090.20
V	517	1,055	1,572
W	594	7,429	8,023
Y	1,198	159	1,357
Yb	384	348	732
Zn	41.90	155.03	196.93
Zr	1,371.50	654.43	2,025.93

3.4. Conclusions

This chapter has served to provide an overview of the methodological tools used in this Thesis to assess 1) potential bottlenecks found for the car industry and 2) resource efficiency in vehicles. For the first, several equations have been proposed which should account for future demand trends in green technologies and other sectors.

For measuring resource efficiency, a novel indicator called thermodynamic rarity has been proposed as an alternative unit of measure than mass for material assessment, as it gives a greater weight to those substances that are more valuable from a physical point of view. Thermodynamic rarity is a universal and much more stable unit of measure than money, reflecting physical criticality of mineral resources.

The methodology does not incorporate energy costs associated to the manufacturing and use phases of the products where the materials are contained, something that can be assessed through conventional LCA. It only focuses on the physical value of the substances per se.

It is also important to state that rarity should not be confused with recyclability. Rarity measures the exergy impact of materials contained in a component, considering the scarcity of these materials in Nature, by means of the ore grade in mines and the exergy required to extract them from a hypothetical bare rock to post-beneficiation conditions.

With this approach, one does not take into account how these materials are found in the specific component. Truly, it is not the same if Co is found homogeneously spread all over the vehicles, or if it is found almost pure in some components. This will not affect the results of the rarity assessment, but will affect recyclability significantly.

Recyclability in turn depends on the components where materials are contained and hence for each metal a myriad of options appear. Recyclability assessments are out of the scope of this Thesis, but are indeed a natural follow up of it. Next chapter is devoted to provide an in depth analysis of metal content in vehicles which will serve to subsequently analyze their resource efficiency through rarity indicator.

Chapter 4. Metal composition of passenger vehicles.

4.1. Introduction to the chapter

The aim of this chapter is to provide an analysis of the metal content in different types of passenger vehicles. Such compositions will be used in this Thesis to carry out resource efficiency analyses. Beyond being useful for this Thesis, the data generated is valuable on its own for further research. This is because, to the author's knowledge, such a detailed raw material composition of vehicles was never published before. The data compilation was undertaken through a combined approach. On one hand a scientific review of literature data was performed and on the other hand an internal IT system from SEAT S.A was used. Data from literature was useful to define the metal composition of hybrid and electric vehicles (PHEV and BEV), while the IT system was valuable for internal combustion engine vehicles - ICEV (petrol and diesel).

4.2. Foreword to the data collection process

Data collection from SEAT S.A IT system allowed to build a matrix with the metal composition of the following models:

- SEAT Leon 350[10] Petrol: 1.4 TSI FR 5d.
- SEAT Leon 350 Diesel: 2.0 CR FR 5d.
- SEAT Leon 370[11] Petrol: 1.4 ACT FR 5d.
- SEAT Leon 370 Diesel: 2.0 CR FR 5d.

Table 2 shows a compilation of the main data generated and assessed along this process:

Table 2: Data generated and assessed. Own elaboration by means of an IT System from SEAT S.A

	Petrol 350	**Diesel 350**	**Petrol 370**	**Diesel 370**
No. of components assessed	1,207	1,153	1,094	1,052
No. of data generated	82,076	78,132	74,392	71,536

This analysis was the first step to have a reliable set of data for the following activities developed in the Thesis:

- To identify what are the most strategic metals of the automobile sector (**Paper III**).
- To calculate the downcycling degree of any vehicle component at the EoL recycling processes and the later definition of recommendations to reduce this downcycling (**Paper IV**)

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[10] SEAT Leon 350 is the model II version (sold from 2005 to 2012)

[11] SEAT Leon 370 is the model III version (sold from 2012 to nowadays)

- To identity the most critical components from a resource efficiency point of view and the definition of eco-design recommendations for these components (**Paper V**).

It is obvious that all vehicles which are in the world automobile fleet have not the same metal composition used in this Thesis. Nevertheless it must be highlighted that the vehicle used (a Hatchback model of segment C) is a very representative one because according to ANFAC data [156] it has been the most sold vehicle in Spain in 2018 and according to ACEA [157] the medium segment has covered between 46 % to 49 % of the total European sales from 1995 to 2017.

Finally, it must be mentioned that because of confidential issues, vehicle metal compositions published in this Thesis and in its associated papers contains aggregated data. These data are presented for the vehicle as a whole and for the following vehicle subsystems: (engine, wheels and brakes, fuel tank and exhaust system, transmission, body, front axle, rear axle, accessories, electrical equipment and frames).

4.3. Vehicle metal composition

To identify what materials are used by different types of vehicles, initially a state of the art obtained from a revision of scientific bibliography has been undertaken. Table 3 summarizes aluminum, steel, copper and cast iron vehicle contents compilations as published by different authors.

Table 3. Common materials used in passenger car vehicles through different authors (in kg).

Author	**Aluminum**	**Steel**	**Copper**	**Cast iron**
Gonzalez Palencia et al. [158]	100 (FCHEV) 200 (BEV) 50 (ICEV)	760 (FCHEV) 770 (BEV) 740 (ICEV)	25 (FCHEV) 150 (BEV) 25 (ICEV)	20 (FCHEV) 20 (BEV) 50 (ICEV)
Spielmann, Althaus [159]	52.41			
Castro, Remmerswaaland, Reuter [160]	31.24			
Schmidt et al. [161]	198			
Well [162]	88.4			
Amatayakul, Ramnas [163]	96	624		
Lewis, Keoleian, Kelly [164]	90 (ICEV) 100 (HEV) 100 (PHEV)	710 (ICEV) 710 (HEV) 750 (PHEV)	50 (HEV) 50 (PHEV)	20 (ICEV) 20 (HEV) 20 (PHEV)

Author	**Aluminum**	**Steel**	**Copper**	**Cast iron**
USGS [45], [44]	88.45	975.22		

As can be seen, such compilations only show major metals found in a car. Yet as stated in previous chapters, the impact of critical materials is becoming gaining more and more importance in the sector. For this reason, a revision of specific works focused on critical materials was undertaken. Table 4 shows these studies.

Table 4. Compilation of critical materials used in passenger car vehicles (in g).

	Author and type of vehicle assessed								
Material	Cullbrand and Magnusson [67]		Du and Graedel [165]			Du et al. [70]	Alonso et al. [69]	Grandell et al. [8]	
	ICEV	PHEV	max	min	ave			PHEV	BEV[12]
Cerium	12.91	0.31	80	6	6	0.02	81		
Cobalt			160	5	6				
Dysprosium	1.96	129.66	25	5	6	0.03	27.45	210	336
Erbium	0	0.18							
Europium	<0.01	<0.01					0.45		
Gadolinium	<0.01	<0.01	0.36	0.01	0.12	0.05	0.36		
Gallium	0.42	0.57	11	0.1	0.25			1.05	1.68
Germanium								0.05	0.08
Gold			0.21	0.01	0.15			0.2	0.32
Indium	0.38	0.08	0.42	0.01	0.15			0.05	0.08
Lanthanum	0	6.68	12	0.8	5.2	12	8.1		
Lithium	1.36	6,256.55							
Molybdenum			170	5	5				
Neodymium	27.6	531.88	300	5	7	2.16	297	360	576
Niobium	89.81	109.14	150	5	10				
Palladium	1.24	1.81	10	0.1	0.25				0.12
Platinum	7.85	5.51	5.5	0.1	0.25				
Praseodymium	2.47	4.01	25	5	6	0.07	30.6	120	192

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[12] Original values are published for a 50 kW motor.

Material	Author and type of vehicle assessed								
	Cullbrand and Magnusson [67]		Du and Graedel [165]			Du et al. [70]	Alonso et al. [69]	Grandell et al. [8]	
	ICEV	PHEV	max	min	ave			PHEV	BEV[12]
Rhodium	<0.01	<0.01							
Samarium	0.73	1.4	3.2	0.1	0.25	0	3.24		
Scandium							1.13		
Silver	17,5	50						6	9.6
Strontium			180	30	140				
Tantalum	6.99	10.83	6	0.1	0.25				
Terbium	0	19.86	0.01	0.01	0.01	0.01	0	21	34
Wolfram			3	0.1	0.2				
Ytterbium	0	0.16					0		
Yttrium	0.02	0.23	0.58	0.08	0.4	0.08	0.59		

Since the storage system is one of the most critical components in PHEV and BEV, a deeper analysis of materials demanded by different types of batteries has been undertaken. In the following table a classification of current types of batteries and their projections are shown.

Table 5. Different battery types and vehicle applications. Source: The Association of European Automotive and Industrial Battery Manufacturers [166]

	Conventional vehicles	**Hybrid vehicles**	**Full electric vehicles**
Lead – Based Batteries	Only as auxiliary battery	Only as auxiliary battery	Only as auxiliary battery
Nickel – Based Batteries	Non expected	Expected	Non expected
Lithium – Based Batteries	Non expected	Expected	Expected

According to the literature review performed, lead based batteries will continue to be used in ICEV passenger cars for a long time to supply the energy for auxiliary devices and the starter system. NiMH batteries will compete in the market of hybrid vehicles with lithium-ion batteries, whereas the latter will be mainly used in full electric vehicles and plug hybrid vehicles. This is because of their high energy density and because their relatively greater cost is less of a barrier in these higher-end vehicles [166]. Although Li:ion technology is expected to be the reference in the following years, from a material point of view there are different types of Li:ion batteries. The following table shows an example of materials demanded in different Li:ion batteries:

Table 6: Metal requirements in kg/kWh of different types of Li:ion batteries.
Source: Simon, Ziemann and Weil [58]

	Battery types				
	NMC/C	**NCA/C**	**LFP/C**	**Li/S**	**Li/air**
Nickel	0.4	1.55	0	0	0
Lithium	0.14	0.24	0.18	0.42	0.15
Cobalt	0.21	0.3	0	0	0
Iron	0	0	1.25	0	0
Manganese	0.4	0	0	0	0
Aluminum	0	0.05	0	0	0

In Li-ion batteries, NMC/C technology represents the current market availability. Nevertheless, an increase of NCA/C is expected due to its higher energy density. Besides, NCA batteries are used by the main electrical vehicle manufactures like TESLA [167] so it is expected to become the most important technology for electrical vehicles in the coming years. LFP/C, Li/S and Li-air batteries are not considered since the implementation of this technology is not clear in the coming years as they are currently on an early development phase.

Taking into account these facts, a deeper study of NCA chemistry batteries has been done. Table 7 shows Li, Co and Ni contents of NCA batteries published by different authors13.

Table 7. Material demand by type of vehicle in gr.

Source: own elaboration through data from Simon, Ziemann, Weil [58]*; Gaines, Sullivan, Burnham* [168] *and U.S Department of Energy* [169]

	[168]	[58]	[169]	Average
Li	9.01	7.2	9.3	8.50
Ni	57.40	46.5	58	53.97
Co	10.91	9	12	10.34

Taking into consideration the results of this literature review, the following vehicle metal compositions were used in **Papers I and II.**

Table 8: Vehicle metal composition (in grams) used in Papers I and II

	ICEV	**PHEV NiMH**	**PHEV Li:ion**	**BEV**
Ag	17.5	28.0	28.0	29.8
Al	110,544	115,544	141,370	200,000
Au	0	0.20	0.20	0.32
Ce	46.95	2,127	49.67	0.15
Co	0	8,313	2,712	9,330
Cr	6,510	6,510	6,510	6,031
Cu	28,500	43,481.92	59,166	150,000
Dy	14.70	165.72	165.72	224.63
Er	0	0.18	0.18	0.18
Eu	0.23	0.23	0.23	0.23
Fe	806,144	853,826	806,144	746,945
Ga	0.42	0.81	0.81	1.12
Gd	0.18	0.17	0.17	0.17
Ge	0	0.05	0.05	0.08
In	0.38	0.38	0.38	0.38
La	4.04	14,555	7.38	7.38
Li	1.36	1.36	2,242	7,709
Mn	5,968	5,968	5,968	5,530
Mo	260	260	260	260

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[13] Values adapted to a battery autonomy of 200 km.

Nb	426.30	426.30	426.30	426.30
Nd	162	2,631	552.79	749.30
Ni	1,780	82,832	16,049	55,724
Pb	5,850	5,850	5,850	5,850
Pd	1.24	0.94	0.94	0
Pr	16.53	2,129	51.48	98.00
Pt	7.85	5.51	5.51	0
Rh	0.01	0.01	0.01	0
Sm	1.98	2.32	2.32	3.15
Ta	6.99	10.83	10.83	10.83
Tb	0	13.62	13.62	26.93
V	852.61	852.61	852.61	790
Yb	0	0.08	0.08	0.16
Y	0.41	0.41	0.41	0.41
Weight analyzed (kg)	967	1,145	1,048	1,190
Weight analyzed (%)	82.5 %	84,7 %	80 %	74.7 %
Other mat. (kg)	206.1	206.1	263.1	402.4
Total weight (kg)	1,173	1,351	1,311	1,592

In Papers III, IV, and V it was possible to use values directly obtained from the car manufacturing company SEAT S.A. This fact allowed us on the one hand the use of more reliable data for diesel and petrol engines and on the other hand to extend the study to more metals. In these papers the following metal compositions were used. In PHEV and BEV cases, the values come from the scientific review previously presented in Table 8.

Table 9: Vehicle metal composition (in grams) used in Papers III, IV and V

	ICEV Diesel	ICEV Petrol	PHEV	BEV
Ag	10.19	19.47	28	29.80
Al	61,103	78,343	141,370	200,000
As	0.14	1.30	0	0
Au	3.15	3.65	0.20	0.32
B	23.76	26.37	0	0
Ba	832.55	777.66	0	0
Be	0.03	0.02	0	0
Bi	8.81	8.84	0	0
Cd	0.15	0.12	0	0
Ce	2.67	0.37	49.67	0.15
Co	9.72	8.06	2,712	9,330
Cr	5,041	5,566	6,510	6,031
Cu	15,584	15,376	59,166	150,000
Dy	0.19	0.48	13.81	18.73
Eu	0	0.0001	0.23	0.23
Fe	701,095	653,524	806,140	746,945
Ga	0.27	0.27	0.81	1.12
Gd	0.0005	0.0005	0.17	0.17
Ge	0.0036	0.003	0.05	0.08
Hf	0.0027	0.008	0	0
Hg	0.047	0.001	0	0
In	0.216	0.21	0.38	0.38
Ir	0.018	0	0	0
La	0.341	0.40	7.38	7.38
Li	22.06	4.63	2,242	7,709
Mg	13,622	3,565	0	0
Mn	4,333	4,211	5,968	5,530
Mo	240.03	187.97	260	260
Nb	154.20	145.57	426.30	426.30
Nd	23.71	18.84	552.79	749.30
Ni	1,590	2,993	16,049.57	55,724
Pb	12,527	11,535	9,750	9,750
Pd	1.99	1.84	0.94	0
Pr	0.066	0.08	51.48	98
Pt	3.79	0.13	5.51	0
Rh	0.12	0.09	0.01	0
Ru	0.012	0.013	0	0

Sb	15.70	35.36	0	0
Se	0.013	0.02	0	0
Sm	0.21	0.33	2.32	3.15
Sn	208.53	234.61	0	0
Sr	148.84	144.08	0	0
Ta	4.65	6.53	10.83	10.83
Tb	0.01	0.02	13.62	26.93
Te	0.20	0.18	0	0
Ti	541.41	536.41	0	0
V	92.81	86.62	852.61	790
W	9.24	3.17	0	0
Y	0.07	0.13	0.41	0.41
Yb	0.0003	0.0002	0.08	0.16
Zn	6,614	6,502	0	0
Zr	12.50	78.42	0	0

4.4. Conclusions

As mentioned in chapter 2, before this Thesis there was not much data available related to vehicle metal compositions (either it was scattered or limited). This is why with the aim to apply the methodology, the first step was to make an in depth literature review and a research about vehicle metal compositions. Fortunately, after this process a compilation of very reliable data was achieved, helping to strengthen the conclusions of this Thesis.

In addition to vehicle metal contents, the composition of other green technologies, including solar photovoltaic, wind power and solar thermal power technologies was analyzed. This is because one of the objectives of this Thesis is the identification of possible future metal shortages affecting the manufacturing of vehicles, but also for other renewable technologies that will strongly compete for the same metals. The information about the metal composition of these technologies was published in the appendix of **Paper I** [170].

Chapter 5. Future material bottlenecks for the green technologies and automobile manufacturing sectors (Paper I)

5.1. Introduction to the chapter

As was explained in Chapter 1, the research line of this Thesis begins giving a global overview about how metal demand will need to increase as a consequence of the energy transition. This period will be led by a global renovation of fleet vehicles where nonpolluting technologies must increase its presence to the detriment of fossil fuel based ones. Moreover, the growing electric vehicle fleet will need to be developed in parallel with a huge increase of renewable technologies to produce clean electricity. As a consequence, all technologies will compete for the materials required for their deployment. This is why this study analyzes material demands for vehicles and renewables. The conclusions will serve to identify those metals that could put at risk the very development of the vehicle sector in the next decades.

5.2. The role of green technologies for the future development

As was explained in Chapter 2 green technologies are crucial to achieve Paris agreements. Figure 2 represents future projections to 2050 and as it can be checked a great growing is expected for any technology.

This situation takes into consideration the repowering effect that happens at the end of life for each technology. For this reason, in 2038 a change in the tendency can be observed, when the first RES installation built at the beginning of the century has to be repowered. The lifetime considered for all renewable technologies is 25 years, as estimated by Raccurt et al. [170]; Bayod-Rujula, Ortego and Martinez [171]. and EWEA [172]. Projections of cumulative installed power for each technology have been built using average values extracted from the following information sources:

- Wind Power: EWEA [173] and IEA [174].
- Solar Thermal Power: Greenpeace [175] and IEA [176].
- Solar Photovoltaics. IEA [177] and Parrado et al. [178].

It is noteworthy that cumulative power will grow linearly up to 2050 for all the studied technologies with similar growing rates. The technology that will have a larger share in 2050 will be solar photovoltaic with more than 3,500 GW, followed by wind power, with 2,500 GW, and finally solar thermal with nearly 900 GW.

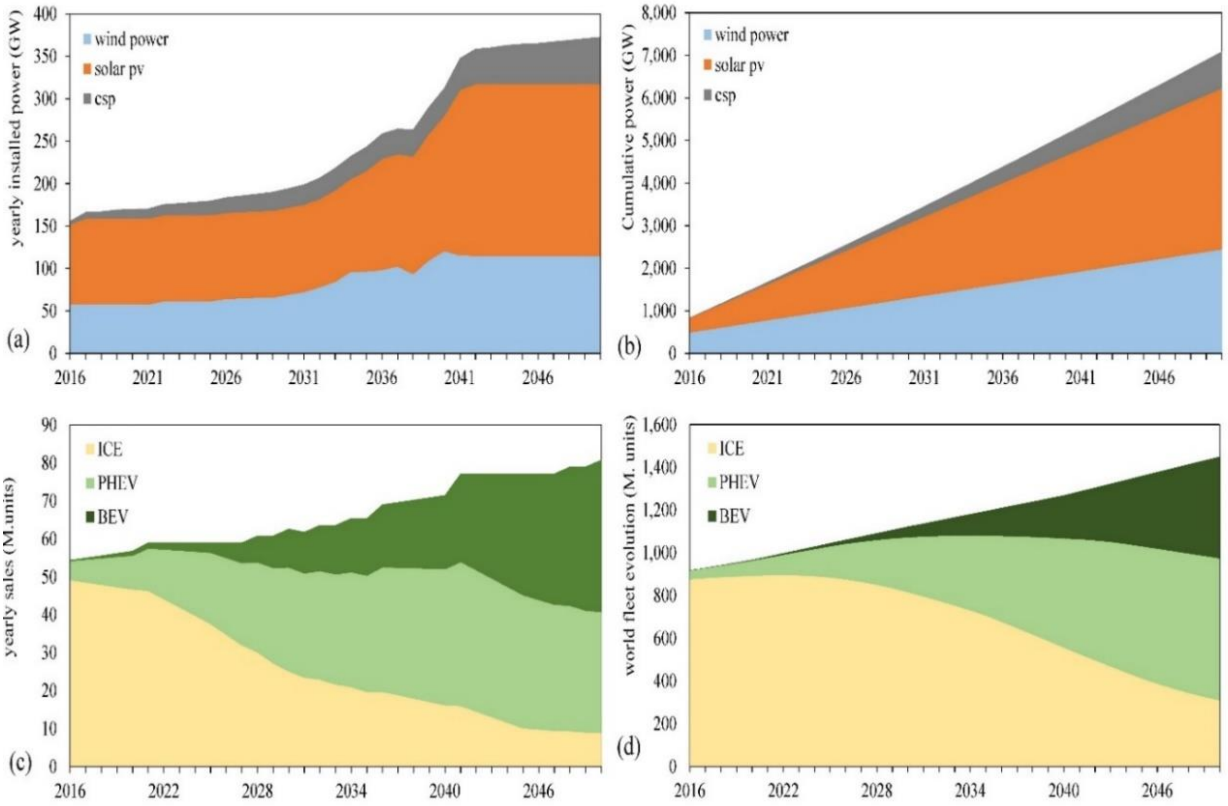


Figure 2: Demand projections for green technologies: a) yearly installed power, b) cumulative power, c) yearly sales of vehicles, d) world fleet evolution.

For each renewable source, different types of technologies can be selected. In the case of wind power two main types of wind turbines have been considered: model 1, with gearbox, and model 2, gearless, each with a constant market share of 75% and 25%, respectively (Lacal-Arantegui [180]). In the case of solar thermal power, today there are two main commercial possibilities: parabolic trough (PT) and central receptor system (CRS). The share of each technology in the market is considered to be 60% for PT and 40% for CRS according to IEA [177]. In the case of solar photovoltaic, a market mainly dominated by crystalline technologies, the share considered is 85%, with thin film technologies contributions (CIGS, CdTe and a-Si) of 5% for each one of them according to Elshkaki and Graedel [30].

In the case of light duty vehicles, the world fleet evolution and the sales projections by type of vehicle has been represented according to information published by the Spanish automobile manufacturer association [180] and Dulac [181]. In 2050 a world fleet of near 1,500 million of LDV is expected. Among them, ICEV will represent 21% of the fleet, PHEV, 45% and BEV, 33%. ICEV sales will decrease from 2016 in favor of PHEV sales.

Additionally, BEV sales will mainly grow from 2025 onwards and in 2045 their sales will be even higher than PHEV. Considering these projections PHEV and BEV total share in the world fleet will be higher than the share of ICEV from 2041 and 2046, respectively.

5.3. Types of bottlenecks

The method developed in **Paper I** has the aim of identifying metal bottlenecks in green technologies which cover also electric vehicles. To accomplish this target this method combines reserves, resources, production and demand data, so as to classify possible constraint risks. Three risk categories were defined: very high, high and medium. This approach considers the expected projections of green technologies, recycling rates of metals initially assumed constant as well as metal demand for the rest of sectors, as shown in Table 10.

Table 10: Risk definitions

Type	**Definition**
Very High	2016 – 2050 cumulative demand ≥ current resources ($D_{a\_T} \geq RES_{2015}$)
High	2016 – 2050 cumulative demand ≥ current reserves ($D_{a\_T} \geq RSV_{2015}$)
Medium	Annual demand ≥ annual primary production ($((d_{a\_T})_t \geq (p_a)_t)$)

The first and most restrictive constraint is associated with cumulative production surpassing available resources. This is because, as stated before, the amount of resources is an indication of the availability of a given commodity in the crust that could be potentially extracted now or in the future.

The second one is related to reserves instead of resources. Note that reserves relate to that portion of resources that can be recovered economically with the application of extraction technology available currently or in the foreseeable future. It should be pointed out that reserves data are dynamic, as they can change with technology, prices, discovery of new deposits, among other factors. Therefore, results obtained with these data have to be considered as an indication rather than as a fact. Then, as reserves data are more dynamic, a bottleneck based on reserves can be considered less critical than one based on resources.

The third constraint is associated to isolated supply shortages. This is assessed with the information coming from the bottom-up and the top-down approaches, through the intersection between future demand and future production estimations. For instance, using nickel expected demand in electric vehicles and other sectors, and nickel estimated production using the Hubbert model approach, a possible bottleneck can be identified beyond 2027 as shown in Figure 3.

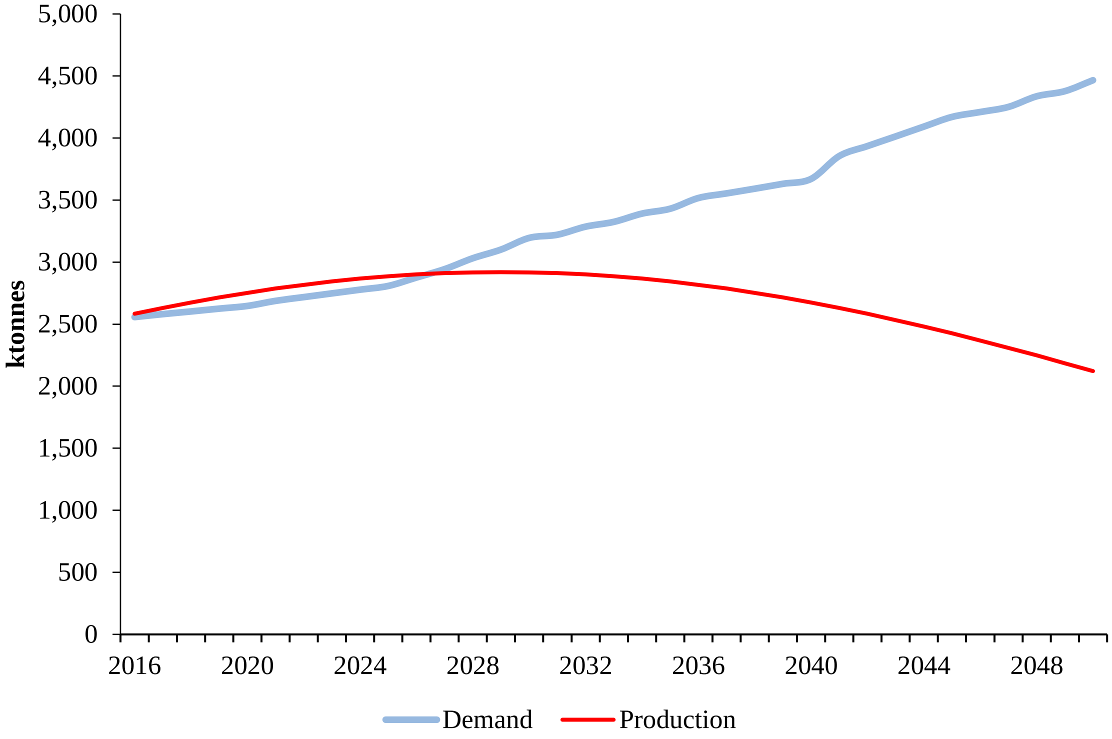


Figure 3: Identification of possible bottlenecks using bottom-up (production) and top-down (demand) combination approaches for the case of nickel.

As for the previous constraint, it must be pointed out that any successful prediction obtained using the model depends on many different factors. According to Valero and Valero [183] the reliability of the estimated reserves and resources is key, because it can shift the peak several years if these increase. A conservative approach is considered in this study, using resources and not reserves data for fitting Hubbert peaks. The nature of the commodities and their production processes are also an important factor in the reliability of Hubbert peak analysis. For instance, it was shown by Valero and Valero [153] that the production of primary metals such as iron, aluminum or copper can be adjusted well to a bell-shaped curve, whereas those obtained as by-products or co-products have significantly poorer fits. For this reason, from the three mentioned constraints, this last one can be considered as the least critical from all, since future production trends have a high uncertainty level and as long as there are enough reserves, markets can almost always (to a certain level) adjust their production.

5.4. Results

5.4.1.Raw material constraints summary

Table 11 summarizes all the studied materials and their risk classification. The sole material with very high identified availability risk is tellurium. At high risk are in addition to tellurium, silver, cadmium, cobalt, chromium, copper, gallium, indium, lithium, manganese, nickel, tin and zinc. Finally, materials which only fall in the moderate future availability risk category are dysprosium, molybdenum, neodymium, selenium and tantalum, as their annual demand may exceed annual production before 2050.

Table 11: Studied materials and risk classification.

	Type of Risk			**Technology affected**			
	Very high	**High**	**Medium**	**Wind**	**PV**	**CSP**	**LDV**
Ag		●	●		x	x	x
Al				x		x	x
Cd		●			x		
Ce							x
Co		●	●				x
Cr		●				x	x
Cu		●		x	x	x	x
Dy			●	x			
Fe				x		x	x
Ga		●			x		x
Gd							x
Ge					x		
In		●	●		x		x
La							x
Li		●	●				x
Mg					x	x	
Mn		●	●			x	x
Mo			●		x	x	x
Nb							x
Nd			●	x			x
Ni		●	●	x	x	x	x
Pd							x
Pr				x			x
Pt							x
Se			●		x		
Sn		●	●		x		
Ta			●				x
Te	●	●	●		x		
Ti					x		
V						x	x
Zn		●		x	x		

In the cases of cadmium, chromium, copper, gallium and zinc it must be mentioned that there are classified as belonging to the high risk but not medium risk category. This fact happens in those materials in which the difference between reserves and resources is notable. For these mentioned metals the ratio between proven resources and reserves are 2.4; 25; 4.2; 192.3 and 8.3, respectively. So it happens that cumulative demand is greater than reserves but production projections based on available resources is always greater than expected demand. If projection demand had been assessed with reserves instead, all medium risk metals would additionally fall in the high risk category. Even if the main goal of the **Paper I** is not to generate a list of critical materials, it is interesting to carry out a comparison between the list of elements that could generate bottlenecks in the development of green technologies with already published criticality assessment papers and reports (Table 12).

Table 12: Comparison between the elements with very high and high risk in this study and their presence in criticality assessment reports.

● = high risk, ◐ = medium risk, ○ = low risk. When there is no categorization available, the risk has been considered high. In the case of the BGS (2015) risk list, values from 4.8 to 6.5 have been considered low risk, 6.6 to 7.5 medium risk, and higher than 7.6 high risk.

	Bae. J [184]	Angerer.D et al.	JOGMEC [186]	EC (2010) [187]	APS [188]	Resnik Institute	DOE [190]	Moss. R et al. [21]	EC (2014) [25]	UKERKC [191]	BSGS [192]
Ag		●			●	●		○		●	◐
Cd						●		○			◐
Co	◐	●	●	●	●	●	○		●	●	●
Cr	◐		●						●		○
Cu	○	●									○
Ga	●	●	●	●	●	●	○	●	●	●	●
In	●	●	●	●	●	●	○	●	●	●	●
Li	●		○		●	●	◐			●	●
Mn	◐		●				○				○
Ni	●		●				○	○			○
Sn		●						◐			○
Te					●	●	◐	●		●	
Zn	○										○

All of the 13 identified elements with very high or high risk to generate bottlenecks have been classified as critical in some studies, but not all of them altogether. For instance, in the case of the risk list carried out by the British Geological Survey [192], all except tellurium are included, but the categorization is different for each element. The methodologies used in each criticality assessment usually take into account the same factors used by other authors or institutions like Moss, Tzimas et al. [21]; European Commission [66,186]; Bae [183]; Angerer et al. [184]; JOGMEC [185]; APS Physics [187]; Resnick Institute [188]; DOE [189]; UKERC [190] and BSGS [191] but with different weights, production concentration, recycling rates, technologies, substitutability, governance, environmental standards of the producing countries, among others.

The main difference with the approach used in other works is that we are considering not only the use of those elements in green technologies and in other sectors but also the geological availability using reserves and resources data compared to the estimated future production trends. Usually these aspects are not addressed in criticality assessment reports.

As an example, chromium, copper, nickel or zinc, which have been identified as presenting high risk in this work, are considered to have low risk by the BSGS. Additionally, silver and nickel have a high risk in this study, but for Moss, Tzimas et al. [21] they both have a low overall risk. Copper is not usually classified as a critical element in any of these studies except for Angerer et al. [185] and Bae [184], but it is indeed used in all the green technologies analyzed in this section and therefore very important to go towards a low carbon economy. On the other hand, some of the elements that were identified to generate bottlenecks, such as cobalt, gallium and indium are considered critical in almost all of the analyzed reports, emphasizing their relevance in this and other sectors of the economy.

5.4.2.Recycling improvements

As stated before, a way to overcome supply bottlenecks is through increasing recycling rates. Note that recycling improvement to avoid high and very high risks are not calculated because in these cases, the problem is not because of supply shortage but because of a lack of available resources in the market due to geological scarcity. In such cases, if expected demand does not change, the most effective way is to invest in exploration to increase reserves. This is because recycling can never achieve 100% efficiency due to second law of thermodynamics restrictions and even if it were possible, exponential growth in demand makes that primary production will always be required to offset the rocketing demand.

Table 13 shows the growing in recycling rates that would need to take place in order to avoid that annual demand surpasses annual production in a business as usual scenario (i.e. without considering substitution of technologies or materials and considering that reserves and resources do not increase). Table 13 also shows the current recycling rate and the value that would be reached in 2050 at this growing speed.

Table 13: Recycling rates evolution to avoid medium risk category. Valero et al. [170]

	Current Recycling	Annual growing	2050 Recycling Rate
Ag	30 %	0.6 %	37 %
Cd	25 %	1.3 %	39 %
Co	32 %	1.8 %	59 %
Cr	20 %	2.5 %	47 %
Dy	10 %	0.9 %	13.7 %
In	37.5 %	0.5 %	44.7 %
Li	1 %	4.6 %	4.8 %
Mn	37 %	0.1 %	38 %
Mo	33 %	0.7 %	42 %
Nd	5 %	0.1 %	5.2 %
Ni	29 %	1 %	41 %
Se	5 %	2 %	10 %
Sn	22 %	0.1 %	22.8 %
Ta	17.5 %	0.1 %	18.2 %

The highest growths should take place for lithium, chromium, cobalt and cadmium with annual growing rates of 4.6 %, 2.5 %, 1.8 % and 1.3 %, respectively. The case of lithium is of special relevance because of its notable future importance for storage systems and the low current recycling rate which is below 1 %. It is also noteworthy how relatively small recycling efforts could avoid the appearing of bottlenecks for certain materials such as manganese, neodymium or tin, which would require annual growing's of around 0.1 %, or silver or dysprosium of less than 1 %.

The problem of this is that recycling would be mainly based on minor metals recovery (cobalt, REE, lithium, tellurium, indium and silver among others). These minor metals began to be used in industrial applications only thirty years ago and there is a lack of information regarding recycling process efficiency, Valero and Valero [101]. Indeed, these metals have special properties which need complex recovery processes and when mixed, the recovery route of one set of metals may impede that of co-existing ones.

Moreover recycling processes have their own limits from a thermodynamic point of view, a fact that was named by Valero and Valero [153] "entropic backfire". This term describes how in all real processes the specific separation of components from a recyclate creates waste which is at each successive step, more difficult to salvage.

Alternative solutions to recycling from the demand side are substitution, dematerialization or resource efficiency and most likely a combination of all, together with increases in reserves will take place.

5.5. Conclusions of Paper I

To reduce emissions and to move towards a complete low carbon economy, green technologies must be promoted. However, to manufacture green technologies many critical elements are needed and, as seen in this paper, raw material availability can produce restrictions and bottlenecks that should be avoided. Having a better understanding of what materials used in each green technology might become critical from a supply side point of view can favor the promotion of policies related to recycling, substitution, or material efficiencies able to prevent those bottlenecks.

Analyzing the materials used in the selected green technologies different constraints have been identified regarding material demand and available reserves, resources and future primary production.

Current green technologies depend on certain materials whose risks have been classified as very high, high or medium. Materials presenting a very high risk are those where cumulative demand from 2016 to 2050 is higher than resources (tellurium). With high risk are those where cumulative demand surpasses reserves (silver, cadmium, cobalt, chromium, gallium, indium, lithium, manganese, nickel, tin and zinc). Medium risk commodities are those whose demand might at some point exceed production before 2050 (silver, cobalt, indium, lithium, manganese, molybdenum, dysprosium, neodymium, nickel, selenium, tin, tantalum and tellurium). Technologies which are affected by these bottlenecks are solar photovoltaic, with indium, gallium, selenium, tellurium and silver requirements, electric vehicles, that need cobalt, lithium, molybdenum and gallium among others, wind power which demands permanent magnets and solar thermal power that requires silver and molybdenum.

Moreover, considering each specific green technology, it is noteworthy that not all the available commercial products have the same impact on raw materials. For instance, for wind power, the demand of permanent magnets is lower in the case of turbines with gearbox. Additionally, in solar cells the demand of critical materials is lower in crystalline silicon technologies than in thin film technologies. Parabolic through contain less “risk materials” than central receiver system in solar thermal power systems and so does PHEV with respect to BEV due to the lower material demand to manufacture batteries.

Therefore, if current material demands and recycling quotes continue in a business as usual scenario, the transition to a low carbon economy will be threatened by the availability of certain substances. This issue should be deeply analyzed to define appropriate strategies that avoid the mentioned bottlenecks.

These strategies may be focused on: (1) investments in geological exploration to increase current reserves and resources; (2) to invest in new technologies able to obtain commodities from unconventional sources, i.e. lithium extraction technologies from salt-lake brines and sea water using lithium ion-sieve (LIS) technology; (3) research in the design of green technologies with lower requirements of critical raw materials such as metal-air batteries, generators without permanent magnets or organic photovoltaic solar cells; (4) investing in recycling technologies that are able to recover critical materials based on environmental friendly processes; (5) a combination of all them by means of defining eco-design strategies that reduce the use of critical raw materials and also improve end of life material recovery. This last option would also prevent that critical raw materials end up in landfills, where their retrieval is considerably harder.

A proper strategy must bear in mind the own characteristics of materials and technical specifications of products and process. The thermodynamic limits of recycling, rebound effects in raw material demand caused by recycling improvements and the fact that substitutability between materials may decrease product performance, raise the price, or both must not be forgotten.

Finally, as there are important gaps in the mineral statistics at world level, further studies must be made concerting evaluation and characterization of mineral deposits to have better assessments of available mineral resources. Having international standards that can be used by the mining companies is a first approach, but other problems related with exploration and technology development must be solved.

Chapter 6. How to measure resource efficiency in a vehicle? (Paper II)

6.1. Introduction to the chapter

In the previous chapter several metals have been identified as possible bottlenecks for the future development of green technologies. This assessment has been made according to geological availability and future expected demand for the studied metals. However, this first global assessment does not give an answer to which are the most critical vehicle components from a raw materials point of view. Moreover, metals found in a car are in very different proportions. While there are kilograms of Fe or Al in passenger vehicles, one can only find several milligrams of other metals such as rare earths. Can these small quantities of minor metals be disregarded?

According to current recycling ELV policies the response to the previous question is affirmative because recycling and reusing targets are defined on a mass basis. This would mean that 1 gr of Co is as important as 1 gr of Fe. That said, it is well known that their scarcity and hence physical values are different. This is why there is an urgent need to consider the quality factor of raw materials in any resource efficiency assessment.

These questions will find an answer in this chapter. To do it, resource efficiency will be assessed from a thermodynamic point of view by applying the concept of thermodynamic rarity which has been explained in chapter Fundamentals. The method is applied to different types of vehicles (ICEV, PHEV and BEV) and vehicle subsystems. The results will be useful to: (1) identify weaknesses of mass based methods applied by current ELV recycling policies; (2) recognize advantages or disadvantages of electric vehicles with respect to conventional ones considering their compositions; (3) to classify main vehicle subsystem from a resource efficiency point of view.

6.2. Mass and Rarity approaches

As was explained in the overview section, the accountability of metals can be done on a mass basis. Alternatively, an economic approach could be used. However, the economic accounting has its weaknesses. One of them is monetary depreciation (the purchasing potential of 1 € of 2017 is different than that of 1 € of 2003). Another problem of the economic approach relies on its fluctuations. For example, cobalt price fell from 90,000 $/ton to 80,000 $/ton in less than one month [194].

This is why a more appropriate indicator to assess the different resources used in a car must be sought. One way to do so is through the thermodynamic rarity approach, which allows to account for the quality of each raw material.

By means of this thermodynamic approach (thoroughly explained in Chapter *Fundamentals*), those metals which are used in very small quantities (even smaller than 1 gram) will be higher rated because of their greater physical value (measured through their Thermodynamic Rarity). This methodology will allow to identify those vehicle parts which are most critical taking into consideration their metal composition.

6.3. Results

6.3.1.Mass and Rarity comparison. Vehicle without batteries.

Figure 4 and Figure 5 represent the contribution of each metal through mass and rarity. Major metals are shown in Figure 4, whereas those with a mass share below 0.1% are represented in Figure 5. All values expressed in mass and exergy units for ICEV, PHEV and BEV are detailed in the annex of **Paper II.**

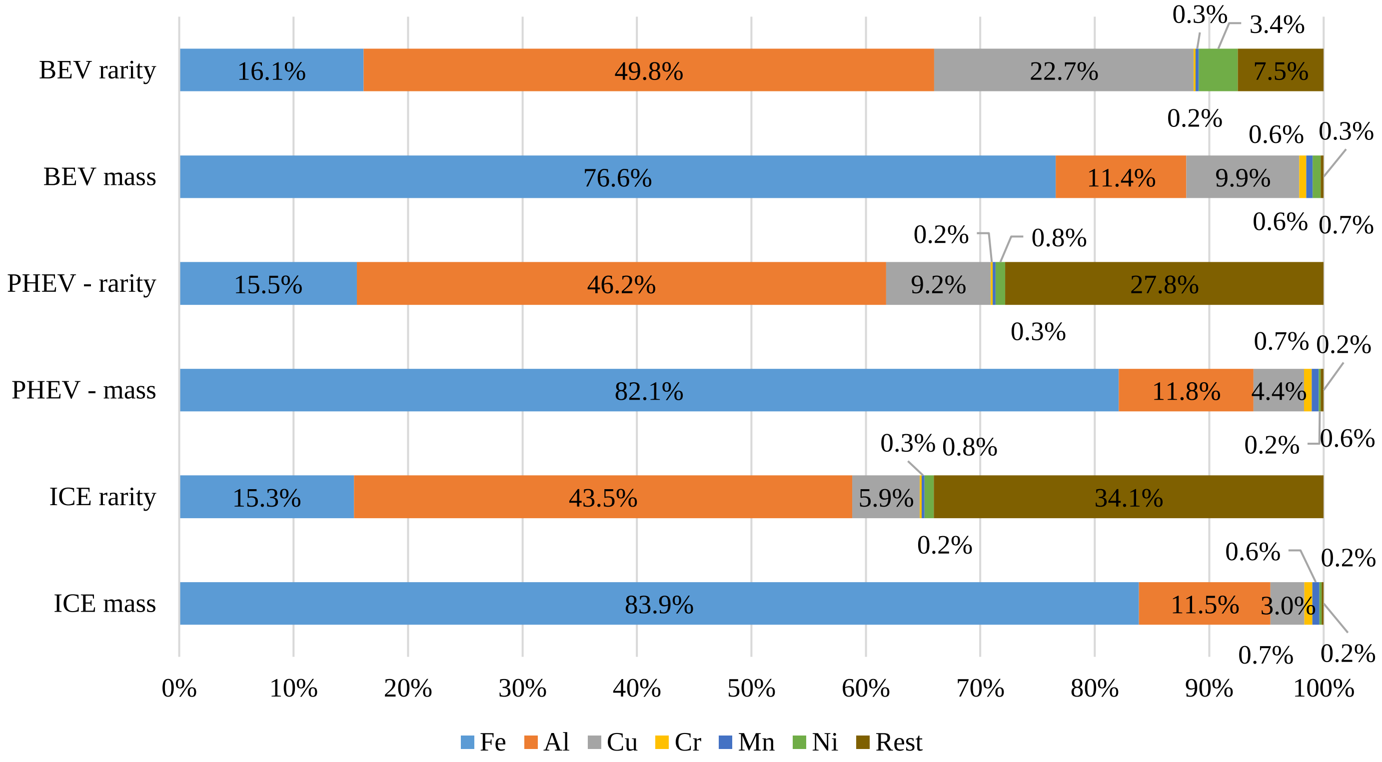


Figure 4: Mass and Rarity for materials with a mass share greater than 0.1 wt%

From Figure 4, it becomes evident how iron, aluminum and copper together account for over 95 wt% of the total amount of metals in the three cases (ICEV, PHEV and BEV). This situation drastically changes when the assessment is carried out in rarity (rt) terms.

Even if iron is the major metal used with mass shares greater than 75 wt%, the rarity share drops to around 15 rt%. On the contrary, aluminum's rarity share increases with respect to a mass assessment (40 rt% vs.12 wt%). This means that small quantities of aluminum used for vehicle´s light weighting purposes have a negative impact on the sustainability of the car from a rarity point of view. Aluminum contribution prevails over iron because of its higher embodied exergy associated to the Bayer process. The case of copper is also representative, since its rarity contribution doubles that of its mass contribution. Minor metals accounting for below 0.1 wt% have significantly greater contributions in rarity terms, i.e. 34.1 rt%, 27.8 rt% and 7.5 rt% for ICEV, PHEV and BEV, respectively. Figure 5 shows this fact in more detail. For instance, around 6 g of platinum and 1 g of palladium are used to build catalytic converters in ICEV and PHEV. Yet considering their rarity values (per gram, the highest among all considered materials), they are as relevant as iron, aluminum or copper, accounting for 22 rt% and 7 rt%, respectively for ICEV, 15 rt% and 5 rt% for PHEV.

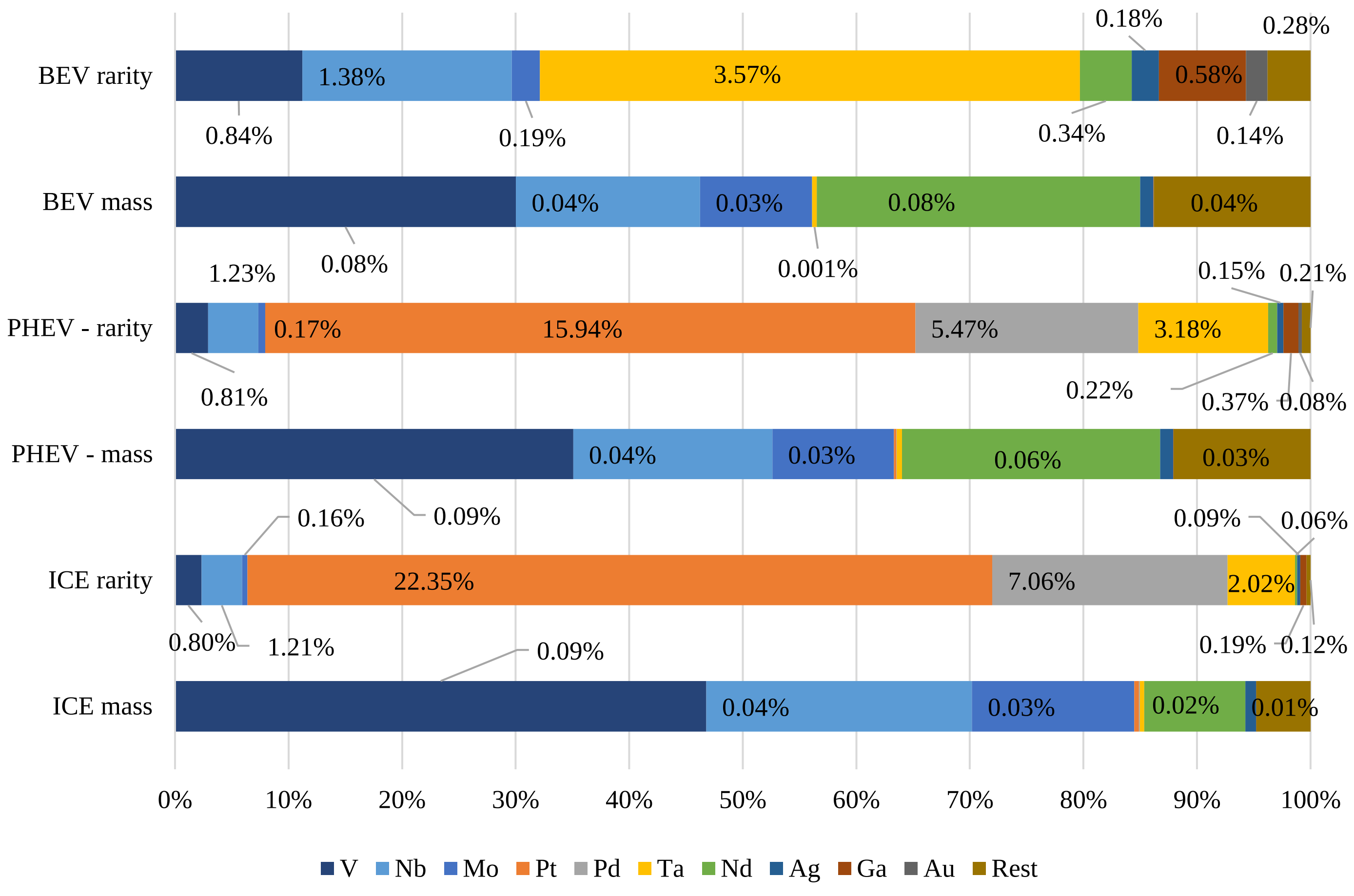


Figure 5: Mass and Rarity for materials with a mass share below 0.1 wt%

The importance of materials used in high strength steel alloys becomes also more evident when using rarity as the unit of measure. Niobium passes from a share of 0.04 wt % to over 1 rt%, whereas vanadium from 0.09 wt% to 0.8 rt%. Something similar occurs to important materials demanded in electric and electronic components such as tantalum, neodymium, silver or gallium. In BEV, tantalum share increases from 0.001 wt% to over 3.5 rt%, neodymium from 0.08 wt% to 0.3 rt%, while gallium and silver pass from less than 0.01 wt% to around 0.6 rt% and 0.2 rt%, respectively.

As a summary, Table 14 shows the metals where recycling efforts should be placed if the unit of measure in the European reuse and recycling target were mass (as it is now) or exergy through rarity indicator.

The situation today is that the target can be achieved if iron and aluminum were fully recycled. Yet with rarity, at least platinum, palladium and copper should be additionally considered depending on the type of vehicle. Note that this is a simplification, as complete recycling is impossible from a thermodynamic point of view, Reuter, Van Schaik, Ignatenko et al. [102] and the maximum achievable recycling rates should be analyzed on a case by case basis. In fact, as Hagelüken and Meskers [195] or Granata, Moscardini, Furlani et al. [196] state, certain high tech metallurgical processes are capable to recover as byproducts precious metals such as PGM from automotive catalysts.

Table 14: Metal contribution to achieve EU Directive 2000/53/EC requirements under rarity and mass approaches

	Reuse and Recycle 85 %	
Type of vehicle	**Rarity**	**Mass**
ICEV	Al, Pt, Fe, Pd	Fe, Al
PHEV	Al, Pt, Fe, Cu	Fe, Al
BEV	Al, Cu, Fe	Fe, Al

6.3.2. Mass and Rarity comparison. Batteries.

Figure 6 represents the mass and rarity contribution for all metals required for batteries analyzed: Lead based, NiMH and Li:ion.

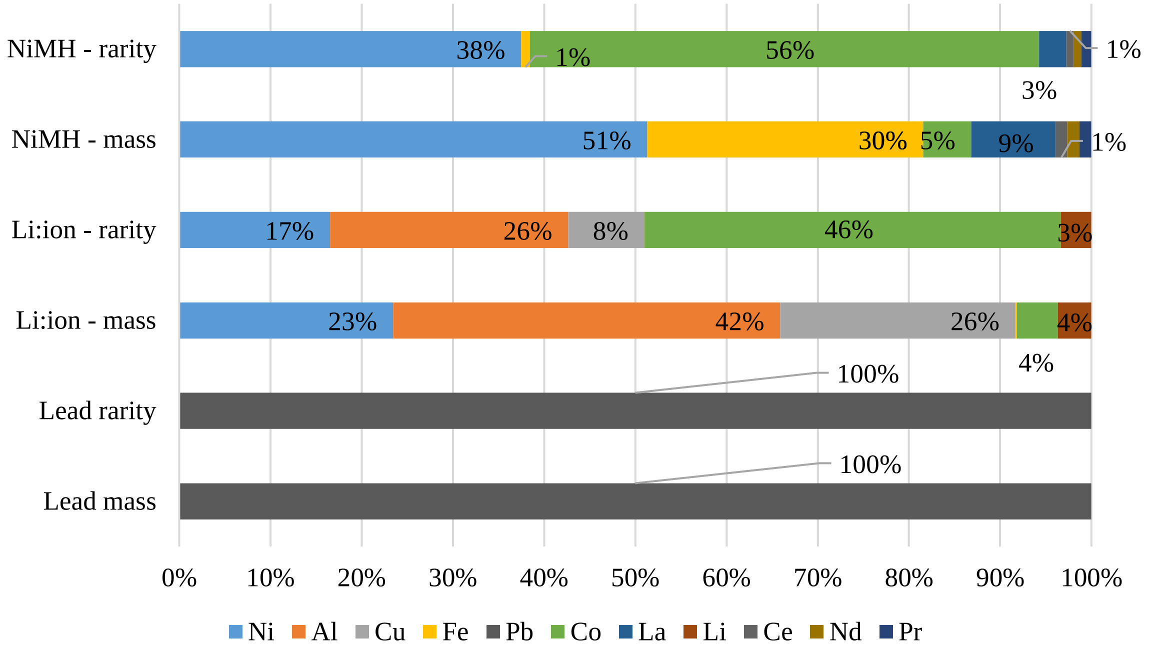


Figure 6: Mass and Rarity comparison in different batteries

The case of lead batteries is straightforward, as its major component is lead. Hence, mass and rarity approaches provide similar results. For Li:ion, Co becomes very relevant in rarity terms, accounting for 46 rt% of the total with respect to the 4 wt%. The rarity share of Cu in turn drops from 26 wt% to only 8 rt%. Something similar occurs with iron in NiMH which passes from 30 wt% to only 1 rt%, while cobalt prevails over the rest, with a 56 rt% rarity share (vs. 5 wt%).

With these results, one can now identify which would be the metals where more recycling efforts should be placed if EU reuse and recycling targets were rarity instead of mass based. This is presented in Table 15. In lead batteries both approaches provide the same results. Yet for NiMH and Li:ion, cobalt becomes the most relevant metal to be recycled.

Table 15: Metal contribution to achieve EU Directive 2006/66/EC requirements under rarity and mass approaches

	Recycling 65 %	
Type of batteries	**Rarity**	**Mass**
Lead	Pb	Pb
NiMH	Co, Ni	Ni, Fe
Li:ion	Co, Al	Ni, Al, Cu

6.3.3.Mass and Rarity comparison. Vehicle components.

One could go a step further and calculate thermodynamic rarity values by component and type of vehicle. By doing this, it would be easier to identify which are those car parts with the largest material rarity share, and thus advice for improving their eco-design and material recovery at the end of life. Rarity values are compared to the same results obtained using mass.

As can be seen in Figure 7, both approaches point to the BEV as being the most material-intensive from all types. While the heaviest parts (body, brakes, suspensions, steering) are similar in the four analyzed cases, BEV has an extra weight caused mainly by batteries and electronic components. It is also remarkable that PHEV weight grows from 1,048 to 1,145 kg if the NiMH instead of the Li:ion battery is used. This is because of the lower power density of metallic hydrides with respect to Li:ion. Besides, electrical and electronic component's BEV weight is 68 kg on average, whereas that for PHEV and ICEV only 44 kg and 28 kg, respectively.

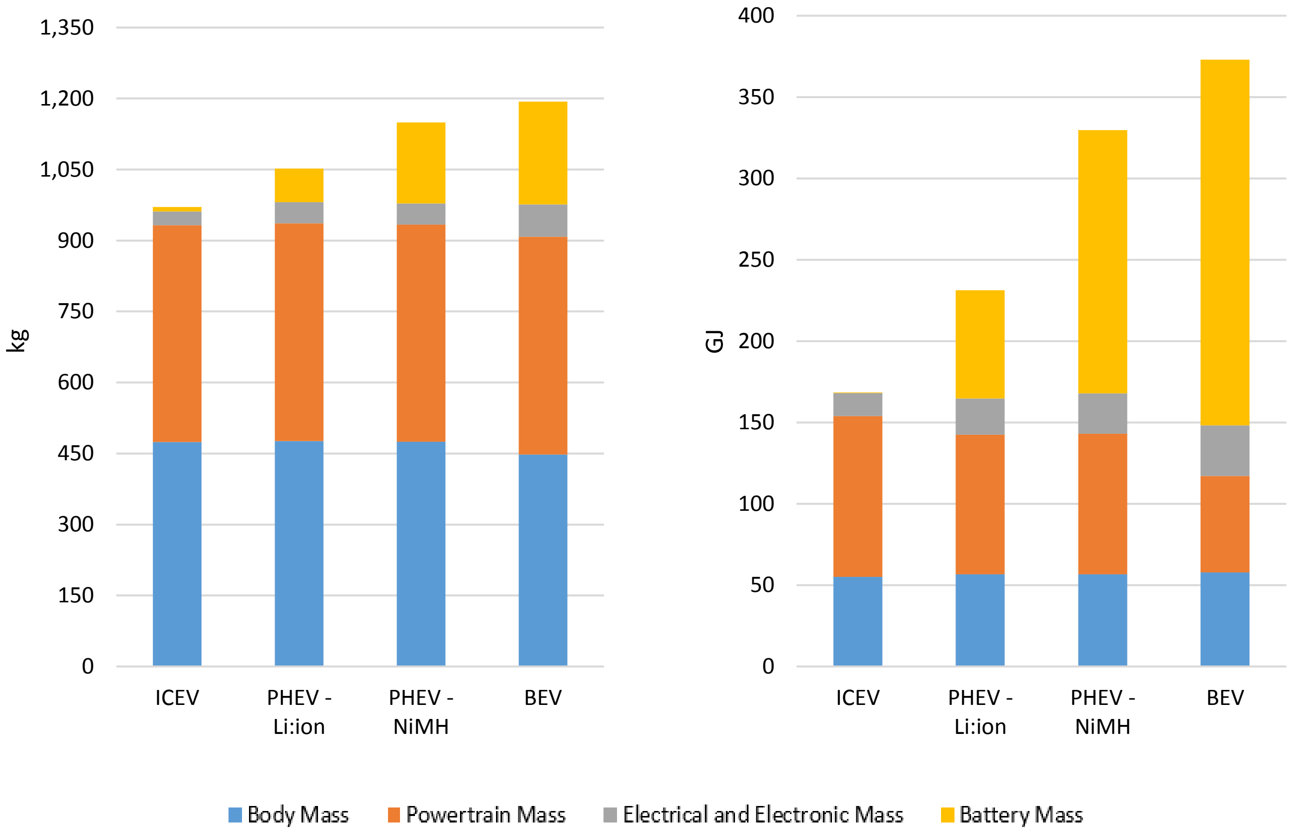


Figure 7: Mass and Rarity by component and type of vehicle

Considered as a whole, an average BEV is around 220 and 140 kg heavier than an ICEV and PHEV, respectively. Such components are not only heavier, but contain critical materials with significant higher rarity contents. Figure 8 shows material contribution to the rarity value for each type of component and vehicle.

From rarity point of view, even if BEV are also the highest material intensive vehicles, the distance to the other two types, especially to the ICEV, is far more pronounced. The rarity of a BEV is 2.2 times greater than that of the ICEV, yet it is only 22% heavier. With respect to the Li:ion-PHEV, BEV has a rarity content that is 61% greater (but 13% heavier). Again, the differences among them are mainly caused by the contribution of batteries and electronic components, but also because of the greater aluminum use in the body's BEV for light weighting purposes. Indeed, light weighting constitutes an important challenge for electromobility because it is one effective way to increase a vehicle's autonomy. Nevertheless this is not without difficulties because battery autonomy heavily depends on their weight.

Battery autonomy is in fact the reason why this component is especially relevant for BEV, less so in Li:ion –PHEV and almost insignificant for ICEV. Nickel and cobalt account for more than 60 rt% of the battery's rarity in BEV and Li:ion-PHEV. Li in turn, accounts for around 3 rt% in both cases. The battery's rarity in NiMH -PHEV case is 2.4 times greater than that of Li:ion –PHEV and similar as in BEV although its autonomy is 4 times smaller.

This is a consequence of the greater Ni and Co demand with respect to the Li:ion battery and the need for rarity intensive elements La, Pr and Nd. Finally in the case of ICEV, with a lead base battery, Pb demands most of the total rarity. All values expressed in mass and exergy terms for batteries are included in **Paper II** as supporting information.

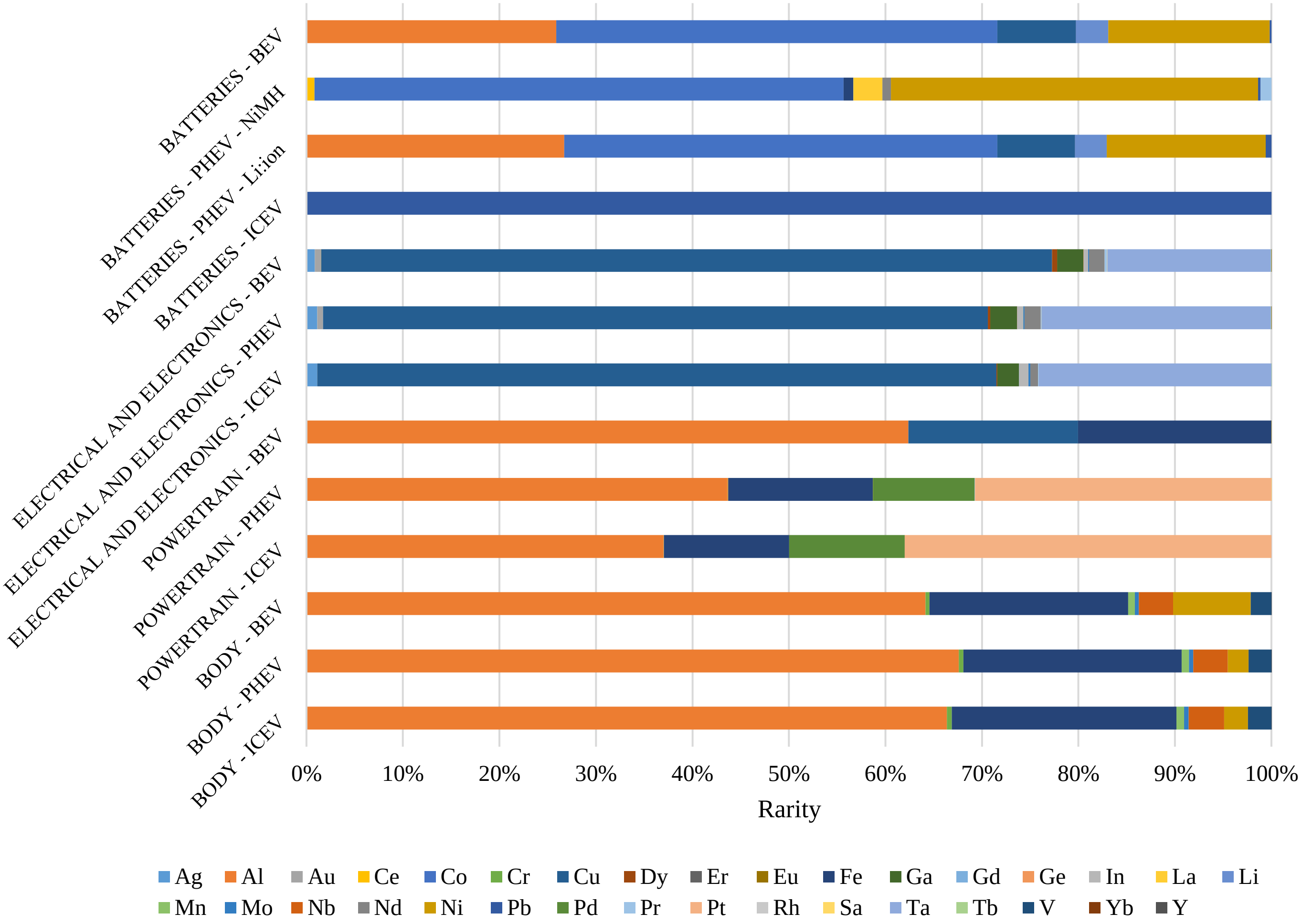


Figure 8: Rarity contribution in different types of vehicles

This unbalance is also very remarkable for the electric and electronic components. BEV and PHEV rarities are 2.2 and 1.7 times greater than in ICEV, respectively. This is mainly due to the greater amount of Cu in the first vehicle types (i.e. Cu share for the BEV is near 80 rt%). That said, tantalum is also an important element, accounting for around 20 rt% of total electrical and electronic rarity.

The most critical component in ICEV and PHEV is the powertrain. This is because of the platinum and palladium content in the catalyzer, which are elements with the highest rarities per gram of all materials considered. Both account for more than 40 rt% of the powertrain's rarity in ICEV and PHEV. Fortunately such elements are also highly recovered getting recycling shares of up to 90 %, BASF [197]. The fact that they can be separated from the molten metal more easily than other elements for their metallurgical properties also helps to achieve the mentioned shares. It should be noted that even if BEV do not contain catalyzers, the greater Al content in the power train with respect to the other two vehicles (with a contribution of 62 rt%), makes this component to have an important rarity's share. Not surprisingly therefore, Al is the material with the highest rarity contribution in the body, with 62 rt% to 68 rt% of the total share depending on the type of vehicle.

Not insignificant either are refractory metals used as steel alloys such as Cr, Mn, Mo, Nb, Ni and V, which account all together for 10 rt% of body´s rarity in the case of ICEV and PHEV and 15 rt% in BEV. Niobium included in the steels of ICEV for instance, contributes to 4 rt% of the body´s rarity, but only 0.09 wt% to its mass, i.e. two orders of magnitude more. While Fe is almost fully recovered as new Fe source through magnetic processes, other metals contained in the body become downcycled or lost. Today there are more than 9 types of steel containing less than 0.5% of critical elements, conferring special properties to the body and for satisfying safety standards and fuel efficiency requirements. Moreover, the future is moving towards the so-called "high-entropy" alloys. These consist of four, five or more elements (such as Nb, Sc, Co, Cr, Ni, Ti, Fe, Al or any other from the periodic table) mixed together in roughly equal ratios, leading to lighter and stronger materials than their conventional counterparts, while being much more resistant to corrosion, radiation or severe wear (Lim [198]). As can be inferred from its name, recovering the elements from high-entropy allows will be even more difficult than it is now. This is because today, when the body goes to the fragmenting process all steel types are mixed together, complicating the recovery of valuable materials such as Nb, Cr, Ni or V. In this respect, Ohno et al.. (2014) demonstrated how around 60 wt% of Ni, Cr and Mo contained in LDV end unintentionally as an iron source in an electric arc furnace steel making process and cannot be recovered. The case of Ni losses in shredding processes is so illustrative. According to the Nickel Institute [90] approximately only 40 wt% of nickel contained in automobiles is reused for its nickel content in steels plate rolls, another 40 wt% is recycled into other metals and becomes unavailable to the nickel recycling loop and finally around 20 wt% ends in landfills.

6.4. Conclusions of Paper II

Considering the added value that rarity concept provides with respect to a conventional mass accounting, the following outcomes have been obtained:

- Although the weight increase in PHEV and BEV with respect to the ICEV is not remarkable, there is a substantial value increment related to those materials needed for electrical - electronic components and batteries. This means that from a thermodynamic rarity point of view, ICEV is better than the PHEV and BEV alternatives.
- If rarity per kilometer of autonomy is assessed, it can be stated that NiMH batteries are worse from a thermodynamic rarity point of view than Li:ion batteries. NiMH has a rarity of 3.25 GJ/km, while Li:ion only 1.33 GJ/km.
- In BEV and NiMH-PHEV and contrary to the other cases, electrical and electronic components and chemical storage devices together are even more important from a rarity point of view than the body and powertrain. Special attention should be paid to: Co, Ni, La and Li (batteries) and Cu, La, Mo and In (electrical and electronic components).
- The powertrain and the body contribute similarly in value in the three cases, yet the first is more critical than the latter. This is mainly due to the use of Al in powertrain components such as engine parts or suspensions. Refractory metals contained in steel alloys contribute substantially to the rarity of the body.

The application of the rarity approach, allows not only to recognize the physical value of materials with a low weight contribution, but also to quantify their specific importance in the vehicle as a whole. Particularly, it has been demonstrated that Al, Co, Cu, Ni and La (used in chemical storage systems), Nb, Cr, Mo and V (used in steel alloys), Ce, Pt and Pd (used in catalytic converters) or Nd, In, Ga and Ta (used in electrical and electronical applications) which weight contribution in the vehicle as a whole is small, are not insignificant when considering their rarity. The demand of these materials will grow in the transition through zero emission vehicles, making PHEV and BEV worse from a thermodynamic rarity point of view than ICEV. This situation will become even more acute in the future with the installation of sensors and connectivity devices in autonomous vehicles.

Therefore, if recycling policies use targets based on mass, even if they are ambitious, they fail in enhancing the recycling of critical raw materials. This could be solved by using thermodynamic rarity as the unit of measure instead. Indeed, even if Fe, Al and Cu account for more than 95 wt% of a vehicle’s metal content, their relative thermodynamic contribution drops to less than 70 rt% in ICEV and PHEV cases, what would lead to recover other types of materials. For instance, a vehicle’s recycling target should pass from 85 wt% (excluding plastics, rubber and glass) to 90 wt% if Ta had to be recovered using rarity as the unit of measure.

With a detailed rarity analysis, it will be possible to identify which parts of the car should be key to recover or to substitute some of their metals (this will be dealt in Chapter 9 – **Paper V**). As it was seen, high-rarity materials are going to form part of the new generation of vehicles. This will probably lead to a future supply risk that may hinder the very development of the electric vehicle as it has been demonstrated in Chapter 5 (**Paper I**).

Chapter 7. Raw material assessment in vehicles. Global considerations. (Paper III)

7.1. Introduction to the chapter

The application of thermodynamic rarity approach has been useful to demonstrate that current methods used by recycling policies fail from a resource efficiency point of view because they do not consider neither the scarcity nor the rarity of each resource. Moreover in the previous chapters (**Paper I and II**) it has been demonstrated how current electric vehicles are not as sustainable as they seem because the impact of those materials used to manufacture batteries, electronic components or motors is significant from a resource efficiency point of view.

That said, in the industry certain terms such as *"scarce"* or *"rare"* are not commonly used and in turn is more common to talk about *"strategic"* or *"business relevant"*. Certainly, there are other non-physical parameters that go beyond a potential geological scarcity, which are critical for the operation of a company: availability from different suppliers (supply risk), substitution alternatives or industrial competitors for the same raw materials (economic importance).

This chapter (**paper III**) is developed with the aim to bring closer the problems related to resource scarcity to the automobile industry. The results will be useful to identify what are the most strategic metals for the automobile industry under a holistic vision. It will also serve to check the reliability of the thermodynamic approach in the automobile case when other non-physical variables are also taken into account.

7.2. Physical and non-physical approach. Strategic Metal Index.

Thermodynamic Rarity can be considered as a new dimension to assess the physical value for any metal. Nevertheless there are other non-physical but relevant factors for the industry. Some of these parameters are the economic importance or supply risks which are used by the European Commission [28] to define the metal criticality. With the aim to give a holistic approach about criticality and to check the reliability of the Rarity indicator with respect non-physical point of view (markets, geopolitics, vulnerability, substitution, dependency) an index named Strategic Metal Index (SMI) has been defined in this section. The SMI ranks raw materials in the automobile sector according to different criteria (both physical like non-physical). The SMI index ranges from 0 to 100 and is calculated considering the following variables:

- A: Automobile manufacturing sector demand of each metal with respect to total production. It is calculated by dividing the cumulative demand (2018 – 2050) of automobile manufacturing sector and the total cumulative demand (2018 – 2050) of all sectors for each studied metal. It gives an idea of the importance of the automobile sector in the world capacity production of this metal.
- B: Available reserves with respect to cumulative demand (from 2018 to 2050) of this metal. It is calculated by dividing the total cumulative demand (2018 – 2050) and the

available reserves. It gives an idea of the directly geological availability of this commodity.

- C: Metal known resources with respect to cumulative demand (from 2018 to 2050) of this metal. It is calculated by dividing the total cumulative demand (2018 to 2050) and the current known resources. As in the previous case it gives an idea of the geological availability of each commodity but based on resources instead of reserves (i.e. not necessarily economically feasible at the time of determination).
- D: Production capacity and annual demand ratio for each metal (from 2018 to 2050). It is useful because it compares for each studied year the expected demand with the production capacity. To do it, the production capacity is modeled by means of the Hubbert theory. This model is explained in section 2.3.
- E: Economic Importance. Value taken from the Critical Raw Material report published by the European Commission [27]. This index ranges from 0 to 10 and so it can be used in SMI by extrapolating it to a 0 to 100 scale. This variable complements the A variable, and offers an idea of the economic dependency of a given metal.
- F: Supply risk. Value taken from the Critical Raw Material report published by the European Commission [27]. This index ranges from 0 to 10 and so to use it in the SMI index it is extrapolated to a 0 to 100 scale. It offers a geopolitics vision of dependency for each commodity.

The SMI is calculated as the sum of the six described variables (A – F) by means of using weighting coefficients for each one, as follows (equation 11):

$$SMI = \alpha{*}A + \beta{*}B + \gamma{*}C + \delta{*}D + \varepsilon{*}E + \zeta{*}F \qquad (11)$$

Where: $\alpha + \beta + \gamma + \delta + \varepsilon + \zeta = 1$

Once the SMI is assessed for each metal, all of them can be ranked. Nevertheless at this stage the challenge is to calculate the required variables. The geological variables (A, B, C and D) are calculated as it was explained in section 3.2. The variables E and F comes from the Critical Raw Material report published by the European Commission [27].

7.3. Results

7.3.1.Metal strategic Ranking

As different variables are needed to calculate the SMI, several scenarios are presented to assess it under different possible situations. The following scenarios have been defined:

- **Geo (geological):** The higher weight (0.6 over 1) is given to metal geological availability variables (B, C and D). The rest of variables are equitably weighted.
- **EU (European Commission):** The higher weight (0.6 over 1) is given to the variables defined by the European Commission (E and F). The rest of variables are equitably weighted.
- **Ams (automobile sector):** The higher weight (0.6 over 1) is given to the automobile demand with respect to total demand (A). The rest of variables are equitably weighted.
- **Equi (equitative):** All variables have the same weight.
- **Exp (experts):** It is a scenario based on the common criteria between the authors and the car manufacturer. Under this scenario the most weight (30 %) is assigned to the automobile dependency of a metal. Moreover the two variables from the European Commission cover 40 % of the value. Finally the geological variables are equitably rated and cover about 30 % of the total SMI index.

The values used for the weighting coefficients are presented in Table 16.

Table 16: Weighting coefficients used for the different scenarios

Scenario	α	β	γ	δ	ε	ζ
Geo	0.13	0.2	0.2	0.2	0.13	0.13
EU	0.1	0.1	0.1	0.1	0.3	0.3
Ams	0.6	0.08	0.08	0.08	0.08	0.08
Equi	0.16	0.16	0.16	0.16	0.16	0.16
Exp	0.3	0.1	0.1	0.1	0.2	0.2

The selection of these scenarios allows us to have a range of values in the SMI calculation. Figure 9 represents the SMI ranking and the uncertainty range for each case. Metals are ranked through the SMI value calculated for an Average scenario. The average scenario is calculated as the average SMI value obtained for each metal from the scenarios represented in Table 2. The SMI for the Average scenario is represented with crosses. Color scale means: Red (SMI ≥ 35); Orange (35 > SMI ≥ 20); Green (SMI < 20). The most critical metals (those which SMI ≥ 50) are Ni (61), Li (57), Tb (56), Co (55), Dy (51) and Sb (51). These metals are followed by Nd (47), Pt (44), Au (40), Ag (40) and Te (40).

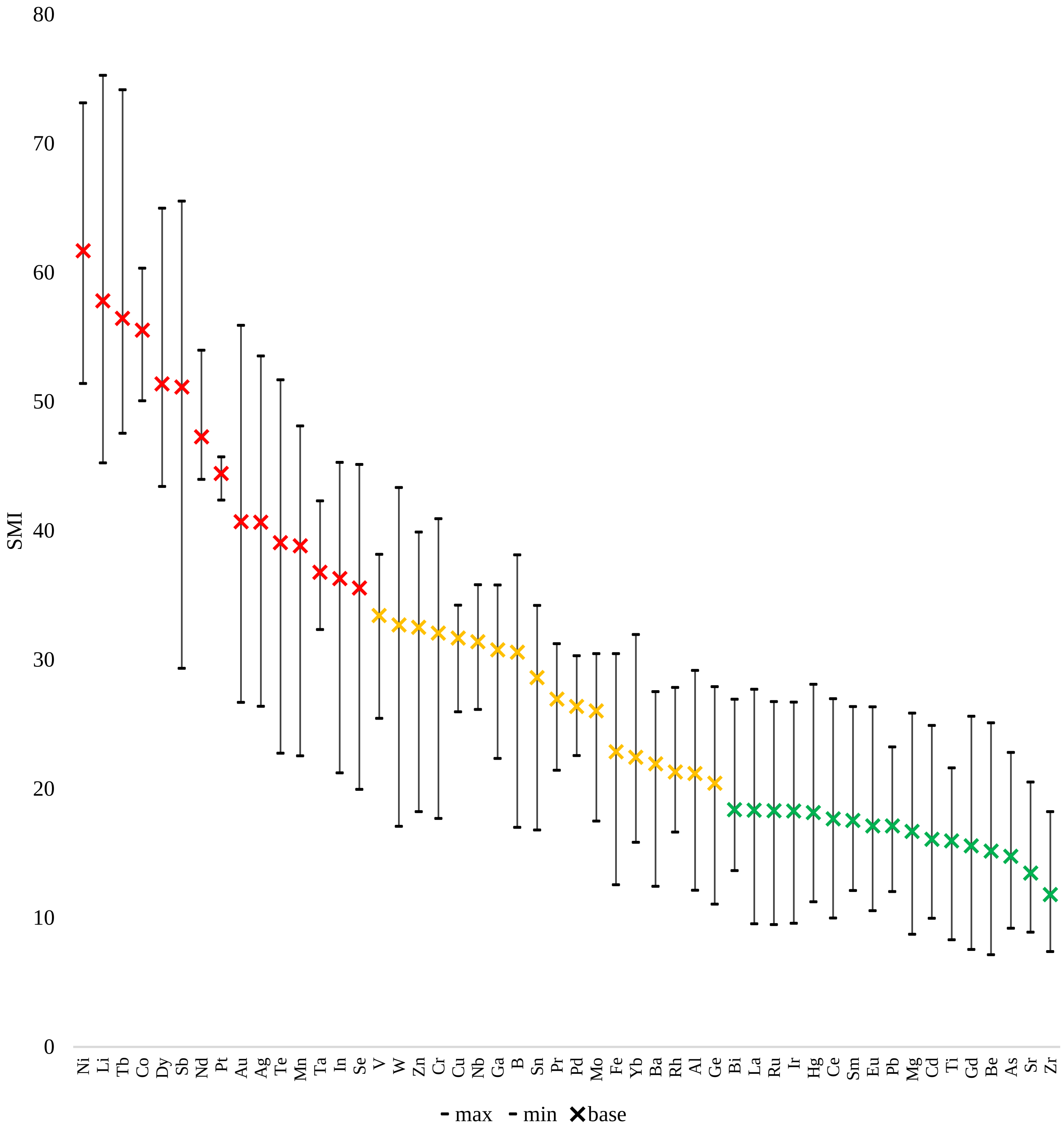


Figure 9: Metal Strategic Ranking. Source: Own elaboration [199].

Considering the possible range of results among the studied metals and scenarios, the lowest corresponds to the Ams scenario for most cases. This scenario assigns the highest impact to the automobile sector demand with respect to the total demand. The opposite case corresponds for Geo and EU scenarios. In appendix (**Paper III)** the values for each metal and scenario are shown.

7.3.2.Most strategic metals and vehicle applications

The next step is to identify the most critical parts considering the metals with an SMI greater than 35 for the Exp scenario. Table 17 contains this information, showing that the most affected components are batteries, which mainly use Ni, Li Co and Mn, all of these metals with an average SMI value higher than 40 and in the case of Ni, Li and Co even higher than 55.

Table 17: Main critical metals and vehicle applications

Metal	SMI range	Applications
Ni	From 51.4 to 73.1	Batteries (NMC and NCA) and steel alloys
Li	From 45.2 to 75.3	Batteries (NMC)
Tb	From 47.5 to 74.1	Lighting and fuel injectors
Co	From 50.0 to 60.3	Batteries (NMC and NCA) and steel alloys
Dy	From 43.4 to 64.9	Permanent magnets
Sb	From 29.3 to 65.5	Steel alloys and paintings
Nd	From 43.9 to 53.9	Permanent magnets
Pt	From 42.3 to 45.7	Catalytic converters
Au	From 26.7 to 55.9	Electronics (contacts coating)
Ag	From 26.4 to 53.5	Electronics (contacts coating)
Te	From 22.7 to 51.7	Steel and lead alloys and electronics
Mn	From 22.6 to 48.1	Batteries (NMC) and steel alloys
Ta	From 32.3 to 42.3	Electronics (capacitors)
In	From 21.2 to 45.3	Screens
Se	From 19.9 to 45.1	Lighting sensors and glasses

The case of Tb stands out, which is mainly used in lightings and fuel injectors. Lighting equipment can be affected by Se shortages, an element that is also used to build glasses. Permanent magnets are also included among the most affected components. Dy and Nd have SMI values of 51 and 47, respectively. High strength steel alloys can also be affected, as Sb and Te are ranked between the most strategic metals. Catalytic converters used to treat combustion gases will be also affected by critical metals, as Pt is included with an average SMI of 44. Finally electronic components that demand Au and Ag for contacts and welding can be affected and also those that use Ta to manufacture capacitors or In, which is mainly used in the screens of combi instruments and infotainment units.

7.4. Conclusions of Paper III

The SMI is presented as a useful index to rank materials demanded to manufacture vehicles according to their possible future strategic importance to the sector and so guide in the formulation of possible eco-design alternatives (this will be presented in Chapter 9). The SMI is calculated through a holistic approach considering physical variables such as reserves and resources and non-physical ones such as supply risks and economic importance of raw materials within and outside the sector.

The SMI should not be understood as a quantitative variable for measuring metal scarcity or criticality. If the SMI value of metal A doubles that of metal B, it does not mean that the former is twice as critical or scarce as the latter. This is for instance the case of aluminum and germanium where the SMI for Al (21.2) is slightly higher than that of Ge (20.4). But in fact germanium is scarcer in the crust than aluminum, and contrary to the latter, due to its global economic importance and supply risks, germanium is considered critical by the European Commission. The SMI rather reflects how scarcity and criticality of a given metal may affect the automotive sector.

Moreover, and contrary to the thermodynamic rarity indicator explained and used in the previous chapter (which uses exergy as the unit of measure to value minerals according to their specific physical features in the crust and mining energy intensities), the assumptions considered implicitly in this method, make that the SMI cannot be considered either as a universal numeraire of metal sustainability in the automobile sector. Such assumptions are: (1) the vehicle composition is considered constant throughout the analyzed years; (2) future mineral reserves discoveries are not considered; (3) the possible growth in the metal demand of other sectors is not considered; (4) Metal production capacity is modeled using a Hubbert approach, which is theoretical; (5) Supply risk and economic importance by the EC might change over time (6) the weighting factors used for each category composing the SMI is arbitrary.

Nevertheless, the SMI complements the thermodynamic approach because it provides a different dimension for the potential identification of raw material shortages in the automotive sector. This dimension incorporates non-physical parameters such as supply risk, sector dependency or economic importance which are indeed key for the automobile industry.

Particularly, in **paper III** we have obtained through the SMI that the main identified shortages are those concerning the manufacturing of batteries in electric vehicles (Ni, Co, Li and Mn), permanent magnets for motors (Nd and Pr), electronic components (Ag, Au, Ta, Te and In), catalytic converters (Pt), fuel injectors (Tb) and paintings (Sb). It is highlighted that these components form part of the most critical vehicle subsystems identified in Chapter 6 (**Paper II**) by applying the thermodynamic approach.

This fact ensures that the thermodynamic approach at least in the automobile case can be considered as self-sufficient. Yet this may not be the case for other sectors and this is why both approaches are always recommended to have a holistic view of the problem.

For the identified components, automobile manufactures should encourage eco-design strategies to reduce the demand of these strategic metals, to find substitutes or to increase their functional recyclability. This is why by means of using these conclusions and those from the recycling processes research (Chapter 8 – **Paper IV**), eco-design alternatives will be presented in Chapter 9 (**Paper V**).

Chapter 8. Resource efficiency of recycling processes. (Paper IV)

8.1. Introduction to the chapter

In the previous chapters, resource efficiency in passenger cars has been assessed from the manufacturer's point of view. Accordingly, different outcomes have been obtained: (1) Possible shortages related to metal supply might occur in the next decades; (2) A method has been proposed to account for resource efficiency in cars; (3) Identification of the most critical vehicle subsystems in terms of their metal contents; (4) Shortcoming analysis related to material use in electric vehicles; (5) Analysis of the most strategic metals for the automobile industry considering both physical and non-physical parameters.

At this point it is the moment to analyze the end of life of a vehicle. The general belief is that there is no problem at sight for the future development of the automobile sector because recycling and reusing rates in the vehicle as a whole are greater than 85 % in weight terms. Yet, what occurs really with all metals in the recycling process? Are these functionally recycled? Are minor but scarce metals recovered to be used again in new vehicles?

The situation is this. In the manufacturing of vehicles many resources and so efforts (time of designers, an enormous mixology of scarce metals, complex manufacturing processes, advance logistics…) are intended to manufacture sophisticate devices such as lightings, sensors or electronics. Accordingly, a lot of resources are spent to produce a high-tech component resulting from a complex mixture of materials. On the contrary when this component ends in a recycling plant, the processes used are designed to spend as less resources as possible. These typical processes are shredding, magnetic, eddy current and gravity separation, specifically designed to consume small quantities of resources while processing an enormous quantity of vehicles each day. In conclusion, it can be stated that much fewer resources are put into play to separate than to mix.

At this point the question is… Is it really easier to separate than to mix? Everybody can check how easy is it to mix water with sugar (it is only necessary to turn the spoon several times in the glass) and how difficult it is to separate them (we need to spend much more energy than before for evaporating the water).

In thermodynamics, this phenomenon is well known: the irreversibility created in any mixing process. Indeed, mixing processes are highly entropic so an enormous quantity of exergy must be spent to separate. Moreover, in this separation process wastes will be always produced.

If thermodynamics already demonstrates that segregation of flows is far more resource intensive than their mixing, why in current separation (recycling) processes much less resources are spent than for mixing (manufacturing)? Are current recycling processes really effective in terms of the recovery of scarce metals used in a vehicle?

With the aim to analyze the recycling processes at the end of life of vehicles, this chapter is presented. To elaborate it and to get a better understanding about ELV recycling, a field study phase was set, in which several technical visits to different ELV installations such as ELV dismantling centers, shredders, post shredders and steel or aluminum alloy makers' plants were performed. The conclusions will not only serve to answer to the previous questions but also to demonstrate quantitatively the loss of scarce metals in current recycling processes.

8.2. ELV recycling processes

Figure 10 illustrates the ELV recycling process where red arrows represent the material flow of a recycling operation, blue boxes show the destination in a landfill, green boxes show the output of recycled material, the yellow boxes show the output to an energy recovery process and the grey box shows reusing. According to Vidovic et al. [200], there are mainly five entities involved: (1) users who must deliver their vehicle to collection facilities; (2) collection facilities i.e., dealers or repair garages, which collect the ELVs; (3) authorized ELV treatment companies, which remove hazardous parts of vehicles that cannot be depolluted in landfills such as fuel, oil, tires, batteries, or air conditioning cooling gas, and remove reusable parts (called in Figure 10 "other components") such as starters, suspensions or engines; (4) shredding plants, which receive decontaminated ELVs and shred them to separate them into three fractions: ferrous metals, non-ferrous metals, and the rest (a mix of rubber, foam, and plastics called ASR) using magnetic processes; (5) post-shredding plants, which receive the non-ferrous metal fraction from shredding plants and apply eddy current and density processes to separate mainly aluminum, zinc, and copper.

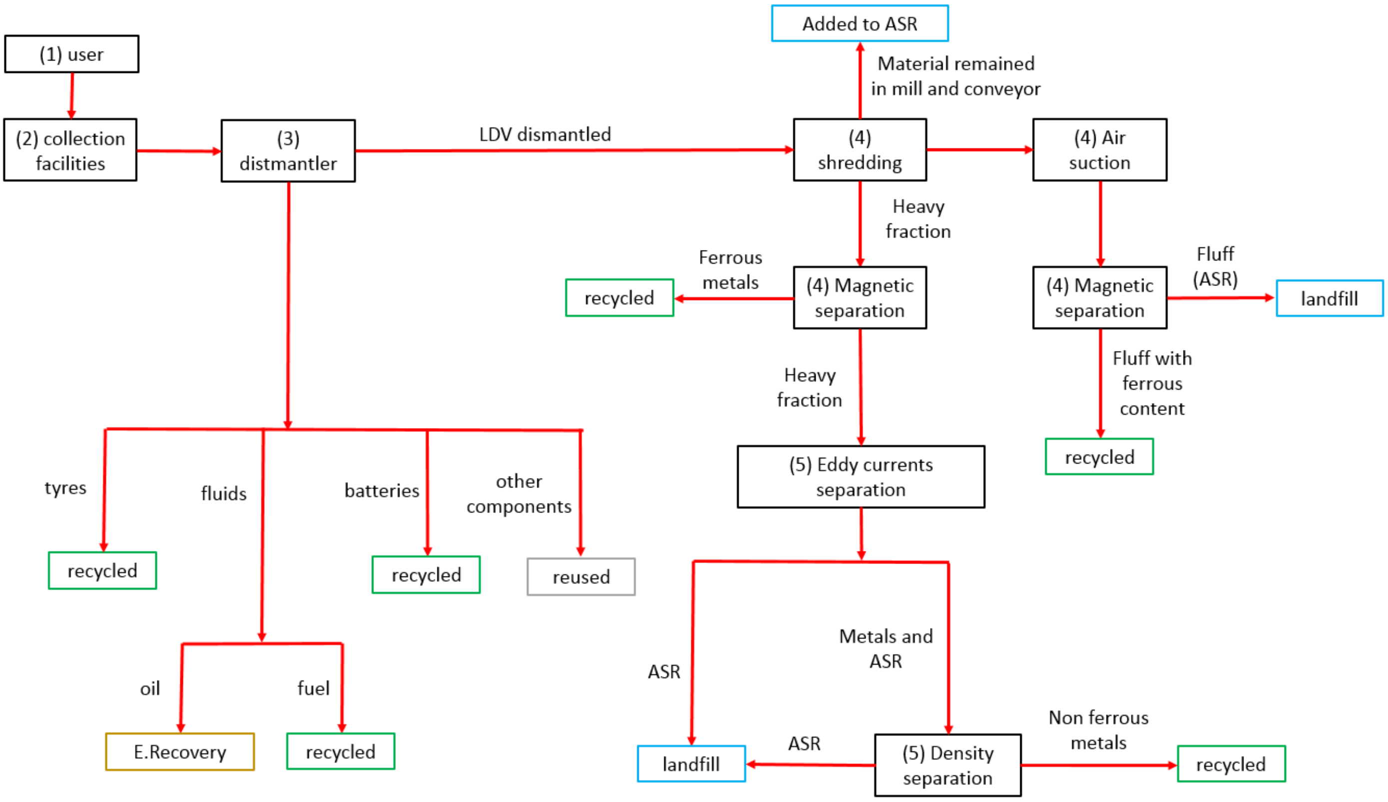


Figure 10: Vehicle recycling scheme. (1) operations performed by users; (2) operations performed by collection facilities; (3) operations performed by dismantlers; (4) operations performed by shredding plants, and (5) operations performed by post-shredding plants. Source: own elaboration.

The scrap resulting from (4) and (5) is sent to smelters to produce steel or aluminum from secondary sources. The ASR resulting from (4) and (5) usually ends up in landfill or energy recovery plants, although the latter option is more complex owing to the heterogeneity of ASR composition, which contains a small fraction of metals that often hinders energy recovery.

Consequently, in a conventional vehicle recycling process, no specific operations to recycle minor but valuable metals is present. According to Ohno et al. [86], this fact entails the loss of most alloy elements either because they are downcycled or because they end up in the automobile shredder residue (ASR), ultimately becoming landfilled.

8.3. Data gathering and downcycling assessment

Downcycling is calculated in this Thesis as the additional quantity of virgin metals that would be required to manufacture a complete vehicle if the starting point were scrap coming from ELV recycling facilities. According to this definition, it is assumed that all metals become diluted in one of the different scrap types from ELV recycling facilities. This is an idealization, since at it was previously explained, a portion of metals (usually below 5% end also in landfill). Yet this approach allows us to identify those components that are more critical from a downcycling point of view and thus provide automobile manufacturers and policy makers with valuable information to improve resource efficiency. It should be stated that this hypothesis is not very far removed from current approaches used by automobile manufacturers. In the homologation of vehicles, manufacturers need to assess the recyclability degree of the new car so as to ensure that they meet the ELV Directive. To that end, it is considered that all metals incorporated in a vehicle are recycled.

Following the definition provided, downcycling assessment methodology follows the scheme illustrated in Figure 11. The starting point is to determine the number of vehicle parts and the metal composition of each part. Therefore, it is necessary to disaggregate components into as small parts as possible, provided that the composition of each given component is known. This activity was performed using two information technology (IT) systems belonging to SEAT S.A. The first one includes a list of vehicle parts and the latter assesses the metal composition of each part (1). The selected parts are those that incorporate any kind of metal, having excluded those made exclusively of plastic, foam, glasses, or rubbers. It is well known that glasses also use some valuable metals like Ag, Ce or Mg however its research has been postponed for a future activity. The battery, catalytic converter and tires are also excluded since they are disassembled before shredding.

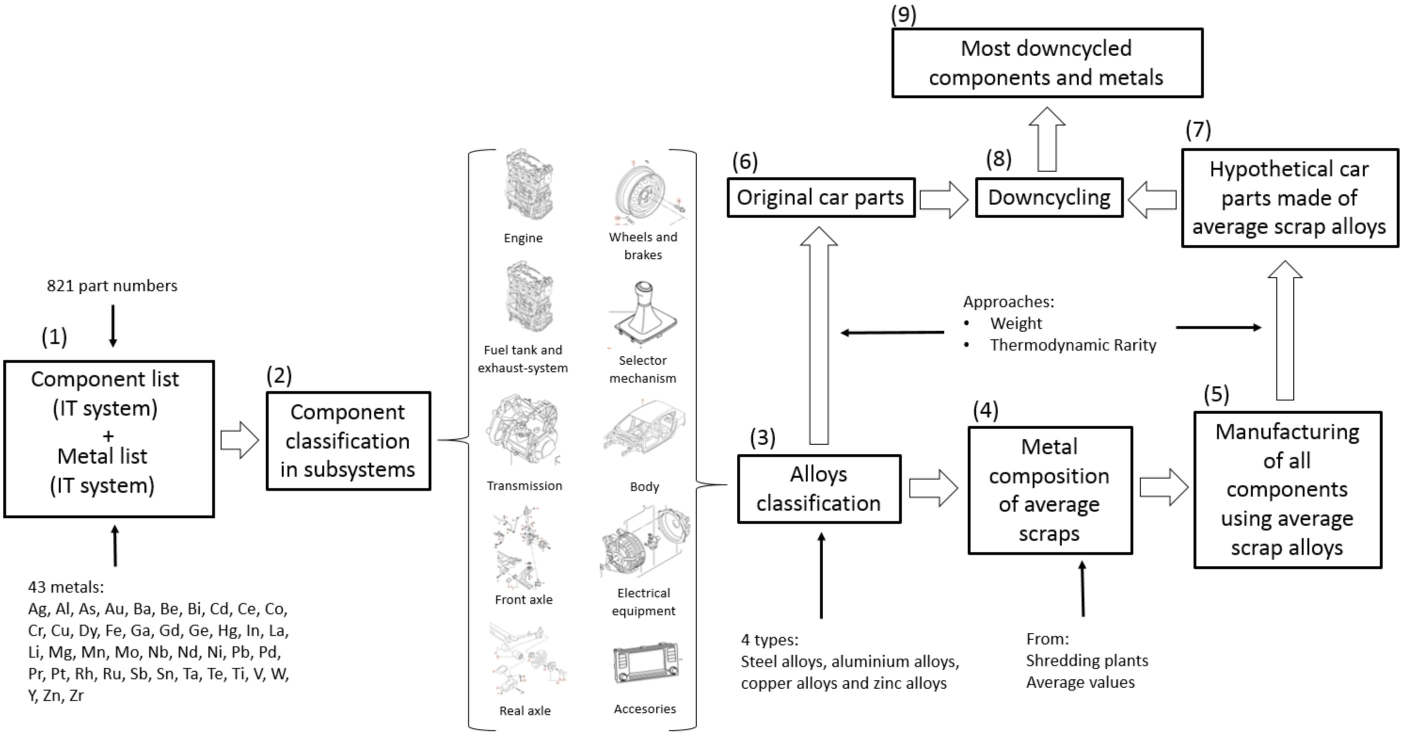


Figure 11: Data gathering and downcycling assessment methodology. Ortego et al. [201].

Owing to the large amount of parts constituting a vehicle, they are aggregated into larger subsystems for facilitating the assessment of results (2). The used subsystems classification is: engine, fuel tank and exhaust system, transmission, front axle, rear axle, wheel-brakes, selector mechanism, body, electrical equipment, and accessories. Subsequently, each part is also classified depending on the type of metal alloy used (3). The metal alloy classifications are: steel, aluminum, copper, and zinc alloys. These groups are used because shredding and post-shredding operations are almost exclusively designed to recycle these metals. It must be noted that magnesium has not been considered because it is typically fed into a second lifecycle as a secondary alloy, thus becoming a part of the aluminum cycle, Ehrenberger et al. [202]. Once the composition of vehicle parts is known, the subsequent step is to determine the composition of the steel, aluminum, copper, and zinc scraps of the ELV obtained after the recycling process (4). These scraps will be used as the input metal in steel, aluminum, copper, or zinc smelting plants. Starting from the scrap metal composition, all the vehicle parts are virtually manufactured, considering that the final weight and composition of each part must be the same as the corresponding original pieces (5). As the composition of scrap (7) differs from that used in original vehicle parts (6), new material has to be added.

This difference, which represents the downcycling degree (8), is calculated not only by weight, but also in terms of thermodynamic rarity for each part. Downcycled parts and metals are finally ranked to identify those for which eco-design should be enhanced (9).

In the case of components manufactured with metals different from those used in steel, aluminum, copper, or zinc alloys such as Ag, Au, Co, Li, Sn, or Ta, the loss is assumed to be 100%, as these metals either become completely downcycled in minor quantities in alloys, thus completely losing the functionality for which they were produced, or are landfilled.

Notably, by using this method, the thermodynamic rarity of the scrap (7) for some vehicle parts is greater than that of the required metal composition. This occurs with parts made of low-quality alloys that do not require certain elements or require them in lower quantity than those that have been trapped in the scrap. An example of this is martensitic steel whose alloy elements (Al, Nb, Ti) are significantly lower than others such as ultra-high strength steel. In the methodology, when this occurs, the rarity of the metals not required to manufacture a certain part from scrap is assumed to be zero, since this addition, although valuable is unintentional and does not confer new properties to the given part.

To perform the rarity assessment, the first step is to obtain the metal composition for each part of the vehicle. Subsequently, the thermodynamic rarity of each part is calculated by means of equation 12.

$$R\ (A) = \sum_{i=1}^{n} m(i) \cdot R(i) \qquad (12)$$

Where:

R = thermodynamic rarity, expressed in kJ/g (values included in appendix of **Paper IV**)
A = vehicle part
m = mass (g)
i = metal assessed

The downcycling degree of each component is calculated as the difference in thermodynamic rarity of each part, using the metal composition of the original pieces and the average scrap metal composition. The average scrap composition is selected considering the type of alloy used to manufacture the vehicle part (steel, aluminum, copper or zinc alloy). Equation 13 shows the expression used:

$$D\ (A) = \sum_{i=1}^{n} \Delta\, R\ (i) \qquad (13)$$

Where:

D = downcycling

A = vehicle part

i = metal assessed

$\Delta R = R_{ave\_metal\_scrap} - R_{ori\_metal\_comp}$

$R_{ave\_metal\_scrap} =$ Thermodynamic rarity of the car part manufactured with average metal scrap.

$R_{ori\_metal\_comp} =$ Thermodynamic rarity of the car part manufactured with the original metal composition.

Downcycling, as defined in Eq. (13), will always be a negative value as it represents a loss incurred from an initial situation to a final situation where quality is lost. A high negative value of downycling indicates that an important quantity of the metals contained in the given car part are not functionally recycled. On the contrary, a small value of downcycling means that these metals are not only recycled but also to a higher degree functionally recycled. It may occur that a heavy car part denoted as “A” has a lower downcyclability degree than a lighter one denoted as “B”. The reason for this can come from two factors: 1) because A, as opposed to B, is composed of mainly fully recyclable materials (such as steel), and/or 2) because B incorporates non-recyclable materials with a much higher rarity than A. As will be seen in section 4 that is the case of the turbo distributor, a much lighter component than for instance the cylinder block, but with a higher downcycling degree mainly due to its chromium and niobium contents.

8.4. Results

8.4.1.Downcycling assessment

Table 18 presents the results obtained by applying the methodology described in the previous section. As evident from Table 18, metal downcycling is equal to 32.8 kg, accounting for 4.5 % of the total analyzed weight of the car, meaning that 32.8 kg of metals have not been functionally recycled. This indicates that the ELV Directive is satisfied, as more than 85 % of the vehicle would be recycled. However, a completely different situation occurs when one assigns a quality value to metals using the thermodynamic rarity indicator. In such a case, the loss increases to 21,647 MJ, or equivalently, −26.95 rt% of the total thermodynamic rarity of the analyzed metals in the vehicle. If the ELV Directive targets are expressed in terms of rarity, current recycling systems would not be enforcing the law. In order, the most downcycled subsystems are: accessories, electrical and electronic equipment, fuel tank, exhaust system, and engine.

Table 18: Downcycling by vehicle subsystem in mass and thermodynamic rarity

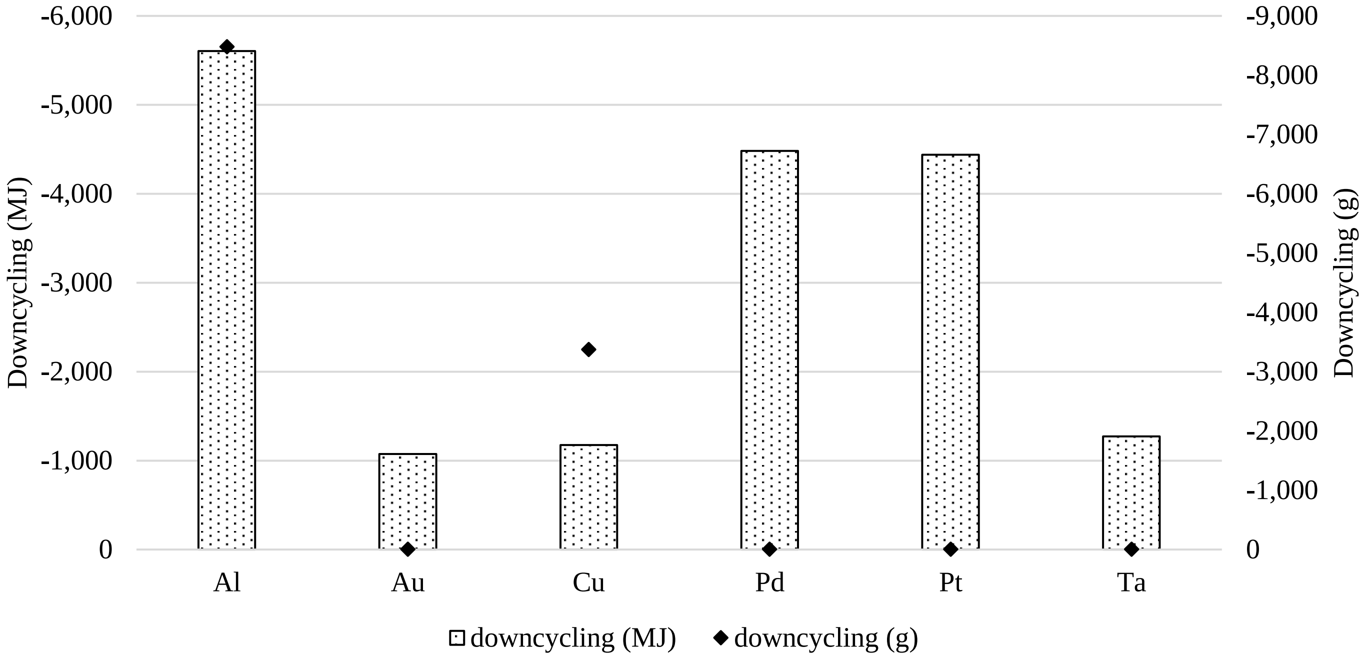
	Mass (g/veh)		Thermodynamic Rarity (MJ/veh)	
Engine	−6,024.39	−5.34%	−10,905.50	−35.64%
Fuel tank and exhaust system	−3,480.60	−19.95%	−762.76	−58.79%
Transmission	−696.55	−1.77%	−168.27	−5.27%
Front axle	−1,729.59	−3.75%	−678.24	−8.23%
Rear axle	−827.91	−3.03%	−313.54	−25.40%
Wheels and brakes	−2,907.38	−5.85%	−1,246.27	−13.97%
Selector mechanism	−114.48	−3.22%	−43.23	−26.82%
Body	−11,602.71	−2.85%	−2,369.72	−13.11%
Electrical and electronic	−5,169.93	−20.85%	−4,461.13	−57.36%
Accessories	−285.73	−10.90%	−698.52	−87.30%
Total	**−32,839.28**	**−4.50%**	**−21,647.22**	**−26.95%**

The values listed in Table 18 are calculated using the scrap composition described in **Paper IV**. Nevertheless, the sensitivity of downcycling values has been assessed using two different scrap compositions. The results vary in the range of 3.9–4.5 wt.% and 23.7–27.0 rt%. **Paper IV** includes as supporting information the scrap composition used in this sensitivity assessment.

Figure 12 (a) and Figure 12 (b) show the downcycling values per metal. Figure 12 (a) illustrates metals whose downcycling is greater than 1,000 MJ and Figure 12 (b) illustrates those whose downcycling is lower than this value. Using the thermodynamic rarity approach, the most downcycled metals are Al, Pd, Pt, Cu, Ta, and Au. Aluminum has the highest loss in thermodynamic rarity for two main reasons: (1) its greater rarity value (661.64 GJ/ton) with respect to other common metal like iron (31.85 GJ/ton) and (2) because aluminum used as an alloying element in steel is not functionally recycled (not used as aluminum source). In this model the average Al content in the steel is 0.75 %, whereas that in the average steel scrap only 0.08 %. This means that on average, 0.67 % of Al would need to be added to the steel alloy. The difference in Al content is a consequence of the use of ultra-high strength steel alloys (UHSS) in the analyzed vehicle. UHSS requires a larger aluminum content (2%) than conventional steel alloys (such as martensitic high strength steels with an Al content of below 0.02%). The analyzed vehicle uses UHSS in several heavy parts such as the floor or cross member footwell. This is why the average aluminum content in steel is rather high (0.75%).

Notably, even if Cu is the most downcycled metal by weight, in terms of rarity, Pd, Pt, and Ta are more relevant. In the cases of Pt and Pd, although catalytic converters are disassembled and recycled prior to the shredding operation, there are more quantities of these metals in other components such as particle filters or rear windscreen cleaner motor. Regarding metals with downcycling figures less than 1,000 MJ, the most relevant metal is Zn followed by Ni and Nb; all of them are used as steel alloys. Nickel and niobium are relevant because, even if their concentrations in the car are low, their specific rarities are high compared to other studied metals such as Zn. For Zn, notably, although there are specific post-shredding processes to recover it, these are only appropriate for parts made almost exclusively with Zn (i.e., a silent block bracket). Zinc contents in steel alloys are, in turn, downcycled or lost.

(a)



(b)

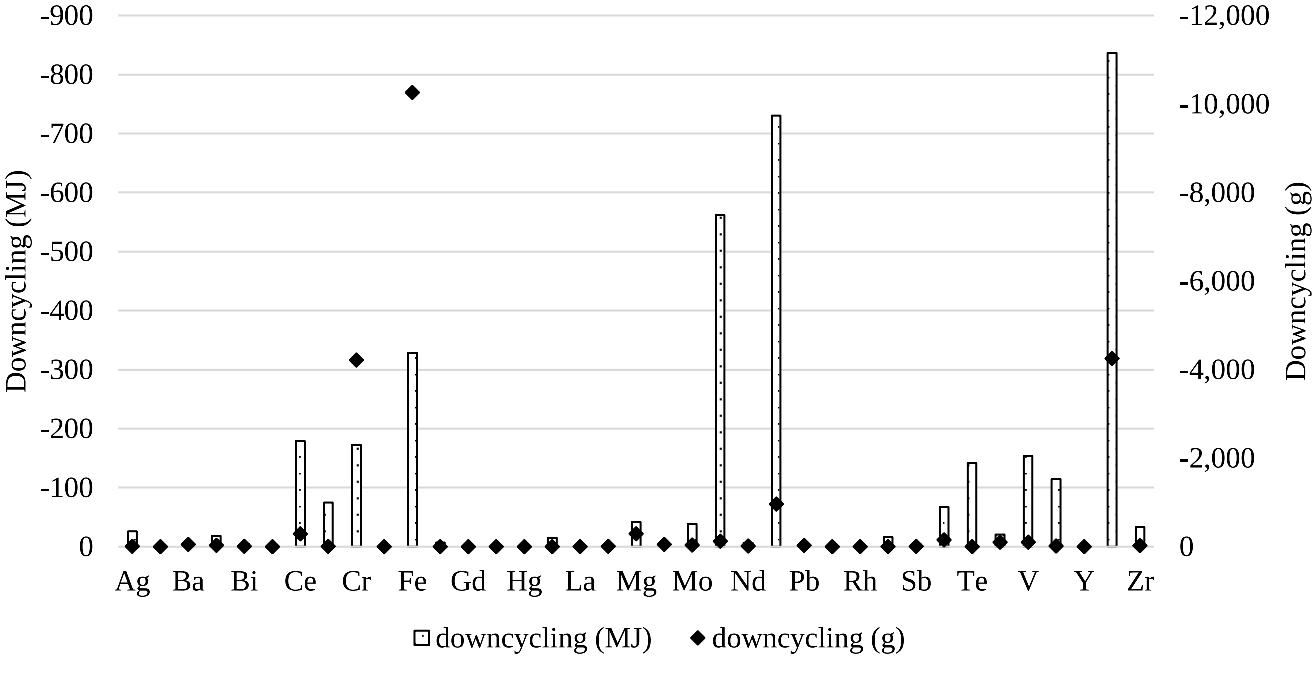


Figure 12: Downcycling by metal measured by weight and rarity. (a) Metals whose downcycling is greater than 1,000 MJ and (b) metals whose downcycling is lower than 1,000 MJ.

Finally, Table 19 presents the top 3 most downcycled vehicle parts for each subsystem given in Table 18, with the three most downcycled metals presented for each case. This type of analysis allows identifying the parts where eco-design efforts should be made in order to recover the most from valuable raw materials. The list has been made by ordering downcycling in percentage with respect to the initial thermodynamic rarity value for each subsystem. In the case of the engine, Pt and Pd used in particle filter, Nb and Cr used in turbo distributor, and W and Nb used also in turbo guide van housing, are notable. In the matter of fuel tank and exhaust subsystems, the most downcycled metals are Ni and Cr used in alloys for exhaust pipe, closing cap, and clamp. In relation to transmission, Ni and Mo used to manufacture shafts are the most downcycled metals. In the front axle, the steering wheel is highlighted, owing to the use of Au, Ta, and Cu in the electricity transmission system located in the steering rod. In the rear axle, Al is the most downcycled metal, which is also present in axle dampers. The breaking system is included in the wheels and brakes category; in this subsystem, the metals Al, Cu, Ga, Ta, and Ni used in sensor, distributor, and pump are the most downcycled. In the selector mechanism category, Ni, Cr, and Zn used as steel alloys in the clear level and ventilator together with Ta, Al, and Pd used in foot-adjusting are notable. The inner mirror is the most downcycled part in the body owing to its gold content for the anti-glare system. Also highlighted should be the seat belts that use Al, Zn, and Ni. In electrical and electronic equipment, the metals used in sensors such as Ta, Au, Ni, Pd, or Pt are the most downcycled. Finally, with respect to accessories, which also include any electrical equipment, the most downcycled parts are those that use Au and Ta such as the control unit or aerial amplifier and those that use Au and Pd such as the speed sensor.

Table 19: The top 3 most downcycled components in each category

Description	**Vehicle subsystem**	**Thermodynamic Rarity (MJ/veh)**	**Downcycling (%)**	**metal 1**	**metal 2**	**metal 3**
Particle filter	Engine	8,613.48	−99.72%	Pt	Pd	Cu
Turbo distributor	Engine	260.71	−97.86%	Nb	Cr	-----
Turbo guide vane	Engine	185.32	−88.77%	W	Nb	Cr
Clamp	Fuel tank and exhaust system	12.35	−75.88%	Ni	Mo	Cr
Front pipe	Fuel tank and exhaust system	379.57	−74.89%	Ni	Al	Cr
Closing cap	Fuel tank and exhaust system	0.91	−73.38%	Ni	Cr	Zn
Shaft	Transmission	11.68	−33.74%	Ni	Mo	Cr
Reverse shaft	Transmission	35.35	−28.92%	Ni	Sn	Mo
5th gear shaft	Transmission	32.74	−28.44%	Ni	Mo	Cu
Input pinion	Front axle	13.11	−27.87%	Ni	Cr	-----
Track control arm	Front axle	260.76	−20.07%	Mo	Nb	V
Steering wheel	Front axle	147.94	−19.70%	Ta	Au	Cu
Axle dampers	Rear axle	206.55	−80.74%	Al	Cu	Zn
Feathering	Rear axle	0.30	−17.13%	Zn	-----	-----
Rear axle	Rear axle	840.17	−16.31%	Al	V	Ni
Break assistance pump	Wheels and brakes	352	−82.10%	Al	Ga	Ta
Brake distributor	Wheels and brakes	9.05	−58.76%	Al	Cu	Ni
Brake sensor	Wheels and brakes	7.02	−57.80%	Al	Cu	Ni
Foot adjusting	Selector mechanism	12.93	−76.22%	Ta	Al	Pd
Clear level	Selector mechanism	0.78	−71.85%	Ni	Cr	Zn
Ventilator	Selector mechanism	0.11	−58.41%	Ni	Cr	Zn
Seat belt	Body	84.02	−83.90%	Al	Zn	Ni
Bracket	Body	9.74	−76.30%	Ni	Cr	-----
Inner rear mirror	Body	185.02	−74.90%	Au	Fe	Mg
Airbag circuit	Electrical and electronic	118.51	−98.81%	Ta	Au	Pd
Rain sensor	Electrical and electronic	7.23	−98.51%	Ta	Au	Pd
Temperature sensor	Electrical and electronic	45.01	−98.39%	Pt	Ni	Cu
Speed sensor	Accessories	5.16	−98.46%	Au	Pd	Cu
Control unit	Accessories	600.52	−95.04%	Ta	Au	Al
Aerial amplifier	Accessories	37.41	−83.53%	Au	Ta	Pt

Paper IV incorporates the list of vehicle parts ordered by downcycling rate measured in MJ. This list contains 27 parts representing 80% of the total downcycling of the vehicle (17.317 out of a total of 21.647 MJ).

One can additionally perform an economic analysis to put this loss into perspective. Accordingly, we have used commodity prices as published by the United States Geological Survey [203]. These data are included in **Paper IV** as supporting information. This loss would be equivalent to €174.74 per car, which indicates that, over the lifetime of a vehicle model, the total loss would be €183 M (considering an annual production of 150,000 units per year during 7 years). Note that this figure only represents an order of magnitude of the stringent importance of this issue, as price fluctuations can be significant even within a year.

8.4.2.Downcycling reduction recommendations

As main result of this chapter several recommendations are suggested to reduce downcycling in ELV recycling processes. It must be taken into consideration that the recommendations listed below does not consider the vehicle design phase because this approach will be analyzed in Chapter 9.

a. Disassembly of electric and electronic components that use valuable metals such as Au, Ag, REEs, platinum group metals (PGMs), Sn, Ta, or Te before shredding. Some of the most identified critical parts are: panel instrument, lighting switchers, LED lamps, power window motors, windscreen cleaner motors, electronic control units, rain sensors, electric mirrors, aerial amplifiers, and infotainment devices. According to Li et al. [204] this operation could be done even using automation by means of robots and would allow that specific recycling processes are implemented at a later stage.

b. Application of hybrid recycling processes for the aforementioned parts as in the case of waste electric and electronic equipment (WEEEs) as it was suggested in previous studies by Arda et al. [47], Awasthi and Li [205] and Cui and Zhang [206]. These recycling processes should be mechanical-hydrometallurgical-biometallurgical. This is because as Ardente et al. [207] published the sole application of mechanical techniques is not compatible with the recycling of other materials such as indium in the displays or REEs in LEDs. Using this approach, valuable metals such as Au, Ag, Cr, Cu, Ga, In, Mg, Mo, Nb, Ni, Pd, Pt, Sn, Ta, V, or W would be recycled. This operation could be even developed in WEEE recycling plants as some of them are already implementing these processes.

c. Disassembly of engine and gearbox components made of special steel alloys (high content of Cr, Mo, Nb, Ni, Ti, or W). Some of these components include the exhaust pipe, o-rings, turbos, pinions, and gear shafts. Owing to the excessive time required for removing some of these parts (i.e., removing o-ring from an engine requires the cylinder head cap, cylinder head, connecting rods, and pistons to be disassembled before and this operation requires at least 1 h), an intermediate situation could be implemented. This situation could be that engines and gearbox are disassembled from the rest of the vehicle before shredding. Notably, in a vehicle manufacturing plant, the entire powertrain (including front axle, gearbox, engine, and rear axle) is joined to the body in less than 30 second and hence, this operation could also be implemented via a reverse approach.

d. Application of specific shredding processes for different vehicle parts mainly made of steel and aluminum alloys (i.e., engines, gearboxes, and bodies) to produce different scrap qualities with the aim of manufacturing different qualities of alloys using them. Moreover, this measure would avoid the contamination of steel alloys due to high levels of some metals. The elements that have lower oxygen affinity than iron, such as Cu, Sn, Co and Ni (remember that all of these metals were classified under the high risk category (chapter 5*)*, remain in the final alloy. As it was published by Daehn, Cabrera and Allwood [208] and Harsco Minerals [209] the use of low quality scraps provokes the production of off-specification steel and in addition to the direct impact of this on the steelmaker it could also be considered to be a loss of these valuable elements.

e. For the above, it is important for ELV authorized treatment centers to be equipped with information systems showing the location of the components that must be disassembled before and indicating the proper procedure for the same. This recommendation could be implemented using the International Dismantling Information System [210], which currently shows information related to batteries, fluids, or airbags and in which the most important vehicle manufacturers participate.

f. To implement novel post shredder treatments to recycle critical metals from the scrap obtained as output after the application of conventional recycling methods and from the ASR.

8.5. Conclusions of Paper IV

Automobile recycling processes are designed to recycle metals that contribute to the largest part of the vehicle's weight (i.e., steel and aluminum alloys). Yet vehicles have evolved into complex machines that require a myriad of different and valuable metals. As a result of a desynchronization between manufacturers and recyclers companies, many valuable metals end up downcycled or even worse, in landfills.

As it was shown in this chapter, thermodynamic rarity is a very useful indicator for measuring downcycling, as it accounts not only for the quantity, but also for the quality of the metals that become functionally lost in ELV recycling processes. This same analysis carried out in mass terms would lead to conclude that downcycling does not practically occur (less than 5 %), since the car is composed (by weight) almost exclusively of iron, aluminum and copper, elements that are usually functionally recycled. On the contrary, with thermodynamic rarity, minor, but valuable metals have a much higher specific weight, and as such, the downcyclability degree of the analyzed car increases to around 27 %. This is because rarity is a physical measure of resources, considering their relative scarcity in the crust and the energy required to obtain the specific commodities with prevailing technologies. This way, even if gold or platinum are imperceptible metals in the overall weight of the car, they are not when converting their tonnages in rarity terms. This simple aspect has a key application in the car industry and in any resource intensive industry. Mainly, it allows very quickly, to identify those parts of the car that are more valuable from a material point of view.

Accordingly, from more than 800 different metal parts that contain a car, the method allows to select those that are most downcycled and to define recommendations for reducing the downcycling level.

Chapter 9. Recommendations through eco-design. (Paper V)

9.1. Introduction to the chapter

In previous chapters, resource efficiency from the manufacturing and recycling point of views were assessed. This was done through thermodynamic rarity, which has been proven to be a reliable indicator to identify the most critical and strategical components of the vehicle from a raw materials point of view (as it was demonstrated in Chapter 7*)*. In this chapter, a procedure aimed at vehicle designers based on this approach is established. Subsequently, a list of recommendations aimed at vehicle designers are stated. The recommendations are proposed by means of analyzing through the established procedure, the specific components identified as critical. It must be taken into consideration that these recommendations are focused on the design phase, while the recommendations given in the previous chapter were defined from the recycler's point of view.

The conclusions of this chapter will serve as a base to define eco-design strategies of vehicles, which must go beyond "design for recycling" as it is understood now. Instead, the strategy should be oriented towards "design for functional recycling", with the aim that scarce and valuable metals do not become lost at the EoL and form part of the technosphere as much time as possible.

9.2. Procedure for the identification of critical vehicle components

The identification procedure of the most critical vehicle components is done by using two thermodynamic indicators: thermodynamic rarity [kJ] and Rarity intensity [kJ/g]. The first one has been previously explained in detail and the second one considers also the thermodynamic value with respect to the weight of the component. The second allows to identify those components that despite having little weight, have a high concentration of valuable metals with respect to their total weight.

To assess the thermodynamic rarity of each vehicle component it is necessary before to have the metal composition for each one. To do it, Table 20 was built in which the quantity of each studied metal for each vehicle component is represented.

Table 20: Example of table to make the thermodynamic assessment

	Metal 1	…..	Metal n
Component 1			
…..			
Component n			

Once this table is built, the thermodynamic rarity assessment is made by multiplying the weight of each metal by the thermodynamic rarity value of each metal. (Equation 14).

$$Rarity\ (A) = \sum_{i=1}^{n} m(i) \cdot Rarity\ (i) \tag{14}$$

Where A is a vehicle component, m is the mass in gr, Rarity is expressed in kJ/gr and i is the studied metal. In this case 46 metals were analyzed. The studied metals and their thermodynamic rarity values are included in **Paper V** as supplementary information. Note that the quantity of iron and aluminum contained in the vehicle were initially removed. This was done for two main reasons: (1) because current ELV recycling processes are already recovering these metals in shredding plants, so from a metal sustainability point of view these are not critical and (2) because the weight contribution of these metals are much larger than the rest. In the case study analyzed in this **paper V**, iron and aluminum contribute to 84.3 % and 8.1 % of the total metal weight, respectively. This significant mass contribution does not allow to see clearly the criticality of other used metals which weights are several orders of magnitude lower and that are not functionally recycled but downcycled with iron and aluminum (i.e. incorporated in minor quantities in the matrix of iron or aluminum blocks with no functional use).

After the thermodynamic assessment, all vehicle components are classified into 10 groups considering both indicators. The classification is the following: one category for those component whose rarity is higher than 1 GJ, and 9 additional categories (from A to I) according to thermodynamic rarity and rarity intensity values. The value ranges of each category (from A to I) is calculated by dividing the total range of rarity and rarity intensity into five equal parts.

The reason to make one category called rarity higher than 1 GJ and to exclude it from the rest of categories (from A to I) is because there are three vehicle components (the engine, gearbox and front axle) which are included without a disaggregation level in smallest components (i.e crankshaft, engine head, clutch, servo steering or fuel pump). As a result these parts have a very high rarity value compared to the rest, and must be studied individually to find recommendations. After this classification, we consider that eco-design measures should be focused on parts with thermodynamic rarity values higher than 1 GJ and those which belong to A - G groups.

9.3. Results

The vehicle used as a case study is a SEAT Leon III model, which belongs to the segment C and is a hatchback automobile. It is equipped with a 2.0 Diesel engine and manual gearbox. Its total weight is 1,270 kg and 780 kg if only its metal content is considered. This vehicle has 1,051 parts but only 794 include metals. This happens because there are a good number of components which are fully made using plastics, rubbers, glasses or textiles (excluded from this study).

9.3.1.Critical components identified

After the thermodynamic assessment from an initial list of 794 components, 31 were identified as critical. Table 21 summarizes the number of vehicle parts for each category of criticality.

Table 21: Number of vehicle parts, parts classification and selected critical components

Total components	794
Critical components	31
Components in category (>1GJ)	2
Components in category (A)	0
Components in category (B)	0
Components in category (C)	0
Components in category (D)	2
Components in category (E)	4
Components in category (F)	7
Components in category (G)	16
Components in category (H)	49
Components in category (I)	714

The classification procedure is shown in Figure 13, representing the value ranges for rarity and rarity intensity as well as the different classification groups (from A to I). It is highlighted that the largest number of parts have both small rarity and rarity intensity. Nevertheless there are others that have at least high values in one of the two indicators.

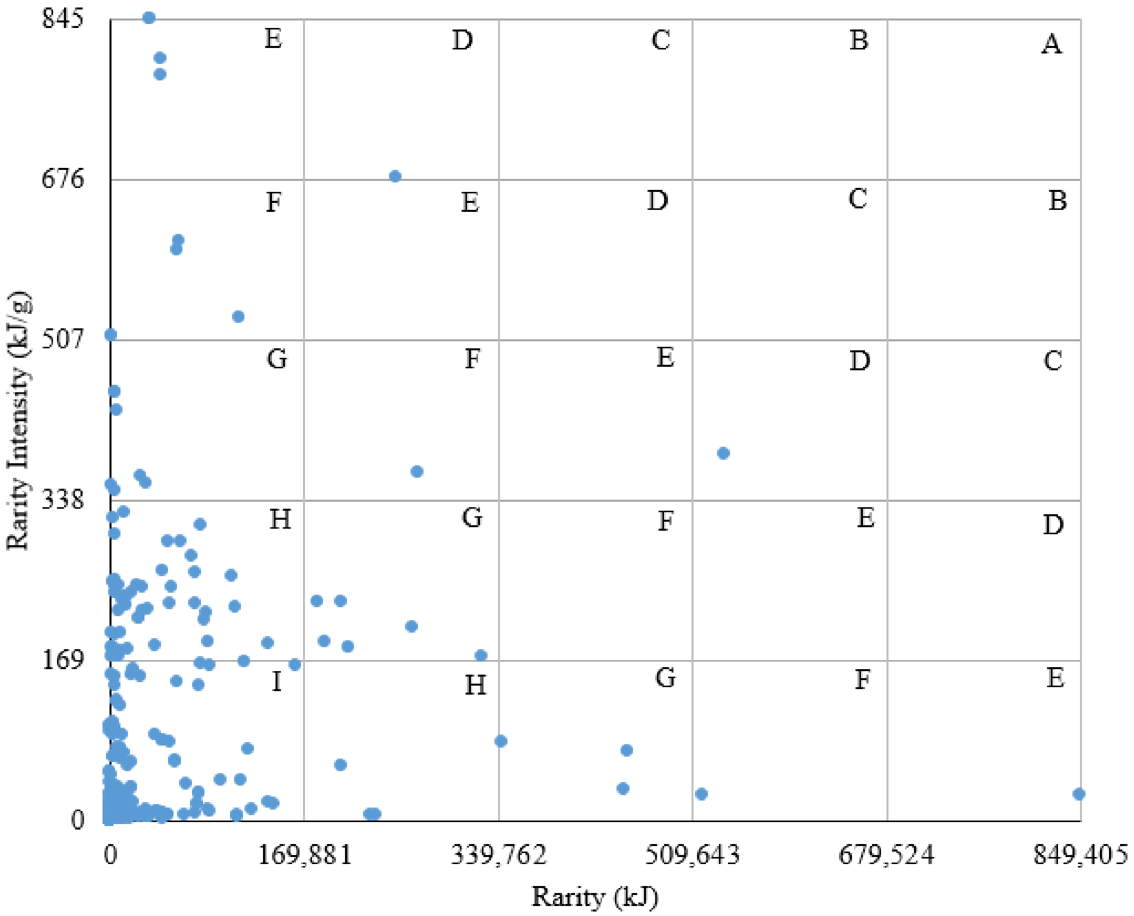


Figure 13: Components classification. On the left the categories zones and on the right the position for each of the 794 components assessed

These critical components have a total rarity of 39.6 GJ. This figure is 85 % above the total vehicle rarity (46.2 GJ). This classification procedure is in line with the Pareto rule, because less than 20 % of vehicle components (31 components over 794) have more than 80 % of the vehicle's rarity (39.6 GJ over 46.2 GJ). Table 22 shows the selected components.

Table 22: List of critical components identified

Description	Rarity (kJ)	Rarity Intensity (kJ/g)	Group
Engine	32,099,655.39	191.52	>1GJ
Gearbox	1,734,110.12	33.14	>1GJ
Infotainment unit	538,664.92	386.19	D
On board supply control unit	250,164.31	677.90	D
Front axle	849,407.35	26.81	E
Exhaust gases temperature sensor	44,318.77	785.39	E
Aerial amplifier (left side)	35,217.40	845.45	E
Aerial amplifier (right side)	35,217.40	845.45	E
Battery	518,856.02	25.19	F
Combi Instrument	269,509.99	367.46	F
Airbag control unit	113,556.86	529.44	F
Door control unit (driver)	60,603.42	610.61	F
Door control unit (passenger)	59,165.19	600.97	F
Lamp for ambience lighting (driver)	2,147.97	511.30	F
Lamp for ambience lighting (passenger)	2,147.97	511.30	F
Generator	453,144.52	71.54	G
Intermediate exhaust pipe with rear silencer	450,583.58	32.45	G
Starter	344,093.86	82.64	G
Wiring	326,124.54	172.64	G
Wiring for rear lighting	265,318.42	202.30	G
Exterior rear mirror (left side)	209,219.21	180.97	G
Exterior rear mirror (right side)	202,880.78	230.21	G
Wiring for front lighting motor	188,196.00	188.48	G
Rear screen cleaner motor	182,001.13	230.49	G
Additional brake light	31,345.25	354.58	G
Lighting switcher	26,870.75	362.84	G
Rain sensor	7,124.03	431.08	G
Air quality sensor	4,922.18	346.80	G
Speed sensor (left front tyre)	4,548.35	450.91	G
Speed sensor (right front tyre)	4,548.35	450.91	G
Cable shoe used for anti-twist device	1,726.88	352.43	G

From the previous list, the battery is excluded in the eco-design assessment. This is so because batteries are already disassembled from ELV in the authorized treatment centers to be subsequently sent to specific recycling plants according to the requirements of EU Directive 2006/66/EC [211].

Once critical components are identified, eco-design recommendations are proposed. In this process, each component is also compared with the same used in the previous vehicle version (SEAT Leon II model) to analyze the evolution of the raw material performance of that specific car part. The template used to state eco-design recommendations is included in **Paper V** as supporting information.

9.3.2.Eco-design proposals

The recommendations are classified into the following four categories: (Type 1) Facilitating disassembly; (Type 2) Critical metal substitutability; (Type 3) Retrofitting; (Type 4) New approaches. A deeper explanation about each category is described below.

(Type 1) Facilitating disassembly: The aim of this category is to define recommendations oriented to facilitating disassembly. In order to do that, we first need to know disassembly times of the identified parts. This information is retrieved from an internal SEAT IT system.

This measure is proposed because as it was published by Talens, Ardente and Mathieux [212] the difficulty of separating parts from products limits the development of circular economy strategies. Moreover their potential has been previously assessed by Santini et al. [213] and may reduce dismantling time to a third by simply innovating joining. From their point of view in the case of automobiles, pre-treatment based on dismantling can significantly reduce the amount of Automotive Shredder Residue (ASR) disposed in landfills. A clear example is the case of Ta. Tantalum is very difficult to recover through metallurgical processes unless the parts containing them are removed and processed separately from the others like Ballester, Schaik and Reuter [214]. These measures would allow that these parts could be easily disassembled in ELV authorized treatment centers. Subsequently, these components could be sent to two types of industries: (i) Specific recycling centers, where the most valuable metals are recovered applying mechanical and chemical processes. (ii) Retrofitting companies, where a component could be refurbished and updated for its eventual use in new or used vehicles.

(Type 2) Critical metal substitutability: As explained previously, vehicle parts are considered critical because they use valuable and scarce metals. One eco-design approach is to substitute those metals by less critical ones. Substitutability must be carefully analyzed, because substitution usually also affects the performance of the components, due to changes in some properties like density, electrical conductivity, thermal conductivity or dilatation coefficient. At this stage, substitutability recommendations are based on information included in USGS [215] reports.

(Type 3) Retrofitting: The fact that a vehicle arrives to its end of life does not necessary mean that all parts constituting the vehicle have lost their functionality. Indeed, the lifetime of many car components is greater than that of the vehicle as a whole. This is something very well known by ELV authorized centers whose main business is based on the selling of EoL car parts. Another option is retrofitting. If the lifetime of certain components is high enough, these could eventually be retrofitted and updated to be subsequently used in new or used vehicles. It is well known that retrofitting is an effective way to maintain products in a closed loop, reducing both environmental impacts and manufacturing costs, Pigosso et al. [216]. By means of this measure, it would be possible to reduce the demand of critical metals to manufacture new vehicles and to increase the time that a component stays in the technosphere. Note that retrofitting should be done with care, because this might be a barrier for potential vehicle buyers. Yet retrofitting can take place with long lasting parts that are not necessarily visible to the end user. This is in fact already being done in some industrial vehicles, which use retrofitted engines from previous used models as in the case of VOLVO [217].

(Type 4) New approaches: Sometimes a component can be improved by means of applying innovative measures that change the component approach or requirements. As an example, some years ago certain vehicles were equipped with phones, but nowadays it is commonly extended that radio devices allow the use of personal phones through Bluetooth technology. Another example is the substitution of the CD reader through USB bus readers.

The type of eco-design measures applied and the most valuable metals used for each component are summarized in **Paper V** as supporting information. From the initial list of 46 metals (excluding Fe and Al) there are only 23 metals, which are the most valuable ones among the critical components. From all eco-designed proposed measures (1-4), facilitating disassembly and critical metal substitutability have been proposed in all cases. Retrofitting and new approaches measures have been proposed in 16 components.

Information concerning metal content and eco-design assessment for each component are not published due to confidential issues. Below is a description of the most relevant results of the study.

Type 1 recommendations - Facilitating disassembly

The generator, which is currently placed at the bottom part of the engine, should be preferably placed in the upper part, as this would facilitate disassembly and the recovery of its valuable metals. The generator is moved by a multifunction belt, meaning that this measure could be easily implemented. The combi instrument could be also designed to be removed from the upper part of the dashboard. This would avoid the airbag and steering wheel to be previously removed (see Figure 14). As for the wires that connect the battery, they have a high thickness (and copper content) due to the maximum power demand required to move the starter. With a redesign they could be also disassembled when the batteries are removed in ELV authorized centers. Finally a common disassembling of engine, gearbox and front axle would allow that specific recycling processes are applied to recover valuable metals of specific components such as: suspension arms (Nb, Mo, V), turbo (Nb, Cr, W), exhaust pipe (Pd, Ni, Zr), exhaust temperature gases sensor (Pt, Ni, Cu) or servo-steering (Cu). This operation could be easily implemented because these components are designed to be quickly assembled in vehicle manufacturing factories.

Figure 14: Combi instrument location

Type 2 recommendations - Critical metal substitutability

Copper is the metal that appears most frequently in all selected components (30 times). Copper is followed by three metals with high rarity values such as gold, tantalum and palladium that appear 20, 19 and 17 times, respectively. This is why substitutability recommendations are mostly focused on such metals. Below we list some of the possible alternatives:

Aluminum instead of copper in certain wirings: as is well known, aluminum is an alternative to copper for wiring. It should be taken into account though that aluminum has 61 % of the copper conductivity but it has only 30 % of the weight. An aluminum cable with the same conductivity than copper will weight up to 50 % less but it will be also thicker. Moreover, the use of aluminum as a conductive material implies the addition of other elements such as Fe, Cu, Mg or Cr. On the other hand, the linear expansion coefficient is around 36 % higher than for copper, what might constitute a problem in several applications with high temperatures.

Silver plating instead of gold plating in electronic contacts: gold, as a native element, has very useful properties such as high conductivity, corrosion resistance, high melting point or reflectivity. These properties makes that the electronic sector has become the most important gold consumer. Nevertheless, electronic parts are rarely made entirely of gold because of the material´s cost. This is why manufacturers use electroplating to apply a thin layer of gold over the main material that comprises the component. As an alternative, silver plating can be also used. Silver has as main benefit its lower cost. Moreover it has other key properties such us the highest electrical and thermal conductivity of any metal. That said, according to Song et al. [218] its main weakness with respect to gold plating comes from its corrosion resistance. For a better corrosion resistance, a nickel undercoat with silver plating can be used. This alternative should be carefully analyzed mainly for those components responsible for safety systems.

Ceramic capacitors instead of tantalum capacitors: Ceramic capacitors have the highest market share but tantalum capacitors provide a feasible alternative if higher breakdown strengths are required. The reduced costs, smaller size (suitable for space-constrained electronic circuits), high-frequency characteristics, higher reliability, ripple control and longevity are driving the market to replace tantalum capacitors with ceramic capacitors wherever possible. Nevertheless, for Smith et al. [219] from an environmental point of view the highest electrical energy consumption during fabrication alongside the use of nickel paste are the major environmental hotspot for ceramic capacitors. So the environmental benefits associated to substitution must be carefully assessed.

At this point it must be also highlighted that the substitution of precious metals such as Pt or Au can have counterproductive effects because they play a key role in driving the economics of recycling, Reuter and Schaik [220]. Nevertheless, since they are not being recycled in vehicles, it will always be better if they are substituted by less critical materials.

Type 3 recommendations - Retrofitting

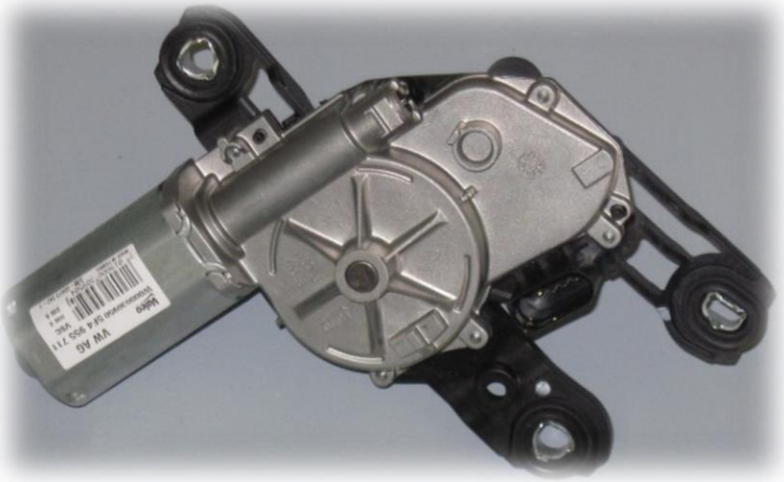
From a retrofitting point of view (eco-design measure 3), it is key the availability of reusable parts. Such parts can only come from models with high production values such as those in segment C. The destination of such parts would be in turn vehicles with smaller sales figures and where the focus is not placed on newest designs. This is why a clear destination of retrofitted parts would be in industrial vehicles. Particularly, retrofitting would be a plausible option for the combi instrument, lighting switcher, rain sensor, air quality sensor or exhausts gases temperature sensor (see Figure 15 with examples about different components that could be retrofitted).

Retrofitting of engine and gearbox parts could be also considered. Particularly for the engine, this could be done by using disassembled cylinder bores such as in some industrial engine cases. This measure would not hinder the engine for being updated to new performance requirements, because these changes mainly affect auxiliary systems like the head engine, the exhaust pipe or the fuel pump.

The gearbox is manufactured with some valuable metals like magnesium, nickel, chromium and molybdenum. In the studied vehicle, the gearbox contains 80 % of the total magnesium used by the vehicle. Moreover the gearbox is a very unfailing and robust component and is therefore a perfect candidate to be retrofitted. Manual gearbox design has not substantially changed throughout the years and this operation is a common technique applied in specialist gearbox repair garages.

15.a lighting switcher

15.b rain sensor



15.c rear screen cleaner motor

Figure 15: Different components that could be retrofitted

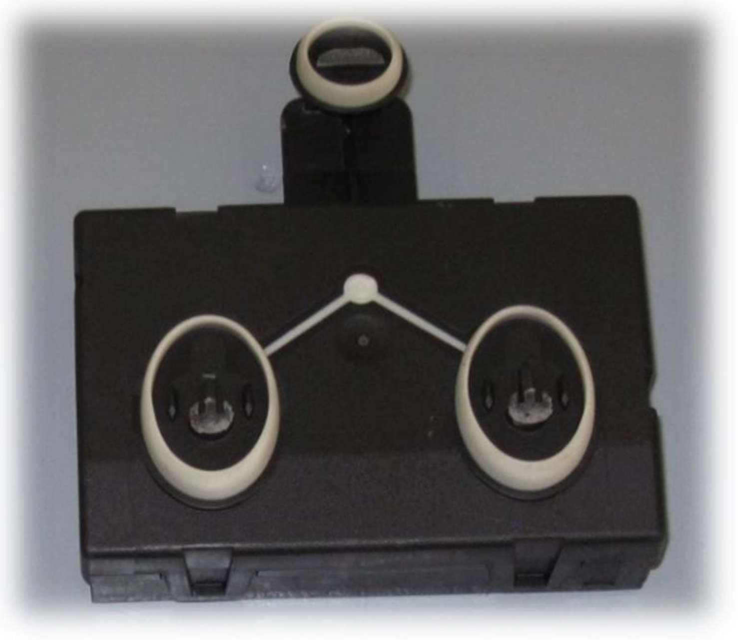
Type 4 recommendations - New approaches

In the field of new approaches (eco-design measure 4), it is recommended to assess the possibility to centralize all electric units (i.e. on board supply control unit, door unit, airbag unit, electronic control unit, combi instrument electronic or electronic from infotainment) in a common unit (see Figure 16 with different examples about electronic units that could be grouped). Through this way, this unit could be easily disassembled and sent from ELV authorized centers to specific recycling plants as it happens with batteries or tires. It is also recommended to assess the impact of changing the vehicle voltage from 12 V to 24 V or 48 V. This measure is being proposed to improve the engine efficiency and the performance of hybrid systems.

Note that this measure could also reduce the section of wiring. In this line, the use of Integrated Starter and Generator Technology as it is used by some manufacturers like VOLVO [221] may well reduce the demand of copper and permanent magnets containing rare earths. Finally, it is proposed to assess the impact that would have the inclusion of combi instrument information and switchers in the screen of infotainment unit. This measure would not only avoid the use of such devices but also the associated wiring.

16.a onboard supply control unit (located under the dashboard)

16.b airbag unit (located under the dashboard)



16.c door control unit (located in doors)

Figure 16: Different control units that could be grouped in a common one

9.3.3. Eco-design measures implementation

The impact of these measures goes beyond the studied vehicle because many models from VW group share the identified critical components. In fact, only those parts with an exterior design such as exterior mirrors, additional brake lights or combi instruments are included in just two models, the analyzed one and the SUV version based on the same platform. This fact also happens with tailor-made components such as wirings.

However a good number of components are shared by several models: door control unit (29 models); starter (30 models); generator (40 models); rain sensor (45 models) or speed sensor (88 models). So the impact of applying eco-design techniques goes usually beyond the specific model.

That being said, the application of the proposed eco-design measures needs a deeper feasibility analysis. As was shown in Chapter 8, it was quantified that around 175 € of valuable metals are lost per vehicle when current ELV processes are applied. Taking into consideration a vehicle model lifetime, the total loss would be as high as 183 M€ (Ortego et al. [201]). Knowing this figure, the next question is if this loss justifies an investment in new eco-design alternatives.

We see that the identified measures can be divided into two main groups according to the number of actors that take part. In the first group, only automobile manufacturers are involved. In the second, more stakeholders such as recyclers or dismantler centers are involved. For instance, one measure related to metals substitution affects in principle only to manufacturers.

However, a measure where components should be disassembled and subsequently sent to specific recycling or component retrofitting plants would involve several actors: dismantlers, recyclers and component manufacturers. In any case the economic benefits should be enough to generate a profit for each actor in the logistic chain.

For manufacturers, the economic feasibility could come from the savings achieved through the substitution of critical but also expensive metals by more common and less expensive ones. Measures related to facilitating disassembly of certain components could be initially and more easily done for vehicles that belong to manufacturers. It is a fact that more and more customers are acquiring services instead of products (renting or leasing instead of purchasing) and hence more vehicles will belong to manufacturers at the end of life. A potential new income source for manufacturers could thus come from the dismantling of valuable components from these ELV or from the application of simple pretreatment operations (i.e.: disassembly of capacitors or printed circuit boards from electronic units) which are subsequently sent to specific recycling plants.

In such cases where dismantling centers need to be involved for disassembly, the business model could be centered on the revenues obtained from those components sent to retrofitting companies or alternatively to recyclers. Recyclers in turn would receive components with high concentrations of valuable metals that would be separated by means of mechanical and metallurgical processes and sent again to car or other types of manufacturers.

9.4. Conclusions of Paper V

In the past, automobile manufacturers have been working on improving the environmental performance of their products mainly through fuel efficiency and low emission techniques. Particularly for Europe, efforts on ELV recyclability were focused on ensuring that an 85 % recycling quote (measured in mass terms) is achieved. However, vehicle manufacturers must take into consideration that meeting European ELV recycling policies does not guarantee a sustainable use of minor metals, which usually end downcycled in electric arc furnaces with steel and aluminum scrap or in the worst case in landfills. On the contrary, it incentivizes to focus on the bulky ones: steel and aluminum. Yet are these the most critical ones in terms of future supply risks for the car industry? A new environmental challenge which is resource efficiency especially for minor raw materials is coming up. These additional efforts must be aligned with the adoption of eco-design strategies to guarantee that resources are really used in a sustainable manner.

Valuable and scarce metals such as Au, Ta, Cu, Pd, Nb or Sn among others, are needed to manufacture certain components like: engines, gearboxes, starters, alternators, electronic control units, motors, LEDs, switchers or sensors. It is a fact that current vehicles are equipped with an increasing amount of electrical components that use such metals, for which no specific recycling processes exist. Moreover, since they are spread around the vehicle, disassembly is an extremely difficult task. For this reason, such components must be eco-designed to be easily disassembled, repaired, updated and retrofitted. They must be designed to be operational as much time as possible. Only when they cannot be used again, such components must be sent to specific recycling centers to obtain the valuable metals by means of using hybrid recycling approaches (physical and chemical) instead of being sent to common shredder plants where only bulk materials are recovered.

If catalytic converters, batteries or tires are sent to specific recycling centers once the vehicle ends in an ELV authorized treatment center, why not to use this same approach for more components such as screens, electronic units, switchers or sensors. Why are the screens used in the infotainment unit or in the combi instrument of a vehicle dashboard shredded? These components are equivalent to domestic tablets and contain the same scarce metals (Ag, In, Pd, Sn, Ta…). Yet contrary to tablets, such vehicle units are not considered as waste electrical and electronic equipment (WEEE) and do not enter the specific WEEE recycling center. If they were considered WEEEs, they would be probably redesigned to be easily and quickly disassembled.

As it has been shown in this chapter, the application of the Thermodynamic Rarity approach through a procedure defined in this chapter offers a new dimension to help in the identification of critical components in a car.

This new dimension is the consideration of the current and future scarcity of each commodity in the crust and the loss of mineral capital associated to mineral extraction. This loss is irreversible and must be taken into account to know the physical value associated to each raw material because it puts the focus on commodities with possible future shortages from a geological point of view. This method is presented as an easy tool to calculate the metal sustainability of components and to complement the traditional LCA assessment by means of a better understanding of the irreversibility associated to raw material extraction.

Through this method, we have shown that a common hatchback vehicle has more than 30 components considered critical from a raw material point of view. Hence, such parts are a priority to be eco-designed so as to increase the metal sustainability in the car. For such identified car parts, different eco-design measures have been proposed. It should be stated that this methodology does not assess the feasibility of implementing eco-design alternatives. It only prioritizes those components which are susceptible to be eco-designed.

Chapter 10. Conclusions / Conclusiones

10.1. General conclusions and reflections

The energy transition towards a low carbon economy is demanding cleaner technologies, which should be free of greenhouse gases and other direct polluting emissions. However, even if they will not operate with fossil fuels, they will demand scarce raw materials used for their manufacturing. As a consequence, resource dependency will probably evolve from fossil fuels to critical raw materials. As was demonstrated in this Thesis and considering forecasts in the increase in renewable technologies and electric vehicles to 2050, there might be some serious bottlenecks in the supply of certain raw materials. Particularly, the automobile manufacturing sector heavily depends on some strategic metals which supply until 2050 might be at medium risk (Mo, Nd, Ta) or at high risk (Ag, Co, Cr, Cu, Ga, In, Li, Mn, Ni).

So in the same way that we are certain about the limited nature of fossil fuels and that we should migrate towards an economy free of them, we cannot ignore the limits of available mineral resources. Note that, as opposed to fossil fuels, once used, minerals do not disappear but become dispersed if not appropriately managed. The result is that they ultimately become unavailable. However, the potential unavailability of mineral resources is a serious problem that is unfortunately ignored in current outlooks toward a low carbon economy.

The automobile manufacturing industry is one of the sectors where more advances to improve their sustainability are being made. That said, the main focus is placed on producing low or zero carbon emission vehicles. These advances are mainly directed to improve the vehicle's energy performance, to reduce their polluting emissions and to find alternative powertrains free of direct emissions. Nevertheless, these huge advances are also demanding more resources to manufacture them. Current vehicles require components that demand scarce metals such as: LEDs for lighting (Ga, Ge, Y); catalytic converters (Pt, Pd, Zr); electronic units (Au, Ag, Sn, Ta, Yb), sensors (Ce, Tb, Se, La), infotainment screes (In, Sn), high strength steel or aluminum alloys (Nb, Mo, Cr, Ti, V, Cs, W) or injectors (Tb). Besides, demand of these scarce metals will grow even more with the massive adoption of electric vehicles that will require large capacity batteries (Co, Ni, Mn, Li), permanent magnets in motors (Nd, Pr, Dy) and more electronic components. This does not mean that electric vehicles should not be promoted, yet a careful sustainability analysis regarding the raw materials needed for their development should be accomplished and measures to improve their resource efficiency need to be urgently adopted.

In line with this aim, current ELV legislation in Europe is promoting higher recycling targets. Although these targets are ambitious, they are failing in capturing functional recycling of minor but scarce metals. This is because the unit of measure for setting the targets is the kilogram. According to the current ELV Directive, 1 gr of cobalt is as valuable as 1 gr of aluminum and hence only bulk metals are effectively recycled. However, it is well known that the scarcity in the crust of Co and Al and their extraction and beneficiation costs are very different.

The adoption of policies based on physical parameters considering the quality of metals would avoid this problem. As it has been demonstrated, the Thermodynamic Rarity approach used throughout this Thesis, assigns an objective and universal value to each metal based on the relative scarcity of the element in the crust and the energy costs incurred in the mining and refining process. Scarce and difficult to extract metals are more critical than abundant ones from a thermodynamic rarity point of view. If the raw materials used in a car are rated through this approach, their components can be classified considering the physical quality of the metal contents. Moreover, the raw material sustainability of the car as a whole can be assessed.

With this approach, this Thesis has shown that the mineral value (measured in Rarity terms) of those metals demanded by a common electric vehicle is 2.2 times higher than in an equivalent combustion engine one. Considering this fact, it is at least questionable that the mass adoption of the electric vehicle in a business as usual scenario is the definite solution towards achieving sustainable development in mobility. In this respect, appropriate recycling processes should encompass the electrification of vehicles.

Yet after an examination of ELV recycling processes, several weaknesses have been identified. Current recycling operations are designed to manage large quantities of ELV of ferric and non-ferric scraps consuming relatively small amounts of energy to improve cost efficiency. However, they do not guarantee the functional recycling of all metals. ELV shredders are based on mixing processes which are highly entropic. In a conventional vehicle, different steel types are used, being some of them very valuable from the required alloying elements point of view (Cr, Mo, Nb, Ni, Ti or W). That said, the process output only entails one type of ferric scrap which is subsequently sent to a steel making furnace. As a consequence, these minor but scarce metals used as alloying elements become dispersed and lost forever.

Even worse is the case of other non-alloying metals included in, for instance, sensors, LEDs or electronic units. Are they recycled? The answer is straightforward: there are no specific processes designed to do so. Instead, they are shredded, mixed and they usually end in the slags of steel making processes and ultimately in landfills. Accordingly, even if in a vehicle any metal is considered fully recyclable, this Thesis has shown that from a thermodynamic point of view only 73 % of the metal content in a vehicle is functionally recycled. In other words, the mineral capital associated to one out of four vehicles that become recycled is practically lost. Therefore, it can be assumed that in a business as usual scenario the availability of scarce metals will soon be at risk because functional recycling rates are not evolving as fast as their demands.

Considering this situation, it becomes necessary that sustainable alternatives for guaranteeing the supply of scarce metals are urgently developed. As it has been shown for the Seat Leon case study, at least 31 components that are critical from their raw materials point of view have been identified: electronic units, motor, sensors, lighting, switchers, screen or infotainment units are among them. Moreover, it was highlighted that the majority of these components are common for any type of vehicle powertrain (whether electric, hybrid or combustion engines), meaning that global solutions can be adopted. Reduction and substitution of scarce metals is key, and in this respect, important research efforts should be invested.

Another solution is the development of specific recycling processes. These processes must be based on hybrid operations (mechanics-hydrometallurgical-pirometallurgical-biometallurgical) instead of only physical ones. It is impossible to separate through physical treatments that which has been mixed through chemistry. Nevertheless, to be cost effective, the application of these metallurgical operations requires a high concentration of those metals that want to be recovered. For this reason, it is key to select and disassemble such critical components from the rest of the vehicle so that they can be appropriately recycled.

On the other hand, recycling would considerably improve if vehicles were designed thinking in the EoL. In Thermodynamics, it is well known that separating requires far more efforts than mixing. Nevertheless, from an industrial point of view more resources and efforts are aimed at manufacturing complex components with a high metal mixology (and hence highly entropic) than to separate these metals in recycling processes. Indeed, a vehicle manufacturing plant uses complex and highly automated processes, just in time logistic operations, energy resources, human efforts and strict quality requirements to produce large volumes of vehicles. Yet their recycling is mainly based on simple, low cost processes.

For instance, if current tantalum capacitors recycling processes require the use of metallurgical operations, those components that use them (i.e. a steering electronic unit) should be designed to be easily disassembled. This approach would allow that such components are subsequently sent to a specific recycling center. Moreover, if no specific recovery processes are available for certain materials, their use should be avoided or limited. Something similar should happen with the use of REEs (Nd, Pr and Dy) in the motor, Ga, Ge, Y in LEDs, Ag, Au, Sn in electronics or In in screens. If domestic tablets or LED lamps are sent to a WEEE installation once the EoL is achieved, why is the EoL treatment procedure different with the navigator screen or the vehicle front lighting? Why are these vehicle components shredded? Are these metals different? It is evident that the ELV economic value is only marginal when compared with a new one. Yet its weight and raw material contents are the same as when it was new.

Moreover, and considering its raw materials primary availability at the end of the life, they might have become even scarcer than when the car was manufactured. On the other hand, what is the lifetime of a switcher, combi instrument or rain sensor? Certainly, many components of the car last much longer than the car itself. So, why are they shredded instead of reused in ELV?

In short, there are different solutions to guarantee sustainable use of raw materials in the vehicle manufacturing sector and a combination of all should take place: 1) avoidance, substitution or reduction of the use of scarce and difficult to recycle metals; 2) eco-design considering the EoL; 3) adoption of reverse logistic operations, what entails among others, automation of disassembly processes; 4) adoption of recycling operations, ensuring functional recycling. This will entail the application of specific metallurgical treatments; 5) reuse or retrofitting of long lasting components beyond the car's EoL.

At last but not least important is a reflection on the vehicle lifetime as a whole. Why does society consider that a conventional vehicle is old when it is about 10 years old? Why are manufacturers changing vehicle exterior designs every 5 years? The lack of regulations about vehicle durability and the fast evolution of vehicle designs incentivize the renovation of the fleet without considering the Earth's limits. This unlimited consumerism will be constrained sooner or later by the limitation of natural resources. At this moment, adaptation will be certainly more painful than if radical changes are applied now.

This Thesis has shown that current designing and recycling processes of vehicles are unsustainable from a raw materials point of view. This was demonstrated through the application of a thermodynamic approach which also helped in offering eco-design guidelines for improving the overall resource efficiency of a car. It is irresponsible of talking about clean and sustainable vehicles without considering the Earth's limits and the thermodynamic laws.

10.2. Contributions

The main contributions of the Thesis are listed below from **A** to **J** letter:

A) It has been demonstrated that in the energy transition resource dependency will evolve from fossil fuels to raw materials. The amount of new technologies that will lead this transition such as renewables or electric vehicles are highly dependent on scarce metals. Current reserves and recycling values of scarce metals are not enough to guarantee the future development of green technologies. If we trust in green technologies to achieve a low carbon economy, more efforts in dematerialization, substitution of critical minerals and recycling must be urgently done.

B) It has been assessed when possible raw material bottlenecks could put at risk the development of green technologies. This has been done by means of a method which is based on known reserves, available resources, capacity production, expected demand and recycling improvements. In the case of the automobile manufacturing sector, the following metals were identified in the medium risk category: Mo, Nd, Ta, whereas Ag, Co, Cr, Cu, Ga, In, Li, Mn, Ni would belong to the high risk one. Moreover, it has been estimated that demand could exceed the capacity of production for the following commodities: Ni (2027-2029); Co (2030-2050); Ag (2031-2042); Ta (2033-2050); Nd (2034-2041); Mo (2038-2042); Mn (2038-2050); In (2041); Li (2042-2045).

C) It has been calculated how recycling rates should evolve to avoid some of these bottlenecks. The annual growing of functional recycling rates must grow up until 2050 at least at the following annual growing rates: Ag (0.6 %); Cd (1.3 %); Co (1.8 %); Cr (2.5 %); Dy (0.9 %); In (0.5 %); Li (4.6 %); Mn (0.1 %); Mo (0.7 %); Nd (0.1 %); Ni (1 %); Se (2 %); Sn (0.1 %) and Ta (0.1 %).

D) An innovative method based on physical parameters has been applied to calculate the material criticality of different types of vehicles (ICEV, PHEV and BEV). This has been useful to demonstrate that the electric vehicle is not as sustainable as it seems from the raw materials point of view. The application of Thermodynamic Rarity indicator shows that the demand of scarce metals in BEV is significantly higher than that of ICEV (172 GJ vs 387 GJ). This increment is mainly due to the use of scarce metals necessary to manufacture batteries, motors and electronics.

E) This report has demonstrated the weakness of current ELV recycling policies which targets are based on weight. Such policies do not incentivize the recycling of minor but valuable metals like critical raw materials. An alternative approach based on the second law of Thermodynamics using an indicator called Thermodynamic rarity as the unit of measure has been proposed. Current ELV policy encourages the recycling of major metals, mainly Fe, Al and Cu because they account for more than 95 wt% of a vehicle's metal content. Considering their physical quality (through rarity indicator), their relative thermodynamic contribution drops to less than 70 rt%. Around 30 % of the thermodynamic rarity value of the car is included in less than 5 % of the overall mass which is not recycled. This simple statement could encourage that recycling policies change the method to guarantee a more sustainable use of scarce metals.

F) To the author's knowledge, a comprehensive set of data with the metal composition of different types of vehicles equipped with different powertrains (ICEV – petrol and diesel, PHEV and BEV) has been published for the first time. In total 52 metals where evaluated. The set of data published in Chapter 4, is in itself a very valuable input information for future research.

G) An index to classify the most strategic metals for the automobile manufacturers has been developed. The method has a holistic vision and combines physical parameters such as available reserves, known resources or metal production capacity and non-physical parameters like automobile sector demand with respect to world production; economic importance and supply risk. This method has served to identify as top ten strategic metals for automobile manufacturing sector: Ni, Li, Tb, Co, Dy, Sb, Nd, Pt, Au, Ag, Te, Mn, Ta, and Se. Although this method considers non-physical aspects, it identifies the same critical vehicle components as those identified by the thermodynamic approach (batteries, electronics, permanent magnets, catalytic converters, injectors) so it ensures that the thermodynamic method can be considered at least in the automobile case as self-sufficient.

H) The lack of effectivity of current ELV recycling processes to recover minor metals has been demonstrated and quantified. Even if from tonnage point of view a high portion of the vehicle is recycled, the application of the method has demonstrated that 27 % of the metals measured in rarity terms are not functionally recycled. This means that the mineral capital associated to one out of four vehicles that become recycled is practically lost. Moreover, this figure does not considered other vehicle components like tires or glazing, which also demand scarce metals. Hence, the final figure is even higher.

I) A set of recommendations have been proposed to reduce the problem of downcycling in ELV recycling processes. The recommendations were explained in Chapter 8 (**Paper IV),** nevertheless the most important ones are described again below since they are part of the main Thesis contributions:

  I.1. To disassembly those components with valuable metals such as Au, Ag, REEs, platinum group metals (PGMs), Sn, Ta, or Te before shredding. Some of the most identified critical parts are: panel instrument, lighting switchers, LED lamps, power window motors, windscreen cleaner motors, electronic control units, rain sensors, electric mirrors, aerial amplifiers, and infotainment devices. This operation should be done even using automation by means of robots and would allow that specific recycling processes are implemented at a later stage.

  I.2. To apply hybrid recycling processes for the aforementioned parts. These recycling processes should be mechanical-pirometallurgical-hydrometallurgical-biometallurgical. This is because the sole application of mechanical techniques is not compatible with the recycling of other materials such as indium in the displays or REEs in LEDs. Using this approach, valuable metals such as Au, Ag, Cr, Cu, Ga, In, Mg, Mo, Nb, Ni, Pd, Pt, Sn, Ta, V, or W would be recycled. This operation could be even developed in WEEE recycling plants as some of them are already implementing these processes.

  I.3. To disassembly those components made with special steel alloys (high content of Cr, Mo, Nb, Ni, Ti, or W). Some of these components include the exhaust pipe, o-rings, turbos, pinions, and gear shafts. Owing to the excessive time required for removing some of these parts (i.e., removing o-ring from an engine requires the cylinder head cap, cylinder head, connecting rods, and pistons to be disassembled before and this operation requires at least 1 h), an intermediate situation could be implemented. This situation could be that engines and gearbox were disassembled from the rest of the vehicle before shredding. Notably, in a vehicle manufacturing plant, the entire powertrain (including front axle, gearbox, engine, and rear axle) is joined to the body in less than 30 second and hence, this operation could also be implemented via a reverse approach

I.4. To apply shredding processes for different vehicle parts made from different qualities of steel and aluminum alloys (i.e., engines, gearboxes, and bodies). This would produce different scrap qualities which in turn would be the source of new alloys. In turn, this would avoid the contamination of steel alloys with high levels of some metals. This problem mainly happens with elements that have lower oxygen affinity than iron, such as Cu, Sn, Co and Ni which remain in the final alloy and contaminate it.

J) From the eco-design point of view several recommendations to improve the resource efficiency in vehicles have been stated. These recommendations were published in Chapter 9 (**Paper V),** however they are described again below since they are part of the main Thesis contributions:

J.1. *Facilitating disassembly*: The generator, which is currently placed at the bottom part of the engine, should be better placed in the upper part, as this would facilitate disassembly and the recovery of its valuable metals. The generator is moved by a multifunction belt, meaning that this measure could be easily implemented. The combi instrument could be also designed to be removed from the upper part of the dashboard. This would avoid that the airbag and steering wheel are previously removed. As for the wires that connect the battery, they have a high thickness (and copper content) due to the maximum power demand required to move the starter. With a redesign they could be also disassembled when the batteries are removed in ELV authorized centers. Finally, a common disassembling of engine, gearbox and front axle would allow that specific recycling processes are applied to recover valuable metals of specific components such as: suspension arms (Nb, Mo, V), turbo (Nb, Cr, W), exhaust pipe (Pd, Ni, Zr), exhaust temperature gases sensor (Pt, Ni, Cu) or servo-steering (Cu). This operation could be easily implemented because these components are designed to be quickly assembled in vehicle manufacturing factories.

J.2. *Critical metal substitutability:* Aluminum could be used instead of copper in certain wirings: as is well known, aluminum is an alternative to copper for wiring. It should be taken into account though that aluminum has 61 % of the copper conductivity but it has only 30 % of the weight. An aluminum cable with the same conductivity than copper will weight up to 50 % less but it will be also thicker. Moreover, the use of aluminum as a conductive material implies the addition of other elements such as Fe, Cu, Mg or Cr. On the other hand, the linear expansion coefficient is around 36 % higher than for copper, what might constitute a problem in several applications with high temperatures. Silver plating instead of gold plating in electronic contacts: gold, as a native element, has very useful properties such as high conductivity, corrosion resistance, high melting point or reflectivity. These properties make that the electronic sector has become the most important gold consumer. Nevertheless, electronic parts are rarely made entirely of gold because of the material´s cost. This is why manufacturers use electroplating to apply a thin layer of gold over the main material that comprises the component. As an alternative, silver plating can be also used. Silver has as main benefit its lower cost. Moreover, it has other key properties such us the highest electrical and thermal conductivity of any metal. Its main weakness with respect to gold plating comes from its corrosion resistance. For a better corrosion resistance, a nickel undercoat with silver plating can be used. This alternative should be carefully analyzed mainly for those components responsible for safety systems. Ceramic capacitors instead of tantalum capacitors: Ceramic capacitors have the highest market share but tantalum capacitors provide a feasible alternative if higher breakdown strengths are required. The reduced costs, smaller size (suitable for space-constrained electronic circuits), high-frequency characteristics, higher reliability, ripple control and longevity are driving the market to replace tantalum capacitors with ceramic capacitors wherever possible.

J.3. *Retrofitting:* From a retrofitting point of view, it is key the availability of reusable parts. Such parts can only come from models with high production values such as those in segment C. The destination of such parts would be in turn vehicles with smaller sales figures and where the focus is not placed on newest designs. This is why a clear destination of retrofitted parts would be in industrial vehicles. Particularly, retrofitting would be a plausible option for the combi instrument, lighting switcher, rain sensor, air quality sensor or exhausts gases temperature sensor. Retrofitting of engine and gearbox parts could be also considered. Particularly for the engine, this could be done by using disassembled cylinder bores such as in some industrial engine cases. This measure would not hinder the engine for being updated to new performance requirements, because these changes mainly affect auxiliary systems like the head engine, the exhaust pipe or the fuel pump. The gearbox is manufactured with some valuable metals like magnesium, nickel, chromium and molybdenum. In the studied vehicle, the gearbox contains 80 % of the total magnesium used by the vehicle. Moreover, the gearbox is a very unfailing and robust component and is therefore a perfect candidate to be retrofitted. Manual gearbox design has not substantially changed throughout the years and this operation is a common technique applied in specialist gearbox repair garages.

J.4. *New approaches:* In the field of new approaches, it is recommended to assess the possibility to centralize all electric units (i.e. on board supply control unit, door unit, airbag unit, electronic control unit, combi instrument electronic or electronic from infotainment) in a common unit. Through this way, this unit could be easily disassembled and sent from ELV authorized centers to specific recycling plants as it happens with batteries or tires. It is also recommended to assess the impact of changing the vehicle voltage from 12 V to 24 V or 48 V. This measure is being proposed to improve the engine efficiency and the performance of hybrid systems. Note that this measure could also reduce the section of wiring. In this line, the use of Integrated Starter and Generator Technology may well reduce the demand of copper and permanent magnets containing rare earths. Finally, it is proposed to assess the impact that would have the inclusion of combi instrument information and switchers in the screen of infotainment unit. This measure would not only avoid the use of such devices but also the associated wiring.

10.3. Perspectives

Several aspects that have remained outside the scope of this Thesis and that could complement the work are presented below.

- In the first place, the possibility of analyzing more data about different types of vehicles. In the case of the electric and hybrid vehicles, the data used came from a literature review. This is a first assessment with uncertainties related to the real metal demand by each type of vehicle. In this respect, shortly a comparison between two models with different powertrains (combustion and electric) will be performed within the research group where I belong. Moreover, the methodology used in this Thesis could be applied to different equipment levels to identify resource efficiency aspects related to optional equipment.

- This thesis has been focused on metals. However, in a vehicle there are other materials such as rubbers, plastics, glasses, tires or foams. Currently these materials end usually in landfills and in some cases they even contain scarce metals (glasses, body tires or metal plating used in plastics) so it is urgent to give also solutions for these materials with the aim to close the cycles.

- An important follow up of this Thesis is to analyze the ways and options for recovering metals from critical components. This Thesis has identified them, but now the processes required to recycle them must be defined. This task will be done through metallurgical approaches using simulation tools. The intention is to cooperate with Helmholtz Zentrum Dresden Rossendorf (Freiberg headquarter) using HSC Chemistry software to build a virtual plant to recycle scarce metals from vehicle critical components.

- Once the different metallurgical processes for the recovering of valuable metals from ELV are defined, the impact of these processes needs to be assessed from an environmental and economic point of view. Several questions need to be addressed: How much waste will be generated? What will be the impact of this waste? How many metals can be recycled? What is the economic feasibility of recovering these metals?

- The application of conventional shredding process has encouraged that huge quantities of scarce metals contained in ASR are disposed of in landfills. The potential to convert current landfills in urban mines to recycle scarce metals is a very interesting new research line.

10.4. Principales conclusiones y reflexiones

La transición energética hacia una economía baja en carbono necesita de tecnologías libres de emisiones directas de contaminantes y gases precursores del efecto invernadero. Sin embargo esas tecnologías a pesar de no ser dependientes de los combustibles fósiles para su funcionamiento seguirán siendo dependientes de los materiales que se requieran para su fabricación, por tanto la dependencia de los recursos probablemente migrara desde los combustibles fósiles hasta las materias primas. Como se ha demostrado en esta Tesis, considerando las proyecciones de desarrollo previstas para las energías renovables y los vehículos eléctricos hasta 2050, podría no haber suficientes materiales para su desarrollo. En concreto en el sector de la fabricación de vehículos existe una gran dependencia de algunos metales cuyo suministro hasta 2050 se puede considerar en riesgo medio (Mo, Nd, Ta) o alto (Ag, Co, Cr, Cu, Ga, Li, Mn, Ni).

De igual forma que sabemos que los combustibles fósiles no son infinitos y que debemos de migrar hacia una economía que no dependa de ellos, no se puede ignorar los límites de los recursos minerales. Aunque al contrario que en el caso de los combustibles fósiles, los recursos minerales no desaparecen tras su uso, sino que se dispersan si no se emplean adecuadamente. Como consecuencia de esta dispersión se vuelven inservibles. Sin embargo y al contrario que en el caso de los combustibles fósiles, el problema de la suficiencia de recursos minerales para conseguir una economía baja en carbono no se está abordando con la importancia que requiere.

El sector del automóvil es uno de los sectores que está haciendo más avances para mejorar su sostenibilidad. Estos avances se han centrado principalmente en la mejora del rendimiento de los motores de combustión, la reducción de sus emisiones contaminantes y la búsqueda de nuevas fuentes de energía que permitan un uso exento de emisiones directas. Sin embargo estos avances también están suponiendo una gran demanda de recursos para su fabricación. Estos recursos son de gran valor y escasez y son necesarios para fabricar algunos de los siguientes componentes: LEDs para iluminación (Ga, Ge, Y); convertidores catalíticos (Pt, Pd, Zr); unidades electrónicas (Au, Ag, Sn, Ta, Yb), diferentes tipos de sensores (Ce, Tb, Se, La), pantallas de infoentretenimiento (In); aleaciones de acero o aluminio de altas prestaciones (Nb, Mo, Cr, Ti, V, Sc, W) o inyectores (Tb). Por otro lado esta demanda de metales de gran escasez aumentará más con la penetración masiva en el mercado de los vehículos eléctricos. Estos automóviles necesitaran de grandes baterías (Co, Ni, Mn o Li), imanes permanentes para motores (Nd, Dy, Pr) y de más componentes electrónicos. Esta afirmación no implica que no se deba de apoyar su desarrollo, pero se debe de investigar mucho más para que los coches eléctricos sean más sostenibles desde el punto de vista de sus materias primas.

Como solución para usar los metales de forma más sostenible se están impulsando leyes que incrementan las cuotas de reciclaje de los vehículos. Aunque estas leyes son ambiciosas están lejos de garantizar el reciclaje funcional. Para la actual legislación de reciclaje 1 gramo de cobalto tiene la misma importancia que 1 gramo de aluminio, cuando es bien sabido que su escasez, dificultad de extracción y por tanto capital mineral es totalmente diferente.

Una política de reciclaje que asignara a cada metal un valor objetivo en base a parámetros físico evitaría ese problema. Tal y como se ha demostrado el uso de la Rareza Termodinámica asigna ese valor en función de su abundancia en la corteza terrestre y los costes energéticos necesarios para extraerlos, procesarlos y ponerlos a disposición de las industrias. Desde el punto de vista termodinámico los metales más escasos y difíciles de extraer son más críticos que los más abundantes. Por tanto, si todos los metales empleados por un vehículo fueran evaluados mediante este enfoque, sus componentes se podrían clasificar de forma objetiva considerando el valor físico de sus metales. Además el vehículo en su conjunto se podría evaluar desde una perspectiva de eficiencia en el uso de los recursos.

Mediante este método esta Tesis ha demostrado que el valor mineral de los metales que demanda un vehículo eléctrico es 2.2 superior al de un vehículo de combustión equivalente en tamaño. Teniendo en consideración este resultado se puede afirmar que el actual vehículo eléctrico no es la solución para conseguir un desarrollo sostenible. Por tanto, una mejora de los procesos de reciclaje se debe de desarrollar en paralelo a la electrificación de los vehículos.

Tras un análisis detallado de los procesos de reciclaje de vehículos se han identificado varias debilidades. Son eficaces para gestionar grandes cantidades de chatarras férricas y no férricas pero son ineficaces para reciclar funcionalmente los metales escasos. Los procesos de mezcla que tienen lugar en las actuales operaciones de fragmentación son altamente entrópicos. Un vehículo tiene diferentes tipos de aceros, siendo algunos de gran valor por contener aleaciones con grandes propiedades mecánicas (alto contenido de Cr, Mo, Nb, Ni, Ti o W), sin embargo a la salida del proceso de reciclaje hay una única fracción de chatarra férrica que es llevada a una fundición provocando la dispersión y posterior pérdida de metales aleantes de gran valor.

Pero el mayor de los problemas no sucede con las aleaciones de acero, las cuales al fin y al cabo tienen un proceso que aunque no las recicla funcionalmente al menos si las recicla en parte. ¿Qué sucede con los sensores, los LEDs o las unidades electrónicas? Todos ellos no tienen entre sus composiciones principales aleaciones de hierro y aluminio. ¿Entonces que se recupera de ellos? La respuesta es sencilla, no se recupera nada, pues sus metales se fragmentan, mezclan y diluyen en las operaciones de reciclaje, de tal manera que acaban formando escorias en los procesos de fundición de aluminio y acero o en un vertedero.

Como consecuencia en la actualidad a pesar de que en los cálculos de la reciclabilidad de un vehículo se considera que todo metal contenido por un vehículo es reciclado al 100 %, en realidad y de forma funcional se ha demostrado que se recicla solamente el 73 % del valor total de los metales que se emplean. En otras palabras cada cuatro vehículos que se reciclan, se pierde el valor mineral de uno de ellos. En este momento se puede afirmar que si continuamos con la actual tendencia no habrá suficientes materias primas y aunque confiemos en la evolución del reciclaje, las cuotas de reciclaje no están creciendo tan rápido como la demanda de recursos primarios.

Ante esta situación hay que comenzar a desarrollar alternativas sostenibles al uso de metales escasos. Como se ha demostrado un vehículo convencional tiene 31 componentes que se pueden considerar críticos por los metales que emplean. Entre estos componentes están unidades electrónicas, motores eléctricos, sensores, sistemas de iluminación LED, interruptores, pantallas o cuadros de instrumentación. Además es destacable que la mayoría de esos componentes son comunes a cualquier tipo de vehículo, sea de combustión, híbrido o eléctrico. Para estos componentes es preciso desarrollar alternativas sostenibles desde el punto de vista de sus materias primas. La reducción y la sustitución de metales escasos son fundamentales y en este respecto se deben de hacer importantes mejoras.

Otra solución es el desarrollo de procesos específicos de reciclaje. Estos procesos no pueden estar basados solamente en operaciones físicas sino también en metalurgia. No se puede separar mediante la física aquello que ha sido fabricado a través de la química. Sin embargo para que estos procesos sean viables, se necesita partir de componentes con altas concentraciones en los metales a recuperar y para ello hay que desensamblar esos componentes del resto del vehículo.

El concepto debe de cambiar, hay que diseñar los vehículos en base a criterios de sostenibilidad en el uso de los metales, pensando tanto en su disponibilidad como en su reciclabilidad. Desde la perspectiva termodinámica es bien sabido que separar requiere de un mayor esfuerzo que mezclar. Sin embargo desde una perspectiva industrial se destinan muchos más esfuerzos para fabricar complejos productos con una alta mixología de metales que para reciclarlos. Un fabricante de automóviles emplea procesos sofisticados de fabricación que implican complejas operaciones de producción en cadena, con una automatización muy avanzada, logística *"just in time"* y estrictos requerimientos de control de tiempos, costes y calidad… sin embargo el reciclaje de vehículos se basa en fragmentar vehículos.

A modo de ejemplo, si el actual estado del arte del reciclaje del tántalo de los condensadores implica usar metalurgia, aquellos componentes electrónicos que emplean condensadores de tántalo (por ejemplo la unidad electrónica de una dirección asistida) deben de ser diseñados para que se puedan quitar fácilmente los condensadores y ser llevados a un centro específico de reciclaje. De forma alternativa y en caso de que no se puedan llevar a cabo dichas operaciones se tendrán que emplear condensadores que no empleen tántalo. De igual forma sucede con las tierras raras (Nd, Pr y Dy principalmente) que se emplean en la fabricación de motores eléctricos, con los metales que se emplean en los LEDs (Ga, Ge, Y), en las conexiones eléctricas (Ag, Au, Sn) o en las pantallas (In). Si cuando llevamos una tablet o una luminaria LED que tenemos en nuestro hogar a un punto de recogida de productos fin de vida, son llevados a centros de tratamiento de WEEEs. ¿Por qué la pantalla del navegador de un coche es fragmentada? ¿Acaso los metales que emplean son diferentes?

Está claro que los procesos de reciclaje tienen que ser los más económicos posibles. De igual modo se sabe que el valor económico de un vehículo al llegar a su fin de vida es marginal en comparación con su precio original. Sin embargo el contenido de sus metales es el mismo que cuando era nuevo y seguramente su disponibilidad a nivel de recurso primario, hará que sean más escasos que cuando se fabricó el vehículo. Por otro lado y considerando la vida útil ¿Cuál es la vida útil de un interruptor, un panel de instrumentos, un sensor de lluvia o un motor de un limpia cristales? ¿Por qué se fragmentan componentes que podrían ser remanufacturados para nuevos modelos?

En resumen, hay diferentes soluciones para garantizar un uso más sostenible de los materiales en la fabricación de los vehículos y una combinación de todas ellas se debe de llevar a cabo, a continuación se describen dichas soluciones: 1) Evitar, sustituir o reducir el uso de metales escasos en la naturaleza y difíciles de obtener; 2) Eco-diseñar los vehículos considerando el fin de vida de los mismos y su reciclabilidad; 3) Adoptar operaciones de logística inversa, que impliquen automatizar el desensamblaje; 4) Aplicar operaciones de reciclaje para conseguir el reciclaje funcional de los metales; 5) Reusar o remanufacturar todos los componentes que se pueda, más allá de la vida del vehículo que inicialmente los usó.

Finalmente y no por ello menos importante es el problema de la vida útil. ¿Por qué consideramos viejo un vehículo con poco más de 10 años? ¿Por qué se cambian los diseños exteriores y por tanto los modelos de vehículos cada 5 años aproximadamente? Esta falta intencionada de durabilidad y la rápida evolución de los diseños incentiva una renovación de la flota exacerbada que no tiene en cuenta los límites de los recursos naturales. No podemos consentir que un producto tan demandante de recursos como un vehículo tenga una vida útil tan corta. Este consumismo ilimitado acabara tarde o temprano sucumbiendo ante los límites de la Tierra y para entonces las consecuencias y la adaptación no será nada sencilla. En esta tesis se ha demostrado que los actuales procesos de diseño y reciclaje de vehículos son insostenibles. Las soluciones aquí planteadas se basan en el uso de enfoques objetivos para la medición de la eficiencia en el uso de los recursos y la definición de medidas de ecodiseño. No podemos hablar de vehículos limpios y de desarrollo sostenible, de espaldas a los límites de la Tierra y las leyes de la termodinámica.

10.5. Contribuciones

Las principales contribuciones de la Tesis son descritas a continuación, siendo listadas de la letra A a la J:

A) Se ha demostrado que en la transición energética la dependencia de los recursos evolucionará desde los combustibles fósiles hacia los materiales. Las nuevas tecnologías que lideraran la transición energética, como las energías renovables o los vehículos eléctricos son altamente dependientes de recursos escasos. Si confiamos en las tecnologías verdes para conseguir una economía baja en carbono, se quieren más esfuerzos en sustituir y reciclar los metales escasos que emplean.

B) Se ha evaluado cuando podría haber posibles restricciones de suministro de metales necesarios para el desarrollo de tecnologías limpias. El método desarrollado está basado en las reservas, recursos, capacidad de producción, futura demanda y evolución de las cuotas de reciclaje. En la fabricación de vehículos se identificaron con riesgo medio los siguientes metales (Mo, Nd, Ta) y con riesgo alto (Ag, Co, Cr, Cu, Ga, In, Li, Mn, Ni). Se calcularon además como posibles periodos en los cuales podrían surgir algunas de las restricciones los siguientes: Ni (2027-2029); Co (2030-2050); Ag (2031-2042); Ta (2033-2050); Nd (2034-2041); Mo (2038-2042); Mn (2038-2050); In (2041); Li (2042-2045).

C) Se ha comunicado como deberían evolucionar los ratios de reciclaje para evitar alguna de esas restricciones. El ratio anual de reciclaje debería de crecer hasta 2050 a los siguientes ritmos: Ag (0.6 %); Cd (1.3 %); Co (1.8 %); Cr (2.5 %); Dy (0.9 %); In (0.5 %); Li (4.6 %); Mn (0.1 %); Mo (0.7 %); Nd (0.1 %); Ni (1 %); Se (2 %); Sn (0.1 %) and Ta (0.1 %).

D) Se ha aplicado por primera vez en el sector del automóvil un método innovador basado en parámetros físicos para calcular la criticidad de diferentes tipos de vehículos desde la perspectiva de los materiales que emplean. El método se ha aplicado a tres tipos de vehículos (ICEV, PHEV and BEV) y demuestra que el indicador Rareza Termodinámica en los vehículos eléctricos es mayor que en los de combustión (172 GJ frente a 387 GJ). Este incremento es principalmente causado por el incremente de la demanda de metales necesarios para fabricar baterías y componentes eléctricos y electrónicos.

E) Se ha demostrado que las políticas actuales de reciclaje basadas en masa no promueven el reciclaje de metales escasos. Como alternativa se ha propuesto un método basado en la rareza termodinámica como una de medida. Las actuales políticas de reciclaje propician que se recicle el acero, aluminio y cobre porque entre ellos contabilizan el 95 % de la masa de los metales de un vehículo. Sin embargo su contribución a la rareza termodinámica del coche es inferior a un 70 %. En la actualidad hay un 30 % del valor termodinámico de los materiales de los vehículos en menos de un 5 % de su masa y las actuales policitas no propician la recuperación de esos metales.

F) Se ha publicado un análisis en profundidad sobre las cantidades de metales demandadas por diferentes tipos de vehículos. En total se han evaluado 52 metales para 4 tipos de vehículos (diésel, gasolina, hibrido y eléctrico). Este conjunto de datos constituyen en sí mismo un gran avance para futuras investigaciones.

G) Se ha definido un ranking estratégico de metales para clasificar aquellos metales demandados para fabricar vehículos. Este método combina parámetros físicos como las reservas disponibles o la capacidad de producción, con parámetros no físicos como la demanda del sector del automóvil con respecto a la demanda total; la importancia para la economía o el riesgo de suministro. Este método identifica como los principales metales estratégicos los siguientes: Ni, Li, Tb, Co, Dy, Sb, Nd, Pt, Au, Ag, Te, Mn, Ta y Se. Aunque este método considera aspectos no físicos, sus resultados ofrecen pocas desviaciones respecto a los ofrecidos por el análisis termodinámico, de tal forma que sirve para demostrar que el caso del automóvil el enfoque termodinámico es suficiente para evaluar la criticidad.

H) Se ha demostrado numéricamente la falta de efectividad de las políticas de reciclaje para la recuperación de metales escasos. Basados en el caso de estudio realizado, las pérdidas calculadas a través de la Rareza Termodinámica son un 27 % sobre el total del valor del vehículo. Esto significa que el valor mineral de uno de cuatro vehículos se destruye en los actuales procesos de reciclaje. A esto habría que sumar la situación de otros componentes que no son analizados como los cristales, plásticos y espumas.

I) Se han propuesto una serie de recomendaciones para reducir el subciclaje en los procesos de reciclaje de vehículos. Las recomendaciones fueron explicadas en el Capítulo 8 (**Paper IV)**. Sin embargo las principales se describen a continuación dado que constituyen una de las principales contribuciones de la Tesis.

I.1. Desensamblar aquellos componentes fabricados con metales valiosos como Au, Ag, REE, PGMs, Sn, Ta o Te antes de ser fragmentados. Algunos de estos metales se encuentran en los siguientes componentes: panel de instrumentos, interruptores de luces, lámparas LED, motores de ventanillas, motores de limpiaparabrisas, unidades de control, sensores de lluvia, espejos eléctricos, amplificadores de antena o dispositivos de infroentretenimiento. Esta medida se podría realizar a través de estaciones automatizadas que permitirán un posterior reciclaje de las piezas desmontadas.

I.2. Aplicar procesos híbridos de reciclaje para las citadas piezas. Esos procesos deberían de ser mecánicos-pirometalúrgicos-hidrometalúrgicos-biometalurgicos ya que la adopción de técnicas mecánicas no es compatible con la recuperación de materiales como el indio de las pantallas o las tierras raras de los LEDs. De esta forma algunos metales valiosos como el Au, Ag, Cr, Cu, Ga, In, Mg, Mo, Nb, Ni, Pd, Sn, Ta, V o W podrían ser reciclados. Además la implementación de esta medida se podría llevar a cabo en centros específicos de reciclaje de RAEEs.

I.3. Desensamblar aquellos componentes hechos con aleaciones de acero de alta calidad (alto contenido en Cr, Mo, Nb, Ni, Ti o W). Algunos de estos componentes son los siguientes: tubo de escape, segmentos, piñones, turbo y ejes de cajas de cambio. Dado que algunas de esas piezas requieren mucho tiempo para su desmontaje (p.e: segmentos, bielas, pistones o culata) se podría hacer una situación intermedia en la cual todo el motor y la caja de cambio se desensamblara del resto del vehículo antes de la fragmentación para su posterior reciclaje de forma específica. Hay que tener en consideración que su montaje se hace de forma conjunta en menos de 30 segundos, por tanto su desmontaje podría hacerse de forma inversa.

I.4. Aplicar procesos de fragmentación específicos para diferentes componentes del coche hechos con diferentes calidades de acero o aluminio (p.e motores, cajas de cambio o carrocerías) para producir diferentes calidades de chatarra férrica y no férrica. Esta medida evitaría la contaminación de aleaciones de acero por altos niveles de algunos metales como Cu, Su, Co y Ni que no se pueden eliminar en los procesos de oxidación del acero.

J) Desde la perspectiva del ecodiseño se han propuesto varias recomendaciones. Las recomendaciones fueron explicadas en el Capítulo 9 (**Paper V)**. Sin embargo las principales se describen a continuación dado que constituyen una de las principales contribuciones de la Tesis.

J.1. *Facilitar el desensamblaje:* En la actualidad el alternador suele estar en la parte baja del motor y debería de ubicarse en la zona alta. Esto facilitaría el desmontaje del mismo para la recuperación de metales valiosos. El alternador se mueve por una correa multifunción, de tal forma que su reubicación podría ser fácilmente implementada. En el caso del cuadro de instrumentos se debería de diseñar para ser desmontado por la zona superior del salpicadero. De esta forma no habría que desmontar previamente el airbag y el volante. En el caso de los cables de la batería, que son los que tiene mayor espesor y contenido en cobre, se podrían rediseñar para ser fácilmente desmontados cuando se desmontan las baterías en los CATs. Finalmente si se realizará un proceso de desmontaje común del motor, caja de cambios y tren delantero se podrían recuperar algunos metales los siguientes componentes: brazos de suspensión (Nb, Mo, V), turbo (Nb, Cr, W), tubo de escape (Pd, Ni, Zr), sensor de temperatura de gases (Pt, Ni, Cu) o asistencia de la dirección (Cu).

J.2. *Sustitución de metales críticos:* El aluminio se podría emplear para sustituir al cobre en algunos cableados. Para ello hay que tener en consideración que el aluminio tiene el 61 % de la conductividad eléctrica del cobre pero solamente el 30 % de su peso. De tal forma que a igualdad de conductividad, un cable de aluminio, aunque tendrá más espesor que el cobre pero pesara un 50 % menos. No obstante para la substitución de cobre por aluminio se debe de tener en consideración que para su uso hay que emplear también como elementos aleantes Fe, Cu, Mg o Cr. Por otro lado el coeficiente de dilatación lineal del aluminio es un 36 % superior al del cobre de tal forma que para algunos componentes puede suponer un problema. En algunos contactos electrónicos se podrían sustituir los recubrimientos de oro por recubrimientos de plata. Además de por ser un material menos escaso, el uso de la plata tiene también como ventaja su menor coste. La plata tiene una conductividad eléctrica y térmica mejor que el oro, aunque presenta como principal desventaja su menor resistencia a la corrosión. Para evitar este problema el recubrimiento debería de ser de plata y níquel. En el caso de los condensadores de tántalo se podrían emplear condensadores cerámicos.

J.3. *Reacondicionamiento:* Desde el punto de vista del reacondicionamiento, es vital analizar la disponibilidad de piezas para ser reacondicionadas y montadas en vehículos nuevos. Estas operaciones se podrían realizar desde vehículos con grandes series de fabricación como sucede en el segmento C, hacia otros que se fabrican en menor escala y en los cuales los requerimientos estéticos no son tan importantes, por ejemplo en vehículos industriales. Esta opción sería muy adecuada para: cuadros de instrumentos, interruptores, sensores de lluvia, sensores de calidad de aire, gases o temperatura. Además se podría evaluar también el reacondicionamiento de motores y cajas de cambio. En el caso de los motores, un diseño con camisas intercambiables permitirá la sustitución de estas como se hace en los motores industriales. Por otro lado esta medida no imposibilitaría que el motor se pudiera actualizar a nuevos requerimientos legislativos o de rendimiento ya que los sistemas de inyección, culata o sistema de escape son independientes al bloque. En el caso concreto de la caja de cambios, se emplean también metales de gran valor como magnesio, níquel, cromo y molibdeno. En el vehículo estudiado el 80 % del magnesio estaba en la caja de cambios. Las cajas de cambios son muy robustas y sus desarrollos nos han cambiado sustancialmente en los últimos años de tal forma que es una operación que se podría llevar a cabo fácilmente.

J.4. *Nuevos conceptos:* Se recomienda la posibilidad de centralizar todas las unidades electrónicos (p.e unidad de control de abordo, unidad de control de puertas, unidad de airbag, unidad electrónica de control del motor, cuadro de instrumentos o unidad del sistema de infoentretenimiento) en una unidad común. De esta manera podría ser desensamblada en los CATs y enviada posteriormente a un centro de reciclaje. Por otro lado se recomienda evaluar el impacto de elevar el voltaje de los vehículos de 12 V a 24 V o 48 V. En la actualidad los modelos híbridos están llevando a cabo esta medida para mejorar el rendimiento, pero hay que tener en cuenta que esta medida reduciría también la sección de cableado. En este sentido se propone integrar el alternador y el motor de arranque en una única unidad ya que se reduciría la demanda de imanes permanentes y por tanto de tierras raras. Finalmente se recomienda evaluar el impacto de concentrar toda la información e interruptores del vehículo en una pantalla, ya que permitirá eliminar la necesidad de interruptores, reduciría la demanda de cableado y ese conjunto podría ser fácilmente desmontable para su reciclaje y/o reutilización.

10.6. Perspectivas

Las futuras líneas de investigación que pueden complementar el trabajo desarrollado por esta Tesis se presentan a continuación.

- Primeramente, la posibilidad de investigar más sobre las composiciones de otros tipos de vehículos. En el caso de los vehículos eléctricos e híbridos, los datos empleados vienen de revisión bibliográfica. Esta primera evaluación tiene incertidumbres derivadas de los contenidos de metales de los vehículos. Se espera que en un corto plazo a comparación entre dos modelos con diferentes tipos de propulsión (eléctrica y de combustión) se pueda llevar a cabo. Además, esta metodología se podría aplicar a diferentes tipos de niveles de equipamiento.
- En segundo lugar, investigar el papel de otros materiales. En esta Tesis se han analizado los metales, sin embargo, un vehículo también emplea plásticos, vidrios, neumáticos, espumas o materiales textiles. En la actualidad esos materiales finalizan habitualmente en los vertederos por lo que hay que buscar soluciones para cerrar sus ciclos.
- En tercer lugar habría que investigar las opciones para recuperar metales de los componentes identificados como críticos. Una vez que ya se dispone del listado de los componentes críticos de un vehículo hay que definir los procesos de reciclaje para recuperar los metales críticos que emplean. Para desarrollar está actividad hay que emplear herramientas de simulación de procesos metalúrgicos. Esta tarea se desea realizar con el Helmholtz Zentrum Dresden Rossendorf (sede de Freiberg) empleando el software HSC Chemistry, como resultado se quiere diseñar una planta virtual de reciclaje de componentes.
- En cuarto lugar habría que investigar la viabilidad ambiental y económica de los procesos de reciclaje. Una vez que los procesos metalúrgicos son definidos, es necesario evaluar sus impactos. En la actualidad hay varias preguntas que resolver: ¿Cuánto residuo produciría el reciclado de esos componentes? ¿Cuál sería la toxicidad de dicho residuo? ¿Es viable recuperar esos metales?
- Finalmente, investigar qué procesos de reciclaje se podrían desarrollar para la recuperación de metales de los residuos de fragmentación que han sido depositados en los vertederos durante años. La aplicación de los procesos de fragmentación convencionales ha propiciado que en la actualidad haya vertederos que puedan ser considerados auténticas minas urbanas por el valor de los metales que contienen.

References

[1] United Nations - Framework Convention on Climate Change. Paris Agreement. 21st Conf. Parties, Paris: 2015, p. 3. doi:FCCC/CP/2015/L.9.

[2] European Climate Foundation. Power Perspectives 2030. On the road to a decarbonised power sector. 2011.

[3] European Commission. 2050 - low carbon economy 2015. http://ec.europa.eu/clima/policies/strategies/2050/index_en.htm (accessed September 15, 2016).

[4] European Commission. Transport White Paper. Brussels: 2011.

[5] International Energy Agency. Energy Technology Perspectives: Scenarios & Strategies to 2050. 2010. doi:10.1049/et:20060114.

[6] Alonso E, Sherman AM, Wallington TJ, Everson MP, Field FR, Roth R, et al. Evaluating rare earth element availability: A case with revolutionary demand from clean technologies. Environ Sci Technol 2012;46:3406–14. doi:10.1021/es203518d.

[7] Elshkaki A, Graedel TE. Dysprosium, the balance problem, and wind power technology. Appl Energy 2014;136:548–59. doi:10.1016/j.apenergy.2014.09.064.

[8] Grandell L, Lehtilä A, Kivinen M, Koljonen T, Kihlman S, Lauri LS. Role of critical metals in the future markets of clean energy technologies. Renew Energy 2016;95:53–62. doi:10.1016/j.renene.2016.03.102.

[9] Ravikumar D, Malghan D. Material constraints for indigenous production of CdTe PV: Evidence from a Monte Carlo experiment using India's National Solar Mission Benchmarks. Renew Sustain Energy Rev 2013;25:393–403. doi:10.1016/j.rser.2013.04.030.

[10] Elshkaki A, Graedel TE. Solar cell metals and their hosts: A tale of oversupply and undersupply. Appl Energy 2015;158:167–77. doi:10.1016/j.apenergy.2015.08.066.

[11] Pihl E, Kushnir D, Sandén B, Johnsson F. Material constraints for concentrating solar thermal power. Energy 2012;44:944–54. doi:10.1016/j.energy.2012.04.057.

[12] Miedema JH, Moll HC. Lithium availability in the EU27 for battery-driven vehicles: The impact of recycling and substitution on the confrontation between supply and demand until2050. Resour Policy 2013;38:204–11. doi:10.1016/j.resourpol.2013.01.001.

[13] Mohr S, Mudd G, Giurco D. Lithium resources and production: critical assessment and global projections. Minerals 2012;2:65–84. doi:10.3390/min2010065.

[14] Redlinger M, Eggert R, Woodhouse M. Evaluating the availability of gallium, indium, and

tellurium from recycled photovoltaic modules. Sol Energy Mater Sol Cells 2015;138:58–71. doi:10.1016/j.solmat.2015.02.027.

[15] Robert A, Villalba G, Talens L. Handbook of Recycling - Chapter 4 - Recycling Rare Metals. 2014. doi:https://doi.org/10.1016/B978-0-12-396459-5.00004-0.

[16] Wang X, Gaustad G, Babbitt CW. Targeting high value metals in lithium-ion battery recycling via shredding and size-based separation. Waste Manag 2016;51:204–13. doi:10.1016/j.wasman.2015.10.026.

[17] Vikström H, Davidsson S, Höök M. Lithium availability and future production outlooks. Appl Energy 2013;110:252–66. doi:10.1016/j.apenergy.2013.04.005.

[18] Richa K, Babbitt CW, Gaustad G, Wang X. A future perspective on lithium-ion battery waste flows from electric vehicles. Resour Conserv Recycl 2014;83:63–76. doi:10.1016/j.resconrec.2013.11.008.

[19] Silberglitt R, Bartis J, Chow B, An D, Brady K. Critical Materials - Present Danger to US Manufacturing. 2013. doi:978-0-8330-7883-4.

[20] U.S. Department of Energy. Critical material strategy. 2011.

[21] Moss RL, Tzimas E, Kara H, Willis P, Kooroshy J. Critical Metals in Strategic Energy Technologies. 2011. doi:10.2790/35600.

[22] Graedel TE, Harper EM, Nassar NT, Reck BK. On the materials basis of modern society. Proc Natl Acad Sci U S A 2015;112:6295–300. doi:10.1073/pnas.1312752110.

[23] Alonso E, Gregory J, Field F, Kirchain R. Material availability and the supply chain: Risks, effects, and responses. Environ Sci Technol 2007;41:6649–56. doi:10.1021/es070159c.

[24] Achzet B, Helbig C. How to evaluate raw material supply risks—an overview. Resour Policy 2013;38:435–47. doi:10.1016/j.resourpol.2013.06.003.

[25] European Commission. Report on critical raw materials for the EU. Report of the Ad hoc working group on defining critical raw materials. 2014.

[26] Kamei T. Preliminary Study of Development of the Organization of Rare-Earth Exportation Countries. J Sustain Dev Energy, Water Environ Syst 2013;1:1–13. doi:10.13044/j.sdewes.2013.01.0001.

[27] European Commission. Critical raw materials 2017. http://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_es (accessed September 4, 2018).

[28] Calvo G, Valero A, Valero A. Thermodynamic Approach to Evaluate the Criticality of Raw Materials and Its Application through a Material Flow. Ind Ecol 2017;22.

doi:10.1111/jiec.12624.

[29] Moss RL, Tzimas E, Kara H, Willis P, Kooroshy J. The potential risks from metals bottlenecks to the deployment of Strategic Energy Technologies. Energy Policy 2013;55:556–64. doi:10.1016/j.enpol.2012.12.053.

[30] Elshkaki A, Graedel TE. Dynamic analysis of the global metals flows and stocks in electricity generation technologies. J Clean Prod 2013;59:260–73. doi:10.1016/j.jclepro.2013.07.003.

[31] Sohn I. Long-term projections of non-fuel minerals: We were wrong, but why? Resour Policy 2005;30:259–84. doi:10.1016/j.resourpol.2006.03.002.

[32] Emodi NV, Emodi CC, Murthy GP, Emodi ASA. Energy policy for low carbon development in Nigeria: A LEAP model application. Renew Sustain Energy Rev 2017;68:247–61. doi:10.1016/j.rser.2016.09.118.

[33] Kuldna P, Peterson K, Kuhi-Thalfeldt R. Knowledge brokering on emissions modelling in Strategic Environmental Assessment of Estonian energy policy with special reference to the LEAP model. Environ Impact Assess Rev 2015;54:55–60. doi:10.1016/j.eiar.2015.06.001.

[34] Victor N, Nichols C, Balash P. The impacts of shale gas supply and climate policies on energy security: The U.S. energy system analysis based on MARKAL model. Energy Strateg Rev 2014;5:26–41. doi:10.1016/j.esr.2014.10.008.

[35] Sverdrup HU, Ragnarsdottir KV, Koca D. On modelling the global copper mining rates, market supply, copper price and the end of copper reserves. Resour Conserv Recycl 2014;87:158–74. doi:10.1016/j.resconrec.2014.03.007.

[36] Sverdrup HU, Ragnarsdottir KV, Koca D. Aluminium for the future: Modelling the global production, market supply, demand, price and long term development of the global reserves. Resour Conserv Recycl 2015;103:139–54. doi:10.1016/j.resconrec.2015.06.008.

[37] Sverdrup HU. Modelling global extraction, supply, price and depletion of the extractable geological resources with the {LITHIUM} model. Resour Conserv Recycl 2016;114:112–29. doi:http://dx.doi.org/10.1016/j.resconrec.2016.07.002.

[38] Hubbert MK. Nuclear Energy and the fossil fuels. 1956.

[39] Murray J, King D. Climate policy: Oil's tipping point has passed. Nature 2012;481:433–5. doi:10.1038/481433a.

[40] Capellán-Pérez I, Mediavilla M, de Castro C, Carpintero Ó, Miguel LJ. Fossil fuel depletion and socio-economic scenarios: An integrated approach. Energy 2014;77:641–66. doi:10.1016/j.energy.2014.09.063.

[41] Chapman I. The end of Peak Oil? Why this topic is still relevant despite recent denials. Energy Policy 2014;64:93–101. doi:10.1016/j.enpol.2013.05.010.

[42] Calvo G, Valero A, Valero A. Assessing maximum production peak and resource availability of non-fuel mineral resources : Analyzing the in fl uence of extractable global resources. Resour Conserv Recycl 2017;125:208–17. doi:10.1016/j.resconrec.2017.06.009.

[43] Wells P. Sustainable business models and the automotive industry: A commentary. IIMB Manag Rev 2013;25:228–39. doi:10.1016/j.iimb.2013.07.001.

[44] USGS. Steel Stocks in Use in Automobiles in the United States. vol. 2002. 2005.

[45] USGS. Al Stocks in Use in Automobiles in the United States. vol. 2002. 2006.

[46] International Organization of Motor Vehicle Manufacturers. Sales statistics 2016. http://www.oica.net/category/sales-statistics/ (accessed July 15, 2016).

[47] Arda I, Rene E, Hullebusch ED Van, Lens P. Electronic waste as a secondary source of critical metals : Management and recovery technologies. Resour , Conserv Recycl 2018;135:296–312. doi:10.1016/j.resconrec.2017.07.031.

[48] Simic V, Dimitrijevic B. Risk explicit interval linear programming model for long-term planning of vehicle recycling in the EU legislative context under uncertainty. Resour , Conserv Recycl 2013;73:197–210. doi:10.1016/j.resconrec.2013.02.012.

[49] Hernandez M, Messagie M, De Gennaro M, Van Mierlo J. Resource depletion in an electric vehicle powertrain using different LCA impact methods. Resour Conserv Recycl 2017;120:119–30. doi:10.1016/j.resconrec.2016.11.005.

[50] Schipper L. Automobile use, fuel economy and CO2 emissions in industrialized countries: Encouraging trends through 2008? Transp Policy 2011;18:358–72. doi:10.1016/j.tranpol.2010.10.011.

[51] Zachariadis T. On the baseline evolution of automobile fuel economy in Europe. Energy Policy 2006;34:1773–85. doi:10.1016/j.enpol.2005.01.002.

[52] Hatayama H, Daigo I, Matsuno Y, Adachi Y. Evolution of aluminum recycling initiated by the introduction of next-generation vehicles and scrap sorting technology. Resour Conserv Recycl 2012;66:8–14. doi:10.1016/j.resconrec.2012.06.006.

[53] Løvik AN, Modaresi R, Müller DB. Long-term strategies for increased recycling of automotive aluminum and its alloying elements. Environ Sci Technol 2014;48:4257–65. doi:10.1021/es405604g.

[54] Van Schaik A, Reuter MA, Boin UMJ, Dalmijn WL. Dynamic modelling and optimisation of the resource cycle of passenger vehicles. Miner Eng 2002;15:1001–16.

doi:10.1016/S0892-6875(02)00080-8.

[55] The Ecology Center. Moving Toward Sustainable Plastics. A report card on the six leading automakers. Michigan, USA: The Ecology Center; 2005.

[56] Eurostat. Passenger cars in the EU - Statistics Explained 2015. http://ec.europa.eu/eurostat/web/waste/key-waste-streams/elvs.

[57] Restrepo E, Løvik AN, Wäger P, Widmer R, Lonka R, Müller DB. Stocks, flows and distribution of critical metals in embedded electronics in passenger vehicles. Submitt to Environ Sci Technol 2016. doi:10.1021/acs.est.6b05743.

[58] Simon B, Ziemann S, Weil M. Potential metal requirement of active materials in lithium-ion battery cells of electric vehicles and its impact on reserves: Focus on Europe. Resour Conserv Recycl 2015;104:300–10. doi:10.1016/j.resconrec.2015.07.011.

[59] Riba J-R, López-Torres C, Romeral L, Garcia A. Rare-earth-free propulsion motors for electric vehicles: A technology review. Renew Sustain Energy Rev 2016;57:367–79. doi:10.1016/j.rser.2015.12.121.

[60] Andersson M, Ljunggren Söderman M, Sandén BA. Are scarce metals in cars functionally recycled? Waste Manag 2016. doi:10.1016/j.wasman.2016.06.031.

[61] Ortego A, Valero A, Valero A, Restrepo E. Vehicles and critical raw materials. A sustainability assessment using thermodynamic rarity. Ind Ecol 2018;22. doi:10.1111/jiec.12737.

[62] Kawaguchi H. Various steel sheet applications for automotive. Int. symphosium niobium microalloyed sheet steel Automot. Appl., Warrendale: 2006, p. 45–52. doi:978-0-87339-630-1.

[63] Belanger PJ, Walp MS, Milititsky M. Advanced Steel Products for Lightweighting. Int. symphosium niobium microalloyed sheet steel Automot. Appl., Warrendale: 2006, p. 53–63.

[64] European Environmental Agency. Car ownership rates projections 2010. http://www.eea.europa.eu/data-and-maps/figures/car-ownership-rates-projections (accessed July 15, 2016).

[65] International Energy Agency. Global transport outlook to 2050. Glob. Transp. outlook to 2050, 2012.

[66] Spanish automobile manufacturers association (ANFAC). European Motor Vehicle Parc 2008. 2010.

[67] Cullbrand K, Magnusson O. The Use of Potentially Critical Materials in Passenger Cars. Chalmers, 2012.

[68] Andersson M, Ljunggren Söderman M, Sanden BA. Mapping the content and fates of scarce metals in discarded cars. Life cycle Assess. other Assess. tolls waste Manag. Resour. Optim., Calabria: 2016.

[69] Alonso E, Wallington T, Sherman A, Everson M, Field F, Roth R, et al. An assessment of the rare earth element content of conventional and electric vehicles. SAE Int Jorunal Mater Manuf 2012;5:3–7. doi:10.4271/2012-01-1061.

[70] Du X, Restrepo E, Widmer R, Wäger P. Quantifying the distribution of critical metals in conventional passenger vehicles using input-driven and output-driven approaches: a comparative study. J Mater Cycles Waste Manag 2015:218–28. doi:10.1007/s10163-015-0353-3.

[71] Modaresi R, Müller DB. The role of automobiles for the future of aluminum recycling. Environ Sci Technol 2012;46:8587–94. doi:10.1021/es300648w.

[72] Kushnir D, Sandén BA. The time dimension and lithium resource constraints for electric vehicles. Resour Policy 2012;37:93–103. doi:10.1016/j.resourpol.2011.11.003.

[73] Scrosati B, Garche J. Lithium batteries: Status, prospects and future. J Power Sources 2010;195:2419–30. doi:10.1016/j.jpowsour.2009.11.048.

[74] Grosjean C, Herrera Miranda P, Perrin M, Poggi P. Assessment of world lithium resources and consequences of their geographic distribution on the expected development of the electric vehicle industry. Renew Sustain Energy Rev 2012;16:1735–44. doi:10.1016/j.rser.2011.11.023.

[75] Schmidt T, Buchert M, Schebek L. Investigation of the primary production routes of nickel and cobalt products used for Li-ion batteries. Resour Conserv Recycl 2016;112:107–22. doi:10.1016/j.resconrec.2016.04.017.

[76] Väyrynen A, Salminen J. Lithium ion battery production. J Chem Thermodyn 2012;46:80–5. doi:10.1016/j.jct.2011.09.005.

[77] Batista T, Freire F, Silva CM. Vehicle environmental rating methodologies: Overview and application to light-duty vehicles. Renew Sustain Energy Rev 2015;45:192–206. doi:10.1016/j.rser.2015.01.040.

[78] Du X, Graedel TE. Global In-Use Stocks of the Rare Earth Elements: A first estimate. Environ Sci Technol 2011;45:4096–101. doi:10.1021/es102836s.

[79] European Automobile Manufacturers Association. Vehicle statistics 2014. http://www.acea.be/statistics/article/anfac-vehicles-in-use-report (accessed February 2, 2016).

[80] European Commission. Directive 2000/53/EC on end of life vehicles. 2005.

[81] Zorpas A, Inglezakis V. Automotive industry challenges in meeting EU 2015 environmental standard. Technol Soc 2012;34:55–83. doi:10.1016/J.TECHSOC.2011.12.006.

[82] Simic V, Dimitrijevic B. Resources , Conservation and Recycling Production planning for vehicle recycling factories in the EU legislative and global business environments 2012;60:78–88. doi:10.1016/j.resconrec.2011.11.012.

[83] SIGRAUTO. Stati. ELV Recover Levels Stat 2015. http://www.sigrauto.com/cuarec.htm (accessed July 18, 2016).

[84] Millet D, Yvars P-A, Tonnelier P. A method for identifying the worst recycling case: Application on a range of vehicles in the automotive sector. Resour Conserv Recycl 2012;68:1–13. doi:10.1016/j.resconrec.2012.07.002.

[85] Inghels D, Dullaert W, Raa B, Walther G. Influence of composition, amount and life span of passenger cars on end-of-life vehicles waste in Belgium: A system dynamics approach. Transp Res Part A Policy Pract 2016;91:80–104. doi:10.1016/j.tra.2016.06.005.

[86] Ohno H, Matsubae K, Nakajima K, Kondo Y, Nakamura S, Nagasaka T. Toward the efficient recycling of alloying elements from end of life vehicle steel scrap. Resour , Conserv Recycl 2015;100:11–20. doi:10.1016/j.resconrec.2015.04.001.

[87] Merriam-Webster. Dictionary 1995. https://www.merriam-webster.com/dictionary/downcycle (accessed October 26, 2017).

[88] Ohno H, Matsubae K, Nakajima K, Nakamura S, Nagasaka T. Unintentional flow of alloying elements in steel during recycling of end-of-life vehicles. J Ind Ecol 2014;18:242–53. doi:10.1111/jiec.12095.

[89] Amini H, Remmerswaal JA, Castro MB, Reuter MA. Quantifying the quality loss and resource efficiency of recycling by means of exergy analysis. J Clean Prod 2007;15:907–13. doi:10.1016/j.jclepro.2006.01.010.

[90] Nickel Institute. Recycling of nickel-containing materials in automobiles 2016. https://www.nickelinstitute.org/NickelUseInSociety/MaterialsSelectionAndUse/Automotive/RecyclingNickelInAutos.aspx (accessed August 2, 2016).

[91] Maurice P, Niero M, Bey N, Paraskevas D. Resources , Conservation & Recycling Environmental screening of novel technologies to increase material circularity : A case study on aluminium cans. Resour Conserv Recycl 2017;127:96–106. doi:10.1016/j.resconrec.2017.07.013.

[92] Pan Y, Li H. Sustainability evaluation of end-of-life vehicle recycling based on emergy analysis: a case study of an end-of-life vehicle recycling enterprise in China. J Clean Prod

2016;131:219–27. doi:10.1016/j.jclepro.2016.05.045.

[93] Ohno H, Matsubae K, Nakajima K, Kondo Y, Nakamura S, Nagasaka T. Toward the efficient recycling of alloying elements from end of life vehicle steel scrap. Resour Conserv Recycl 2015;100:11–20. doi:10.1016/j.resconrec.2015.04.001.

[94] Belboom S, Lewis G, Bareel P-F, Léonard A. Life cycle assessment of hybrid vehicles recycling: Comparison of three business lines of dismantling. Waste Manag 2016;50:184–93. doi:10.1016/j.wasman.2016.02.007.

[95] Tian J, Chen M. Sustainable design for automotive products: Dismantling and recycling of end-of-life vehicles. Waste Manag 2014;34:458–67. doi:10.1016/j.wasman.2013.11.005.

[96] Van Schaik A, Reuter MA. The use of fuzzy rule models to link automotive design to recycling rate calculation. Miner Eng 2007;20:875–90. doi:10.1016/j.mineng.2007.03.016.

[97] Ignatenko O, Van Schaik A, Reuter MA. Exergy as a tool for evaluation of the resource efficiency of recycling systems. Miner Eng 2007;20:862–74. doi:10.1016/j.mineng.2007.03.005.

[98] Gutowski TG. Thermodynamics and recycling: A review. IEEE Int. Symp. Electron. Environ. Absol. versus Relat. Environ. Sustain. What can Cradle-to-Cradle Ecoefficiency Concepts Learn from Each Other, 2008, p. 321–32.

[99] Gutowski TG, Dahmus JB. Mixing entropy and product recycling. Electron. Environ. 2005. Proc. 2005 IEEE Int. Symp., IEEE; 2005, p. 72–76.

[100] Nakajima K, Takeda O, Miki T, Nagasaka T. Evaluation method of metal resource recyclability based on thermodynamic analysis. Mater Trans 2009;50:453–460. doi:10.2320/matertrans.MBW200806.

[101] Valero A, Valero A. Thanatia: the destiny of the Earth's mineral resources: a cradle-to-cradle thermodynamic assessment. New Jersey: World Scientific; 2015.

[102] Reuter MA, Van Schaik A, Ignatenko O, De Haan G-J. Fundamental limits for the recycling of end-of-life vehicles. Miner Eng 2006;19:433–49. doi:10.1016/j.mineng.2005.08.014.

[103] Ignatenko O, Van Schaik A, Reuter MA. Recycling system flexibility: the fundamental solution to achieve high energy and material recovery quotas. J Clean Prod 2008;16:432–49. doi:10.1016/j.jclepro.2006.07.048.

[104] Castro MB, Remmerswaal JA, Brezet H, Reuter MA. Exergy losses during recycling and the resource efficiency of product systems. Resour Conserv Recycl 2007;52:219–33.

doi:10.1016/j.resconrec.2007.01.014.

[105] Castro MB, Remmerswaaland JA, Reuter MA, Boin U. A thermodynamic approach to the compatibility of materials combinations for recycling. Resour Conserv Recycl 2004;43:1–19. doi:10.1016/j.resconrec.2004.04.011.

[106] Reuter MA. Digitalizing the Circular Economy: Circular Economy Engineering Defined by the Metallurgical Internet of Things. Metall Mater Trans B Process Metall Mater Process Sci 2016;47:3194–220. doi:10.1007/s11663-016-0735-5.

[107] Van Schaik A, Reuter MA, Castro B, Remmerswaal H. Chapter 9. the Role of Product Design and Liberation in the Optimisation of Recycling Passenger Vehicles. Metrics Mater. Met. Ecol. Harmon. Resour. Technol. Environ. Cycles, 2005, p. 3–706.

[108] Outotec. HSC Sim 9 2017. https://www.outotec.com/products/digital-solutions/hsc-chemistry/hsc-sim-process-simulation-module/ (accessed January 8, 2018).

[109] Meskers C, Reuter MA, Boin U, Kvithyld A. A fundamental metric for metal recycling applied to coated magnesium. Metall Mater Trans B Process Metall Mater Process Sci 2008;39:500–17. doi:10.1007/s11663-008-9144-8.

[110] Rodrigues VP, Pigosso DCA, McAloone TC. Process-related key performance indicators for measuring sustainability performance of ecodesign implementation into product development. J Clean Prod 2016;139:416–28. doi:10.1016/J.JCLEPRO.2016.08.046.

[111] Plouffe S, Lanoie P, Berneman C, Vernier M-F. Economic benefits tied to ecodesign. J Clean Prod 2011;19:573–9. doi:10.1016/J.JCLEPRO.2010.12.003.

[112] Luttropp C, Lagerstedt J. EcoDesign and The Ten Golden Rules: generic advice for merging environmental aspects into product development. J Clean Prod 2006;14:1396–408. doi:10.1016/J.JCLEPRO.2005.11.022.

[113] Rossi M, Germani M, Zamagni A. Review of ecodesign methods and tools. Barriers and strategies for an effective implementation in industrial companies. J Clean Prod 2016;129:361–73. doi:10.1016/J.JCLEPRO.2016.04.051.

[114] den Hollander MC, Bakker CA, Hultink EJ. Product Design in a Circular Economy: Development of a Typology of Key Concepts and Terms. J Ind Ecol 2017;21:517–25. doi:10.1111/jiec.12610.

[115] Parlamento Europeo. Directiva 2009/125/CE del Parlamento Europeo y del Consejo, de 21 de octubre de 2009, por la que se instaura un marco para el establecimiento de requisitos de diseño ecológico aplicables a los productos relacionados con la energía. DOUE Núm 285 2009:26.

[116] Directive 2000/53/EC of the European Parliament and of the Council on End of Life

Vehicles. vol. 2000L0053. 2000.

[117] European Commission. Emissions in the automotive sector 2017. https://ec.europa.eu/growth/sectors/automotive/environment-protection/emissions_es (accessed December 26, 2017).

[118] SEAT. SEAT has become the first company in the automotive sector in Spain to be certified with the ISO 14006 standard in Ecodesign 2016. http://www.seat.com/corporate/news/corporate/seat-ecodesign-certification.html.

[119] Arana-Landin G, Heras-Saizarbitoria I. Paving the way for the ISO 14006 ecodesign standard: an exploratory study in Spanish companies. J Clean Prod 2011;19:1007–15. doi:10.1016/J.JCLEPRO.2011.01.013.

[120] Lee C-K, Lee J-Y, Choi Y-H, Lee K-M. Application of the integrated ecodesign method using the GHG emission as a single indicator and its GHG recyclability. J Clean Prod 2016;112:1692–9. doi:10.1016/J.JCLEPRO.2014.10.081.

[121] Mayyas AT, Mayyas AR, Omar M. Sustainable lightweight vehicle design. Light. Compos. Struct. Transp., Elsevier; 2016, p. 267–302. doi:10.1016/B978-1-78242-325-6.00011-6.

[122] Delogu M, Zanchi L, Dattilo CA, Pierini M. Innovative composites and hybrid materials for electric vehicles lightweight design in a sustainability perspective. Mater Today Commun 2017;13:192–209. doi:10.1016/J.MTCOMM.2017.09.012.

[123] Ozbilen A, Dincer I, Hosseini M. Comparative Life Cycle Environmental Impact Assessment of Natural Gas and Conventional Vehicles. Exergetic, Energ. Environ. Dimens., Elsevier; 2018, p. 913–34. doi:10.1016/B978-0-12-813734-5.00052-4.

[124] Viñoles-Cebolla R, Bastante-Ceca MJ, Capuz-Rizo SF. An integrated method to calculate an automobile’s emissions throughout its life cycle. Energy 2015;83:125–36. doi:10.1016/j.energy.2015.02.006.

[125] Tagliaferri C, Evangelisti S, Acconcia F, Domenech T, Ekins P, Barletta D, et al. Life cycle assessment of future electric and hybrid vehicles: a cradle-to-grave systems engineering approach. Chem Eng Res Des 2016. doi:10.1016/j.cherd.2016.07.003.

[126] Ecoinvent. The Ecoinvent Database 2018. https://www.ecoinvent.org/database/database.html (accessed October 26, 2018).

[127] Domingues AR, Marques P, Garcia R, Freire F, Dias LC. Applying Multi-Criteria Decision Analysis to the Life-Cycle Assessment of vehicles. J Clean Prod 2015;107:749–59. doi:10.1016/j.jclepro.2015.05.086.

[128] Bauer C, Hofer J, Althaus H-J, Del Duce A, Simons A. The environmental performance

of current and future passenger vehicles: Life cycle assessment based on a novel scenario analysis framework. Appl Energy 2015;157:871–83. doi:10.1016/j.apenergy.2015.01.019.

[129] Song J-S, Lee K-M. Development of a low-carbon product design system based on embedded GHG emissions. Resour Conserv Recycl 2010;54:547–56. doi:10.1016/j.resconrec.2009.10.012.

[130] Herrmann IT, Moltesen A. Does it matter which Life Cycle Assessment (LCA) tool you choose? – a comparative assessment of SimaPro and GaBi. J Clean Prod 2015;86:163–9. doi:10.1016/J.JCLEPRO.2014.08.004.

[131] USGS. Mineral Commodity Summaries 2015. United States Geological Service. 2015.

[132] Sverdrup HU, Ragnarsdottir KV. Natural resources in a planetary perspective. Geochemical Perspectives, volume 3, number 2; 2014. doi:10.7185/geochempersp.3.2.

[133] Emsley J. Nature’s Building Blocks: An A–Z Guide to the Elements. Oxford, England, UK: Oxford University Press. 2001.

[134] Frenzel M, Ketris MP, Seifert T, Gutzmer J. On the current and future availability of gallium. Resour Policy 2016;47:38–50. doi:10.1016/j.resourpol.2015.11.005.

[135] Frenzel M, Kertris MP, Gutzmer J. On the geological availability of germanium. Miner Depos 2014;49:471–86. doi:10.1007/s00126-013-0506-z.

[136] Haque N, Hughes A, Lim S, Vernon C. Rare Earth Elements: Overview of Mining, Mineralogy, Uses, Sustainability and Environmental Impact. Resources 2014;3:614–35. doi:doi.org/10.3390/resources3040614.

[137] Hubbert MK. Energy Resources. Washington: 1962.

[138] The United Nations Environmental Programme (UNEP). Recycling rates of metals. A status report. 2011.

[139] Geyer R, Kuczenski B, Zink T, Henderson A. Common Misconceptions about Recycling. J Ind Ecol 2016;20:1010–7. doi:10.1111/jiec.12355.

[140] Oers L van, Guinée J. The Abiotic Depletion Potential: Background, Updates, and Future. Resources 2016;5:16. doi:10.3390/resources5010016.

[141] Wackernagel M, Rees W. Our Ecological Footprint: Reducing Human Impact on the Earth. 1996.

[142] Odum H. Environmental Accounting. Emergy and Environmental Decision Making. 1995.

[143] Stanek W, Valero A, Valero A, Uche J, Calvo G. Thermodynamics for sustainable management of natural resources - Chapter 6 - Thermodynamic method to evaluate resources. Springer; 2017. doi:10.1007/978-3-319-48649-9.

[144] Valero A, Valero A, Vieillard P. The thermodynamic properties of the upper continental crust : Exergy , Gibbs free energy and enthalpy. Energy 2012;41:121–7. doi:10.1016/j.energy.2011.06.012.

[145] Valero A, Valero A. Exergy of comminution and the Thanatia Earth ' s model. EGY 2012;44:1085–93. doi:10.1016/j.energy.2012.04.021.

[146] Valero A, Valero A, Gómez JB. The crepuscular planet. A model for the exhausted continental crust. Energy 2011;36:694–707. doi:10.1016/j.energy.2010.09.034.

[147] Grigor´ev. The average mineral composition of the upper continental crust. Ural Geol 2000;3:3–21.

[148] Rudnick RL, Gao S. 3.01 – Composition of the Continental Crust. Treatise on Geochemistry, 2003, p. 1–64. doi:10.1016/B0-08-043751-6/03016-4.

[149] Faber M, Proops J. Ecological Economics: The Science and Management of Sustainability National Accounting, Time and the Environment. Columbia: 1991.

[150] Cox D, Singer DA. Grade and tonnage model of distal disseminated Ag- Au. 1992.

[151] Valero A, Valero A. From Grave to Cradle A Thermodynamic Approach for Accounting for Abiotic Resource Depletion. Ind Ecol 2013;17:43–52.

[152] Valero A, Valero A, Dominguez A. Exergy Replacement Cost of mineral resources. Environ Account Manag 2013:147–58. doi:10.5890/JEAM.2013.05.004.

[153] Valero A, Valero A. Thanatia, the destiny of the Earth´s mineral resources. 2014.

[154] Swart P, Dewulf J. Modeling fossil energy demands of primary nonferrous metal production: The case of copper. Environ Sci Technol 2013;47:13917–24. doi:10.1021/es4030518.

[155] Calvo G, Mudd G, Valero A, Valero A. Decreasing Ore Grades in Global Metallic Mining: A Theoretical Issue or a Global Reality? Resources 2016;5:36. doi:10.3390/resources5040036.

[156] Spanish automobile manufacturers association (ANFAC). Sale Statistics 2018. http://www.anfac.com/estadisticas.action?accion=estad_turismos (accessed October 26, 2018).

[157] The Association of European Automotive and Industrial Battery Manufacturers (EUROBAT). Segment by body 2017. https://www.acea.be/statistics/tag/category/segments-body-country (accessed October 26, 2018).

[158] González Palencia JC, Sakamaki T, Araki M, Shiga S. Impact of powertrain electrification, vehicle size reduction and lightweight materials substitution on energy use,

CO2 emissions and cost of a passenger light-duty vehicle fleet. Energy 2015;93:1489–504. doi:10.1016/j.energy.2015.10.017.

[159] Spielmann M, Althaus H-J. Can a prolonged use of a passenger car reduce environmental burdens? Life Cycle analysis of Swiss passenger cars. J Clean Prod 2007;15:1122–34. doi:10.1016/j.jclepro.2006.07.022.

[160] Castro MB, Remmerswaaland JA, Reuter MA. Life cycle impact assessment of the average passenger vehicle in the Netherlands. Int J Life Cycle Assess 2003;8:297–304. doi:10.1007/BF02978922.

[161] Schmidt W-P, Dahlqvist E, Finkbeiner M, Krinke S, Lazzari S, Oschmann D, et al. Life cycle assessment of lightweight and end-of-life scenarios for generic compact class passenger vehicles. Int J Life Cycle Assess 2004;9:405–16. doi:10.1007/BF02979084.

[162] Wells P. Automotive materials: the challenge of the globalization and technological change. Cardiff 1998:185.

[163] Amatayakul W, Ramnäs O. Life cycle assessment of a catalytic converter for passenger cars. J Clean Prod 2001;9:395–403. doi:10.1016/S0959-6526(00)00082-2.

[164] Lewis A, Keoleian G, Kelly J. The potential of lightweigh materials and advance combustion engines to reduce life cycle energy greenhouse gas emissions. SAE Int J Mater Manuf 2014.

[165] Du X, Graedel TE. Uncovering the end uses of the rare earth elements. Sci Total Environ 2013;461:781–4. doi:10.1016/j.scitotenv.2013.02.099.

[166] The Association of European Automotive and Industrial Battery Manufacturers (EUROBAT). Battery Materials Analysis May 2014. 2014.

[167] Nitta N, Wu F, Lee JT, Yushin G. Li-ion battery materials: present and future. Mater Today 2015;18:252–64. doi:10.1016/j.mattod.2014.10.040.

[168] Gaines L, Sullivan J, Burnham A, Bel. Life-Cycle Analysis for Lithium-Ion Battery Production and Recycling. Transp Res Board 90th Annu Meet 2010:17. doi:10.1057/9781137332875.0027.

[169] U.S. Department of Energy. U.S. Department of Energy: Critical materials strategy. 2011.

[170] Valero A, Valero A, Calvo G, Ortego A. Material bottlenecks in the future development of green technologies. Renew Sustain Energy Rev 2018;93. doi:10.1016/j.rser.2018.05.041.

[171] Raccurt O, Disdier A, Bourdon D, Donnola S, Stollo A, Gioconia A. Study of the Stability of a Selective Solar Absorber Coating under Air and High Temperature Conditions. Energy Procedia 2015;69:1551–7. doi:10.1016/j.egypro.2015.03.107.

[172] Bayod-Rújula AA, Ortego-Bielsa A, Martínez-Gracia A. Photovoltaics on flat roofs: Energy considerations. Energy 2011;36:1996–2010. doi:10.1016/j.energy.2010.04.024.

[173] EWEA. Wind energy´s frequently asked questions (FAQ) 2016. http://www.ewea.org/wind-energy-basics/faq/ (accessed June 1, 2016).

[174] EWEA. The European offshore wind industry - key trends and statistics 2015. 2016.

[175] International Energy Agency. Technology Roadmap. Wind Energy. 2013.

[176] Greenpeace. Solar Thermal Electricity. Global Outlook 2016. 2016.

[177] International Energy Agency. Technology roadmap. Solar Thermal Electricity. 2014.

[178] International Energy Agency. Technology roadmap. Solar photovoltaic energy. 2014.

[179] Parrado C, Girard A, Simon F, Fuentealba E. 2050 LCOE (Levelized Cost of Energy) projection for a hybrid PV (photovoltaic)-CSP (concentrated solar power) plant in the Atacama Desert, Chile. Energy 2016;94:422–30. doi:10.1016/j.energy.2015.11.015.

[180] Lacal-Arántegui R. Materials use in electricity generators in wind turbines – state-of-the-art and future specifications. J Clean Prod 2015;87:275–83. doi:10.1016/j.jclepro.2014.09.047.

[181] Spanish automobile manufacturers association (ANFAC). European motor vehicle park. 2014.

[182] Dulac J. Global transport outlook to 2050. 2013.

[183] Valero A, Valero A. Physical geonomics: Combining the exergy and Hubbert peak analysis for predicting mineral resources depletion. Resour Conserv Recycl 2010;54:1074–83. doi:10.1016/j.resconrec.2010.02.010.

[184] Bae JC. Strategies and perspectives for securing rare metals in Korea. ritical Elements for New Energy Technologies, an MIT Energy Initiative Workshop Report. 2000.

[185] Angerer DG, Marscheider-Weidemann F, Lüllmann A, Erdmann L, Scharp DM, Handke V, et al. Raw materials for emerging technologies. A report commissioned by the German Federal Ministry of Economics and Technology. 2009.

[186] USGS. The mineral rindustry of Japan. 2010.

[187] European Commission. Critical raw materials for the EU. Report of the Ad-hoc Working Group on defining critical raw materials. 2010.

[188] APS Physics. Energy critical elements: Securing Materials for Emerging Technologies. A report by the APS panel on public affairs & the materials research society. 2011.

[189] Resnick Institute. Critical materials for sustainable energy applications. 2011.

[190] U.S Department of Energy. Critical Materials Strategy. 2011.

[191] UKERC. Materials availability for low-carbon technologies: an assessment of the evidence. 2014.

[192] British Geological Survey. Risk list 2015. 2015.

[193] European Commission. Report on Critical Raw Materials for the EU. European Commission; 2014.

[194] LME. Historical Cobalt Price 2018. https://www.lme.com/Metals/Minor-metals/Cobalt#tabIndex=2 (accessed June 18, 2018).

[195] Hagelüken C, Meskers C. Technology challenges to recover precious and special metals from complex products. R’09 World Congr Davos, … 2009:6.

[196] Granata G, Moscardini E, Furlani G, Pagnanelli F, Toro L. Automobile shredded residue valorisation by hydrometallurgical metal recovery. J Hazard Mater 2011;185:44–8. doi:10.1016/j.jhazmat.2010.08.107.

[197] BASF. Typical Ceramic Auto Catalyst Processing and Refining. 2012.

[198] Lim X. Metal Mixology. Nature 2016;533:306–7.

[199] Ortego A, Valero A, Valero A, Iglesias M, Villacampa M. Strategic metal ranking for the automobile sector. Sustain. Dev. Energy, Water Environ. Syst., Palermo: 2018.

[200] Vidovic M, Dimitrijevic B, Ratkovic B, Simic V. A novel covering approach to positioning ELV collection points. Resour Conserv Recycl 2011;57:1–9. doi:10.1016/j.resconrec.2011.09.013.

[201] Ortego A, Valero A, Iglesias M. Downcycling in automobile recycling process: a thermodynamic assessment. Resour , Conserv Recycl 2018;136. doi:10.1016/j.resconrec.2018.04.006.

[202] Ehrenberger S, Friedrich HE. Life-cycle assessment of the recycling of magnesium vehicle components. Jom 2013;65:1303–9. doi:10.1007/s11837-013-0703-3.

[203] USGS. Publications and Data products 2017. https://minerals.usgs.gov/minerals/pubs/ (accessed October 19, 2017).

[204] Li J, Barwood M, Rahimifard S. Robotics and Computer – Integrated Manufacturing Robotic disassembly for increased recovery of strategically important materials from electrical vehicles 2017;0:1–10. doi:10.1016/j.rcim.2017.09.013.

[205] Awasthi AK, Li J. An overview of the potential of eco-friendly hybrid strategy for metal recycling from WEEE. Resour Conserv Recycl 2017;126:228–39. doi:10.1016/j.resconrec.2017.07.014.

[206] Cui J, Zhang L. Metallurgical recovery of metals from electronic waste: A review. J Hazard Mater 2008;158:228–56. doi:10.1016/J.JHAZMAT.2008.02.001.

[207] Ardente F, Mathieux F, Recchioni M. Resources , Conservation and Recycling Recycling of electronic displays : Analysis of pre-processing and potential ecodesign improvements. "Resources, Conserv Recycl 2014;92:158–71. doi:10.1016/j.resconrec.2014.09.005.

[208] Daehn KE, Cabrera Serrenho A, Allwood JM. How Will Copper Contamination Constrain Future Global Steel Recycling? Environ Sci Technol 2017;51:6599–606. doi:10.1021/acs.est.7b00997.

[209] Minerals HM&. Scrap contaminants 2018. http://www.harsco-m.com/217/Scrap-Contaminants.aspx (accessed August 22, 2018).

[210] IDIS. International Dismantling Information System 2016. http://www.idis2.com/ (accessed October 25, 2017).

[211] Elwert T, Goldmann D, Römer F, Buchert M, Merz C, Schueler D, et al. Current Developments and Challenges in the Recycling of Key Components of (Hybrid) Electric Vehicles. Recycling 2015;1:25–60. doi:10.3390/recycling1010025.

[212] Talens Peiró L, Ardente F, Mathieux F. Design for Disassembly Criteria in EU Product Policies for a More Circular Economy: A Method for Analyzing Battery Packs in PC-Tablets and Subnotebooks. J Ind Ecol 2017;21:731–41. doi:10.1111/jiec.12608.

[213] Santini A, Herrmann C, Passarini F, Vassura I, Luger T, Morselli L. Assessment of Ecodesign potential in reaching new recycling targets. Resour Conserv Recycl 2010;54:1128–34. doi:10.1016/j.resconrec.2010.03.006.

[214] Ballester M, Schaik A van, Reuter MA. Fairphone´s report on recyclability. Does modularity contribute to a better recyclability? 2017.

[215] USGS. Mineral Commodity Summaries 2017. 2017. doi:10.3133/70180197.

[216] Pigosso DCA, Zanette ET, Filho AG, Ometto AR, Rozenfeld H. Ecodesign methods focused on remanufacturing. J Clean Prod 2010;18:21–31. doi:10.1016/J.JCLEPRO.2009.09.005.

[217] VOLVO. Volvo CE’s China Remanufacturing Center in Shanghai draws on more than 70 years of remanufacturing experience. 29/09 2017. https://www.volvoce.com/global/en/spirit-magazine/introducing-remanufacturing/ (accessed December 20, 2017).

[218] Song J, Wang L, Zibart A, Koch C. Corrosion protection of electrically conductive surface. Metals (Basel) 2012. doi:doi:10.3390/met2040450.

[219] Smith L, Ibn-Mohammed T, Lenny Koh S., Ian M R. Life cycle assessment and environmental profile evaluations of high volumetric efficiency capacitors. Appl Energy 2018;220:496–513. doi:https://doi.org/10.1016/j.apenergy.2018.03.067.

[220] Reuter MA, Van Schaik A. Chapter 53 – Gold – A Key Enabler of a Circular Economy: Recycling of Waste Electric and Electronic Equipment. Gold Ore Process., 2016, p. 937–58. doi:10.1016/B978-0-444-63658-4.00053-0.

[221] VOLVO. Integrated starter generator 2001. https://www.media.volvocars.com/global/en-gb/media/pressreleases/5278 (accessed December 20, 2017).

Appendix

The present thesis is based on a compilation of different published manuscript. The impact factors and scope of the corresponding journals are listed below:

A.1. Valero, Al. Valero, A. Calvo, G. **Ortego, A.** *Material bottlenecks in the future development of green technologies. Renewable and Sustainable Energy Reviews.* Vol 93, pp 178-200. **October 2018.**
Impact Factor: 9.18. Journal Citation Reports 2017.
Scope: review papers, original research, case studies and new technology analyses that have a significant review element, which may take the form of a critique, comparison, or analysis. Main topics are: Energy resources, applications, utilization, environment, techno-socio-economic aspect, systems, and sustainability.

A.2. Ortego, A. Valero, Al. Valero, A. Restrepo, E. *Vehicles and Critical Raw Materials. A Sustainability Assessment using Thermodynamic Rarity. Industrial Ecology.* Vol 22. Nº5. **March 2018.**
Impact Factor: 4.35. Journal Citation Reports 2017.
Scope: material and energy flows studies ('industrial metabolism'), technological change, dematerialization and decarbonization, life cycle planning, design and assessment, design for the environment, extended producer responsibility ('product stewardship'), eco-industrial parks ('industrial symbiosis'), product-oriented environmental, policy eco-efficiency.

A.3. Ortego. A, Valero. Al, Valero. A, Calvo. G, Villacampa. M, Iglesias. M. *Strategic metals ranking in the automobile sector. 13th Sustainable Development Energy Water and Environmental Systems Conference. Palermo, Italy.* **4th October 2018.**
Impact Factor: It has no impact factor but it is indexed in Scopus. It has been selected for publication in the journal of Environmental Management.
Scope: It is dedicated to the improvement and dissemination of knowledge on methods, policies and technologies for increasing the sustainability of development by de-coupling growth from natural resources and replacing them with knowledge-based economy, taking into account its economic, environmental and social pillars. Among its areas the following are included: Smart transport systems and policy; Green economy and better governance; Sustainability comparisons and measurements; Transport management.

A.4. Ortego, A. Valero, Al. Valero, A. Iglesias, M. *Downcycling in automobile recycling process: A thermodynamic assessment. Resources, Conservation and Recycling*. Vol 136, pp 24-32. **September 2018.**
Impact Factor: 5.12. Journal Citation Reports 2017.
Scope: The journal emphasizes the transformation processes involved in a transition toward more sustainable production and consumption systems. Emphasis is upon technological, economic, institutional and policy aspects of specific resource management practices, such as conservation, recycling and resource substitution, and of "systems-wide" strategies, such as resource productivity improvement, the restructuring of production and consumption profiles and the transformation of industry.

A.5. Ortego, A. Valero, Al. Valero, A. Iglesias, M. *Towards material efficiency vehicles. Eco-design recommendations based on metal sustainability assessments. SAE International Journal of Materials and Manufacturing.* Vol 11, Issue 3. **September 2018.**
Impact Factor: 0.413. Scimago Journal and Country Rank.
Scope: The Journal is assembled to present and promote wide-ranging research of the following areas: materials (materials development, analysis, modeling, and testing); design (design analysis, modeling, simulations, and optimization) and manufacturing (manufacturing practices, process, simulations, and methodologies).

A.1 Paper I

Valero, Al. Valero, A. Calvo, G. **Ortego, A.** Material bottlenecks in the future development of green technologies. *Renewable and Sustainable Energy Reviews.* Vol 93, pp 178-200. **October 2018.**

Impact Factor: 9.18. Journal Citation Reports 2017.

Scope: review papers, original research, case studies and new technology analyses that have a significant review element, which may take the form of a critique, comparison, or analysis. Main topics are: Energy resources, applications, utilization, environment, techno-socio-economic aspect, systems, and sustainability.

Contribution to the work:

- To make a revision of scientific publications about the state of the art concerning the use of critical raw materials to manufacture renewable technologies.
- To make a revision about the metal composition (g/vehicle) of different kind of vehicles: ICEV, PHEV and BEV.
- To develop the model to calculate the impact in metal demand caused by the future repowering of green technologies.
- To develop the model to calculate the recycling rate evolution to avoid any metal shortages.
- To compare current reserves and resources with expected cumulative demand for each studied metal (risk categories very high and high).

Renewable and Sustainable Energy Reviews 93 (2018) 178–200

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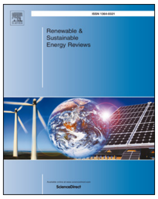

Material bottlenecks in the future development of green technologies

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ABSTRACT

Decarbonizing world economies implies the deployment of “green technologies”, meaning a renovation of the energy sector towards using renewable sources and zero emission transport technologies. This renovation will require huge amounts of raw materials, some of them with high supply risks. To assess such risks a new methodology is proposed, identifying possible bottlenecks of future demand versus geological availability. This has been applied to the world development of wind power, solar photovoltaic, solar thermal power and passenger electric vehicles for the 2016–2050 time period under a business as usual scenario considering the impact on 31 different raw materials. As a result, 13 elements were identified to have very high or high risk, meaning that these could generate bottlenecks in the future: cadmium, chromium, cobalt, copper, gallium, indium, lithium, manganese, nickel, silver, tellurium, tin and zinc. Tellurium, which is mostly demanded to manufacture solar photovoltaic cells, presents the highest risk. To overcome these constraints, measures consisting on improving recycling rates from 0.1% to 4.6% per year could avoid material shortages or restrictions in green technologies. For instance, lithium recycling rate should increase from 1% to 4.8% in 2050. This study aims to serve as a guideline for developing eco-design and recycling strategies.

1. Introduction

In the 21st United Nations Framework Convention on Climate Change celebrated on December 2015 in Paris, it was agreed to keep the increase in the global average temperature to well below 2 °C above pre-industrial levels. Besides, it was proposed that global peaking of greenhouse gas emissions (GHG) should be reached as soon as possible [1]. In this respect, the European Commission, via the Joint Research Centre (JRC), is exploring the most effective way to make the European economy more climate friendly. As it was published in the European low carbon economy roadmap, GHG emissions must be cut to at least 80% below 1990 levels and to accomplish this goal, all sectors must contribute [2].

Both, the electric and transport sectors have a great potential to achieve European targets. The electricity power sector has actually the largest potential for cutting down CO_2 emissions and even eliminating them totally by 2050 [3]. On the other hand, the transport sector, and especially private mobility, could reduce its CO_2 emissions by up to 60% in the same time frame [4]. These changes will imply a renovation in the energy sector towards using renewable sources and zero emission transport technologies.

During this transition period, green technologies like wind power, solar photovoltaic or electrical vehicles will be needed. According to the International Energy Agency projections [5], in 2050, installed power of wind and solar technologies[1] is expected to reach 2208 GW and 2613 GW, respectively in the Reference technology scenario and 3280 GW and 1739 GW, respectively in the 2 °C scenario. Yet this transition must be carefully accomplished as huge amounts of raw materials are going to be required, increasing the pressure on raw material availability.

Wind power demands important amounts of rare earth elements (REE) like neodymium and dysprosium to build permanent magnets for electric generators [6,7] and some studies have shown that demand of both elements might increase by 700% and 2600%, respectively, in the next decades [8]. Additionally, solar photovoltaic demands high quantities of silver for electrical connections, and other materials like

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Abbreviations: **BEV**, Battery Electric Vehicle; **CdTe**, Tellurium Cadmium; **CIGS**, Copper, Indium, Gallium, Selenium; **CM**, Critical raw materials; **CRS**, Central Receiver System; **CSP**, Concentrated Solar Power; **d**, material demand; **D**, cumulative material demand; **EV**, Electric Vehicle; **GHG**, Greenhouse gases; **ICEV**, Internal Combustion Engine Vehicle; **LDV**, Light Duty Vehicle; **LIS**, Lithium ion-sieve technology; **m**, studied technologies; **t**, studied years; **N**, manufactured units; **Nns**, new units added to the global market; **Nrn**, units manufactured to renew installations; **PHEV**, Plug Hybrid Electric Vehicle; **PT**, Parabolic Trough; **PV**, Photovoltaics; **R**, reserves or resources; **r**, material share from recycling; **Re**, recycling quote; **REE**, Rare Earth Elements; **RES**, resources; **RSV**, reserves

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[1] Solar power technologies includes solar photovoltaic and solar thermal power.

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cadmium, tellurium, or indium are used for manufacturing p-n junctions in solar thin film technologies like CIGS or CdTe [9–11]. Solar thermal power (STP) requires also silver for manufacturing reflectors or nickel and molybdenum for manufacturing high strength steel alloys needed in structures [12].

In the field of mobility, Light Duty Vehicles (LDV) based on internal combustion engines will be progressively replaced by vehicles based on electromobility. For instance, it is expected that Plug Hybrid Electric Vehicles (PHEV) and Battery Electric Vehicles (BEV) world sales will surpass Internal Combustion Engine Vehicles (ICEV) sales in 2029 and 2038, respectively [13]. This new generation of vehicles will require more electrical and electronic devices, which will demand materials like neodymium, praseodymium and dysprosium to build permanent magnets [14] and silver, indium, tantalum or lanthanum for electronic components [15]. Besides, electromobility will bring the development of high capacity batteries, which in turn will increase world lithium demand [16,17] and with it prices [18] as well as demand for other commodities such as nickel or cobalt [19,20].

On the other hand, current recycling rates of some of these materials are almost negligible because more often than not the specific required recycling processes do not pay off. That is the case for indium, gallium, cadmium and tellurium in solar modules [21]. Indeed, and even if it has been demonstrated that recycling has a huge improving potential by including pre-recycling processes to recover the metals, current recycling rates are still very low [22]. For instance, less than 3% of the lithium contained in a battery is currently recycled [23] and only 42% of the total battery waste mass can be recycled with current available technology [24]. And even if at least 95% of a car's weight must be recycled or recovered, this only covers the most common metals such as iron, aluminum and copper [25]. As a result, the concern regarding the impact of green technologies on raw material availability is becoming an important issue for countries aiming at guaranteeing their sustainability [26,27] and for the development of green technologies [28,29].

The criticality of materials has been extensively studied using different points of view. These assessments can include several dimensions related to vulnerability, economic importance, supply or ecological risks [30,31], being one of the most relevant the one provided by the European Commission, recently updated [32,33]. Most of these factors are very influenced by geopolitical and socioeconomic elements. This is why critical raw materials (CRM) lists need to be constantly updated. In this respect, geological availability could constitute a more stable factor. Still, as it currently depends on demand, exploration efforts and technological progress, all of which related to the economic interest of the commodities, it also presents a high level of incertitude.

Historically, fluctuations and shortages in demand have generated increases both in price and in geological exploration. One of the most recent examples of mineral shortages can be found in China, with REE trade restrictions that took place during the 2005–2012 period [34,35]. Another example was associated to cobalt production in the early 1970s. Due to political instability of the Democratic Republic of Congo, mining activities were slowed down while demand increased sharply. Besides increasing market prices, this situation also triggered the search for alternatives, such as reducing the use of cobalt or finding substitutes in key applications [36].

Leaving questions related to geopolitical risk aside, material constraints from a geological point of view can be assessed by comparing future demand with current production capacity [37,38] or by comparing reserves with production capacity [39]. Nevertheless, these approaches consider that production is static and that it does not change over time, a trend that has been proven wrong over the years.

Thus, it is an interesting first approach but a dynamic behavior must be incorporated to provide more realistic values. For instance, in the case of the energy sector, models that provide dynamic data, like TIMES-MARKAL or LEAP, can be used to assess the impacts related to fossil fuel supply, emissions and encourage the development of energy policies [9,40–42].

As for non-fossil fuels, several dynamic models have been developed for specific minerals, such as copper [43], lithium [44] or aluminum [45], that rely on information regarding ore grade, production rates or market prices, among other factors, to make future predictions. However, these models need very specific data, definition of variables and functions to estimate future projections, which partly need to be based on numerous assumptions.

Indeed, creating a model that estimates future raw material production is a challenge. Nevertheless, in the case of fossil fuels, the Hubbert peak methodology is admitted as a useful and reliable model [46–48] and has also been applied to non-fuel minerals [49]. This approach considers that production evolution is a function of reserves (or resources), therefore production is not considered to be constant. Obviously the model has weaknesses related to data availability and to unpredictable changes in future production, as it presents a business as usual scenario [50]. That said, it is more reliable than those models which consider a constant yearly production.

To assess raw material constraints related to the growth of green technologies, this paper presents a methodology that identifies possible bottlenecks based on: 1) cumulative raw material demand with current available reserves and resources and 2) expected raw material demand and raw material production projections. With this approach, it is possible to identify which materials could create constraints in the medium to long term for each green technology analyzed. Once this task has been carried out, the recycling improvements that should take place before 2050 to avoid these constraints are calculated.

This information can then be used to promote possible alternatives related to increase geological knowledge, substitutability, investment in new technologies to increase recycling rates, etc. It should be stated that it is not the intention of the authors to propose a new CRM list, but rather to point out which green technologies might be at risk of not achieving current deployment targets due to possible raw material supply shortages.

2. Methodology

When talking about green technologies, many types of technologies come into play, from solar power to geothermal. In this paper, the green technologies considered are: wind power, solar photovoltaic (PV), concentrated solar power (CSP) and the mobility sector, with special emphasis on Electric Vehicles (EV) including Plug Hybrid Electric Vehicles (PHEV) and Battery Electric Vehicles (BEV). For this endeavor, the identification of bottlenecks is done using a combination of bottom-up and top-down approaches, defined as follows:

- Bottom-up approach**:** assessment, on a global basis, of the reserves, resources and estimated production trends from 2016 to 2050 for each commodity (assuming a Hubbert-like production trend).
- Top-down approach: assessment of material requirements for manufacturing green technologies assuming state of the art developments and competition for materials with the rest of sectors, in the 2016–2050 time period.

2.1. Bottom-up

As extraction is ultimately limited by the amount of minerals present in the crust with sufficient concentration, it is important to identify raw material availability in terms of reserves and resources.

According to the USGS (United States Geological Survey), resources (RES) are concentrations of naturally occurring materials on the Earth's crust in such form that economic extraction is currently or potentially feasible. Reserves (RSV) in turn are the portion of resources which can be economically extracted or produced at the time of determination. Reserves figures are thus lower than resources and more dynamic, since identified resources can be reclassified as reserves when commodity prices rise or when there is a decrease in production costs. Different sources have been compared, first using global databases (i.e. USGS [51]) and then analyzing books and scientific papers that focus on certain elements for comparative purposes [52–55]. Those considered more accurate have been used in this paper. For instance, information regarding reserves and resources of rare earth elements (REE) comes from [51,56].

As annual production rates need to be synchronized with the rising demand of materials, projections regarding future raw material production are equally required. In this paper it is assumed that material production will follow the Hubbert peak model. Hubbert [57,58] showed that trends in fossil fuels production always followed the same pattern. The curve of production started to increase slowly before rising steeply and tending towards an exponential increase over time. This trend goes on until reaching an inflection point, upon which the curve starts to decrease, generating a bell-shaped curve of normal distribution. The area below the curve depends on the combination of the available reserves or resources and historic production data of the commodity. Production of commodity a in year t is given by Eq. (1):

$$p_a(t) = \frac{R}{b_0\sqrt{2\pi}}e^{-\frac{1}{2}\left(\frac{t-t_0}{b_0}\right)^2} \tag{1}$$

where R are the reserves (RSV) or resources (RES) of the commodity and parameters b_0 and t_0 are the unknowns. The function's maximum is given by parameter t_0, and it verifies that:

$$p_a(t_0) = \frac{R}{b_0\sqrt{2\pi}} \tag{2}$$

With this approach, the maximum production peak of the commodity can be obtained, meaning the year when production starts to decrease. Additionally, future yearly projections of production can be obtained using a business as usual scenario. Using this methodology it is presumed that production will continue with an exponential growth, as it has been the case for most commodities (see Figs. 1 and 2). Yet geological availability in form of reserves or resources will prevent at some point further growth.

2.2. Top-down

For the top-down approach, the use of critical raw materials in each green technology has been assessed by reviewing more than 50 scientific papers regarding materials used in each technology. Regarding material demand, it was considered that a certain amount of raw materials comes from recycling processes. As the available information on recycling rates is usually very aggregated or general, the recycling rates used in this study come from the United Nations Environmental Program [59], and are listed in Appendix A. Eq. (3) shows how material demand in the studied green technologies is calculated for a given year for each commodity:

$$d_{agt} = \left[\sum\nolimits_{i=1}^{i=m} N\cdot M\cdot(1-r)\right] \tag{3}$$

where d_{a_gt} is the quantity of primary material a demanded for the analyzed green technologies (gt) during a given year; N is the number of yearly manufactured units of each technology; M is the quantity of material a demanded by each technology to manufacture one functional unit – FU (for renewables, FU = 1 MW; for passenger cars FU = 1 vehicle); r is the share of material which comes from recycling and m is the number of studied technologies.

The impact of recycling on primary production is assumed as one-to-one displacement because reprocessing does not change material properties. It should be stated though that, as Geyer et al. [60] demonstrated, this approach is not a rule because rebound effects in demand could appear. Therefore robust models to predict the impact of recycling on primary demand must be still developed.

As the projections presented in this study go until 2050 and the technology lifetime is lower, material demand from renovation and repowering activities in renewable energies and passenger vehicle fleet must be considered. This effect is taken into consideration using Eq. (4).

$$N = N_{ns} + N_{rn} \tag{4}$$

where N_{ns} is the number of new units which are added to the global market and N_{rn} is the number of units manufactured to renew old installations.

The studied "green" technologies will have to compete for materials with many megasectors such as construction, chemicals, metal industry or electronics. For instance, 17% of gallium is used in the solar sector and the remaining is used in integrated circuits, LED, alloys, batteries and magnets [33]. In this respect, the expected boom of the internet of things will be an important competitor for many essential metals in the renewables sector. For this reason, material demand for other sectors must be taken into account in the analysis. Unfortunately, information regarding material consumption in other sectors is scattered and in many cases not available. Consequently, in this paper it is assumed that material demand for other sectors (d_{a_os}) will be constant until 2050

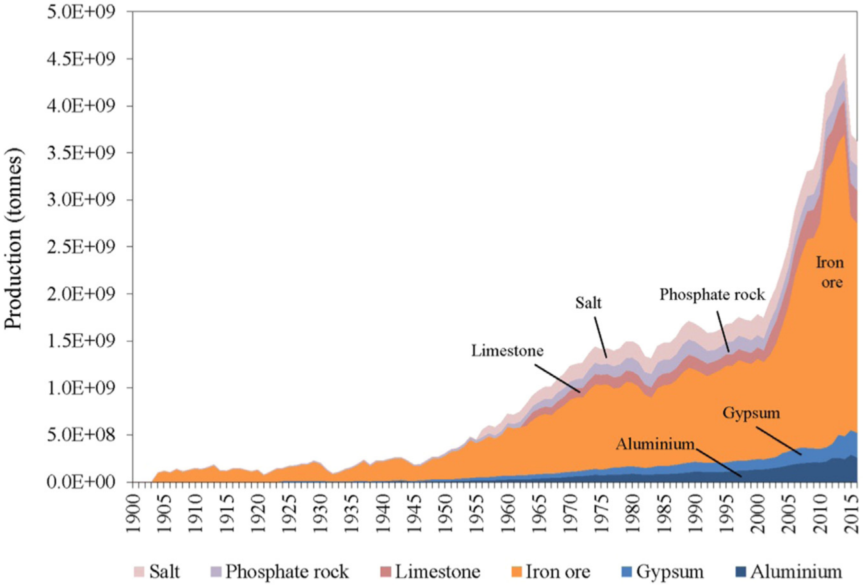

Fig. 1. Cumulative production of most common minerals throughout the 20th century and beginning of the 21st century. Own elaboration from USGS data.

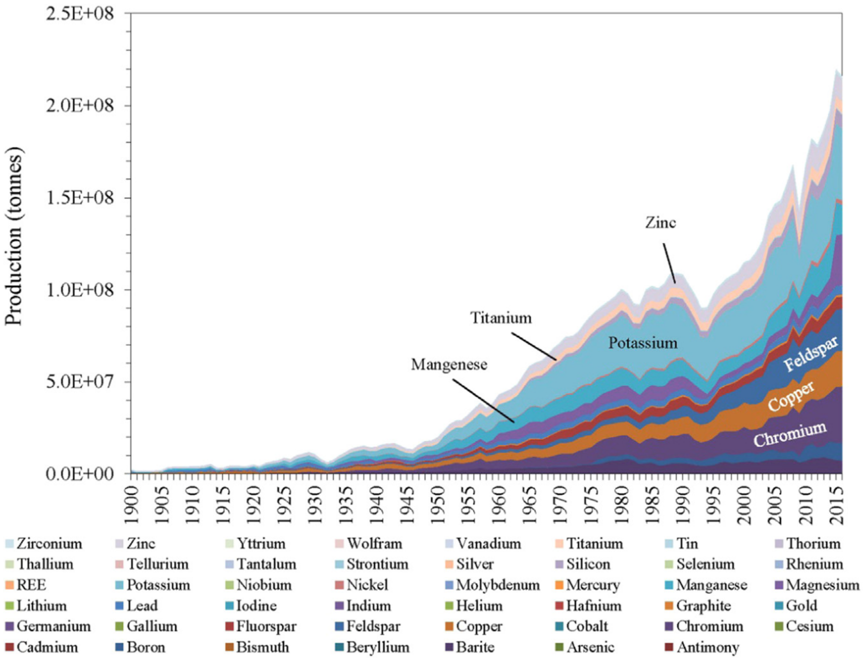

Fig. 2. Cumulative production of certain minerals, excluding those of Fig. 1, throughout the 20th century and beginning of the 21st century. Own elaboration from USGS data.

and equivalent to the difference between total material production in 2015 $(P_a)_{2015}$ and material demand for green technologies for that same year $(d_{a\_gt})_{2015}$ (Eq. (5)). Obviously, this is a very conservative assumption as historically material demand for other sectors has usually increased year by year. That said, this assumption allows us to identify the lower boundary for potential material constraints regarding material competition of green technologies with other sectors.

$$d_{a\_os} = (P_a)_{2015} - (d_{a\_gt})_{2015} \tag{5}$$

Accordingly, total material demand for a given commodity a in year t $(d_{a_T})$is calculated by means of Eq. (6), whereas the total cumulative material demand for commodity a (D_{a_T}) from 2016 to 2050 is obtained through Eq. (7).

$$(d_{a\_T})_t = (d_{a\_gt})_t + (d_{a\_os})_{2015} \tag{6}$$

$$D_{aT} = \sum_{t=2016}^{t=2050} [(d_{aT})_t] \tag{7}$$

2.3. Identification of bottlenecks

This methodology combines reserves, resources, production and demand data, so as to determine possible constraint risks. Three risk categories have been defined for the cumulative demand and annual production of the selected materials: very high, high and medium. This approach considers expected projections of green technologies, recycling rates of metals (assumed as constant), as well as metal demand for the rest of the sectors, as shown in Table 1.

Table 1
Risk types and definitions.

Risk type	Definition
Very High	2016–2050 cumulative demand ≥ current resources $(D_{a\_T} \geq RES_{2015})$
High	2016–2050 cumulative demand ≥ current reserves $(D_{a\_T} \geq RSV_{2015})$
Medium	Annual demand ≥ annual primary production $((d_{a\_T})_t \geq (p_a)_t)$

The first and most restrictive constraint is associated with cumulative production surpassing available resources. This is because, as stated before, the amount of resources is an indication of the availability of a given commodity in the crust that could be potentially extracted now or in the future.

The second one is related to reserves instead of resources. Note that reserves relate to that portion of resources that can be recovered economically with the application of extraction technology available currently or in the foreseeable future. It should be pointed out that reserves data are dynamic, as they can change with technology, prices, discovery of new deposits, among other factors. Therefore, results obtained with these data have to be considered as an indication rather than as a fact. Then, as reserves data are more dynamic, a bottleneck based on reserves can be considered less critical than one based on resources.

The third constraint is associated to isolated supply shortages. This is assessed with the information coming from the bottom-up and the top-down approaches, through the intersection between future demand and future production estimations. For instance, using nickel expected demand in electric vehicles and other sectors, and nickel estimated production using the Hubbert model approach, a possible bottleneck can be identified beyond 2027 as shown in Fig. 3.

As for the previous constraint, it must be pointed out that any successful prediction obtained using the Hubbert model depends on many different factors, such as the reliability of the estimated reserves and resources data, which can delay the peak several years if these increase [61]. A conservative approach is considered in this study, using resources and not reserves data for fitting Hubbert peaks. The nature of the commodities and their production processes are also an important factor in the reliability of the Hubbert peak model. For instance, in [62] it was shown how the production of primary metals such as iron, aluminum or copper can be well fitted to a bell-shaped curve, whereas those elements obtained as by-products or co-products have significantly poorer fits. For this reason, from the three mentioned constraints, this last one can be considered as the least critical of all, since future production trends have a high uncertainty level and as long as there are enough reserves, markets can almost always (to a certain level) adjust their production.

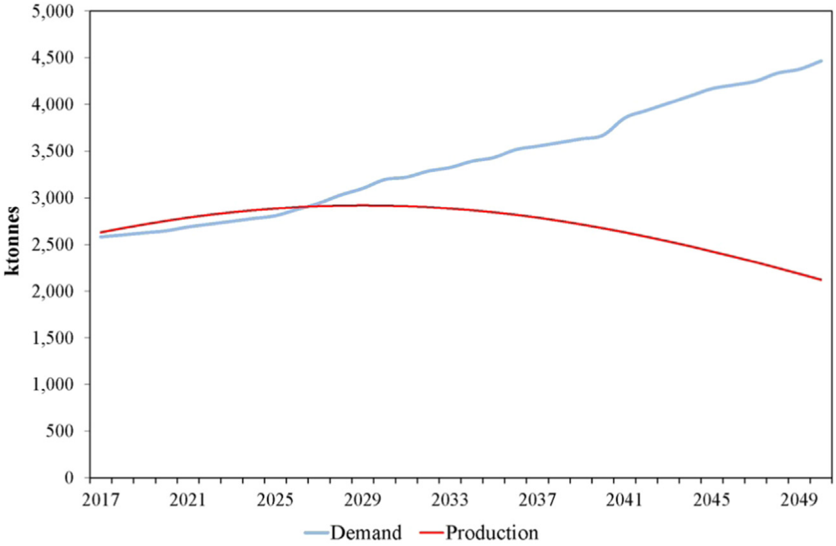

Fig. 3. Identification of possible bottlenecks using bottom-up (production) and top-down (demand) combination approaches for the case of nickel. In this case, the bottleneck takes place beyond 2027.

2.4. Recycling improvements

There are many ways to overcome identified bottlenecks. In addition to increasing material supply (i.e. investment in exploration efforts to increase reserves and eventually resources), from the demand side, change of technologies, improving material efficiency or substitution of materials for a given application or technology (i.e. bio-based materials for metals) are some possible options. It should be though not forgotten that substitution can, in some cases, reduce product performance or even increase prices [29]. An alternative way to overcome a certain identified bottleneck is by increasing recycling rates. The annual recycling growth needed to avoid that annual demand exceeds annual production in any year until 2050 is calculated with Eq. (8).

$$Re_f = Re_i*\left(1+\frac{r}{100}\right)^{f-i} \tag{8}$$

Where Re is the recycling quote of a given metal in a year, f and i are final and initial years and r is the annual growth recycling rate (%) with respect to the previous year.

It should be stated that in reality, a combination of all above mentioned options will likely take place. That said, this method gives an indication of where to encourage recycling efforts.

3. Results

Once all the information regarding reserves, resources, demand in green technologies and metal demand for all sectors have been compiled, bottlenecks for each technology can be identified.

3.1. Green technology's projections

Demand projections for each green technology are shown in Fig. 4. Yearly installed power (Fig. 4a) considers the repowering effect that takes place at the end of life for each technology. For this reason, a change in the tendency can be observed in 2038, a moment at which the first RES installation built at the beginning of the century has to be repowered. The lifetime considered for all renewable technologies is 25 years (CSP [63]; wind power [64]; solar photovoltaic: [65]). Projections of cumulative installed power for each technology (Fig. 4b) have been built using average values obtained from the following information sources:

- Wind Power [66,67],
- Solar Thermal Power [68,69],
- Solar Photovoltaics [70,71].

It is noteworthy that cumulative power will grow linearly up to 2050 for all the studied technologies with similar growth rates. The technology that will have a larger share in 2050 will be solar photovoltaic with more than 3500 GW, followed by wind power, with 2500 GW, and finally solar thermal with nearly 900 GW.

For each renewable source of energy, different types of technologies can be selected. In the case of wind power two main types of wind turbines have been considered: model 1, with gearbox, and model 2, gearless, each with a constant market share of 75% and 25%, respectively [72]. In the case of solar thermal power, today there are two main commercial possibilities: parabolic trough (PT) and central receptor system (CRS). The share of each technology in the market is considered to be 60% for PT and 40% for CRS [69]. In the case of solar photovoltaic, a market mainly dominated by crystalline technologies, the share considered is 85%, with thin film technologies contributions (CIGS, CdTe and a-Si) of 5% for each one of them [38].

In the case of light duty vehicles, the world fleet evolution and the sales projections by type of vehicle (Figs. 3c and 3d, respectively) have been represented according to information published by ANFAC and IEA [13,73]. In 2050 a world fleet of near 1500 million of LDV is expected. Among them, ICEV will represent 21% of the fleet, PHEV, 45% and BEV, 33%. ICEV sales will decrease from 2016 in favor of PHEV sales.

Additionally, BEV sales will mainly grow from 2025 onwards and in 2045 their sales will be even greater than PHEV. Considering these projections shown in Fig. 4d, PHEV and BEV total share in the world fleet will be higher than the share of ICEV from 2041 and 2046, respectively.

3.2. Material demand

The assumptions and hypothesis considered to estimate material demand in each green technology throughout the studied time period are fully developed in Appendix B. Prevailing technologies have been assumed and hence materials that are currently used have been considered. Metal demand for the rest of the sectors has been assessed with Eq. (5). Table 2 shows a summary of the estimated cumulative primary material demand by technology and by element from 2016 to 2050.

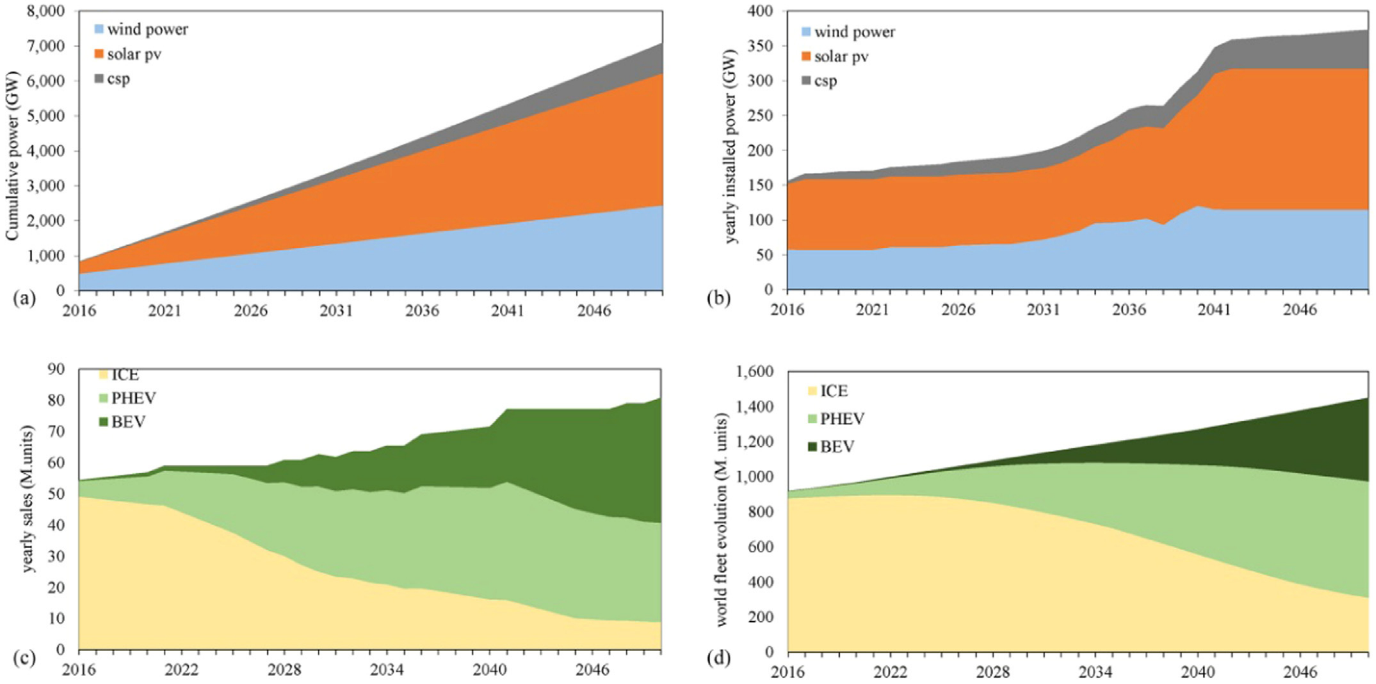

Fig. 4. Demand projections for green technologies: a) yearly installed power and b) cumulative power of wind, solar PV and CSP technologies; c) yearly sales of vehicles and d) world fleet evolution for ICEV, PHEV and BEV.

Wind turbines will basically demand common metals such as aluminum, copper, iron and nickel in huge amounts, along with other scarcer commodities such as dysprosium and neodymium. Solar PV and CSP will demand a greater variety of materials, but EV is the technology that will require more different elements. For instance, among all the technologies analyzed in this paper, gadolinium, platinum group elements, cerium or praseodymium are commodities that will only be demanded in EV. Overall, iron, aluminum, copper and nickel will be the minerals demanded in larger amounts.

Table 2
Cumulative expected material demand from 2016 to 2050 by element and by technology. Data are expressed in ktons.

	Wind	PV	CSP	EV	Rest of sectors	Total
Ag	–	385.57	9.78	28.53	725.87	1149.74
Al	1548.56	–	6070.92	148,355.01	9,974,161.39	10,130,135.88
Cd	–	31.18	–	–	851.29	882.47
Ce	–	–	–	44.14	2180.19	2224.33
Co	–	–	–	4988.46	4172.23	9160.69
Cr	–	–	2203.26	7202.75	1,098,084.62	1,107,490.63
Cu	13,223.52	12,117.75	1707.52	92,311.94	647,903.40	767,264.13
Dy	3.69	–	–	11.82	5.35	20.87
Fe	301,604.65	–	5,194,916.88	557,455.38	79,311,435.17	85,365,412.08
Ga	–	1.28	–	0.99	14.75	17.02
Gd	–	–	–	0.24	42.38	42.62
Ge	–	2.35	–	0.06	4.49	6.90
In	–	17.59	–	0.34	15.91	33.84
La	–	–	–	9.97	1025.70	1035.67
Li	–	–	–	6001.46	20,796.26	26,797.73
Mg	–	148.41	1871.59	–	298,648.37	300,668.36
Mn	–	–	2156.44	5200.17	638,828.94	646,185.54
Mo	–	31.79	93.84	247.65	9556.38	9929.66
Nb	–	–	–	303.02	1984.93	2287.95
Nd	250.52	–	–	844.73	585.12	1680.37
Ni	243.69	3.23	896.69	31,011.55	89,340.09	121,495.26
Pd	–	–	–	0.42	7.42	7.84
Pr	–	–	–	92.77	256.25	349.02
Pt	–	–	–	2.63	7.66	10.30
Se	–	10,777.03	–	–	57,625.96	68,403.03
Sn	–	1680.70	–	–	8646.65	10,327.35
Ta	–	–	–	12.70	41.90	54.60
Te	–	35.04	–	–	3.55	38.58
Ti	–	–	7.08	–	219,239.78	219,246.87
V	–	–	1.78	1173.28	2732.75	3907.81
Zn	–	27.43	724.17	–	481,209.15	481,960.75

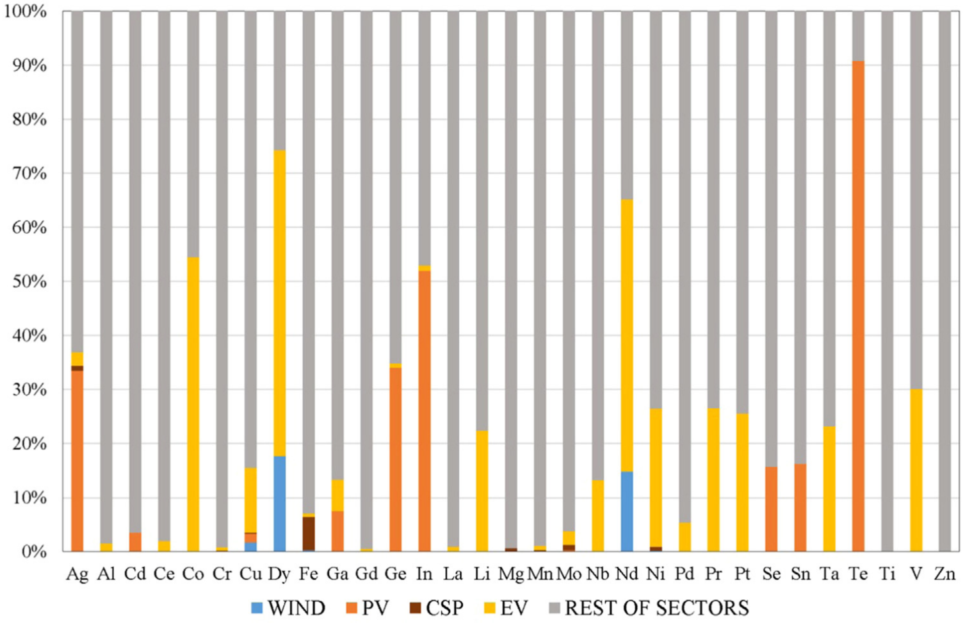

Fig. 5. Material demand share by element and by type of technology. For each element, the cumulative material demand from 2016 to 2050 was calculated so to represent the corresponding share of each technology in the figure.

3.3. Available resources and reserves compared to material demand

The most restrictive constraint takes place when cumulative demand of the technologies analyzed is larger than current resource estimations. To better understand these constraints, one must know the percentage that each technology demands for each studied material, this is represented in Fig. 5. For instance, there are certain elements that are used only in one of the green technologies analyzed, being the rest of the production of this metal used in other sectors. An example is the case of lanthanum which is used in vehicles to manufacture electrical and electronic components but also in fiber optics, high intensity lighting and high sensitivity sensors.

Combining Fig. 5 with Fig. 6, one can better understand which technologies present more risks related to material constraints. Fig. 6 shows the obtained cumulative demand of metals from 2016 to 2050 and their associated current resources and reserves. This figure is represented in logarithmic scale so that all materials can be represented in a single diagram. Using silver as an example, over 1 million tons could be needed from 2016 to 2050, as seen in Fig. 6. Approximately, 34%, 2.5% and 0.9% will be needed in PV, EV and CSP, respectively, being the rest used in other sectors (Fig. 5).

Fig. 6 also provides valuable information regarding cumulative production and availability (reserves and resources). As it can be seen, demand may exceed available reserves in the cases of silver, cadmium, cobalt, chromium, copper, gallium, indium, lithium, manganese, nickel, lead, platinum, tellurium and zinc. Nevertheless, when comparing demand with resources information, demand only may exceed resources in the case of tellurium. Still, it is important to mention that reserves

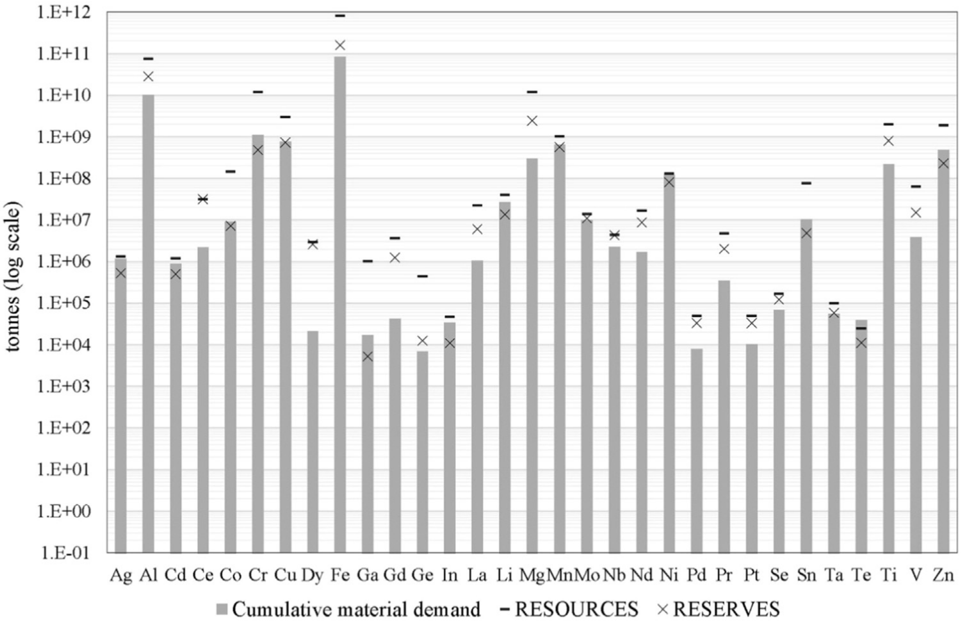

Fig. 6. Comparative analysis between cumulative material demand by element from 2016 to 2050 with material reserves and resources data (vertical axis is in logarithm scale).

and resources information for tellurium are usually inaccurate or incomplete as it is a by-product mainly obtained during copper and lead-zinc refining processes.

Table 3
Maximum production peaks and bottlenecks (year where demand exceeds production) calculated with resources data.

Metal	R2	Production peak	Expected bottleneck time period
Se	0.83	2008	2016–2032
Ni	0.95	2033	2027–2029
Dy	0.95	2219	2029–2034
Co	0.90	2142	2030-beyond 2050
Ag	0.71	2025	2031–2042
Ta	0.83	2039	2033–2050
Nd	0.96	2105	2034–2041
Te	0.46	2065	2035-beyond 2050
Mo	0.94	2030	2038–2042
Mn	0.84	2030	2038–2050
In	0.98	2032	2041
Li	0.92	2037	2042–2045
Sn	0.71	2086	2042-beyond 2050

3.4. Annual demand and production comparison

By means of the bottom up approach explained in Section 2.1, data of maximum production peaks using resources data have been calculated (Table 3). For the materials shown in Table 3, estimated demand exceeds production before 2050, therefore a possible bottleneck can be identified. Materials are arranged according to the nearest identified bottleneck year. The reliability of Hubbert-peak functions is also shown. This reliability factor has been used to calculate the time period in which bottlenecks could appear, having as lower boundary the intersection between supply and demand curves and the upper boundary the resulting year obtained from dividing the intersection year by R2. This way, a conservative approach has been assumed, since theoretical

Table 4
Studied elements with technologies were they are used and risk classification. Elements highlighted in grey fall into the "very high risk" and "high risk" categories, where cumulative demand from 2016 to 2050 exceeds resources and reserves, respectively.

	Type of Risk			Technology affected			
	Very high	High	Medium	Wind	PV	CSP	LDV
Ag		●	●		x	x	x
Al				x		x	x
Cd		●			x		
Ce							x
Co		●	●				x
Cr		●				x	x
Cu		●		x	x	x	x
Dy			●	x			
Fe				x		x	x
Ga		●			x		x
Gd							x
Ge					x		
In		●	●		x		x
La							x
Li		●	●				x
Mg					x	x	
Mn		●	●			x	x
Mo			●		x	x	x
Nb							x
Nd			●	x			x
Ni		●	●	x	x	x	x
Pd							x
Pr				x			x
Pt							x
Se			●		x		
Sn		●	●		x		
Ta			●				x
Te	●	●	●		x		
Ti					x		
V						x	x
Zn		●		x	x		

Table 5
Comparison between the elements with very high and high risk in this study with other criticality assessment reports. These reports may have considered critical other elements that are not shown on this table.

	Bae [71]	Angerer et al. [78]	JOGMEC [79]	APS [80]	Resnick Institute [81]	DOE [82]	Moss et al. [28]	EC (2010) [85]	EC (2014) [33]	EC (2017) [32]	UKERKC [83]	BSGS [76]
Ag		●		●	●		○				●	◐
Cd					●		○					◐
Co	◐	●	●	●	●	○		●	●	●	●	●
Cr	◐		●						●			○
Cu	○	●										○
Ga	●	●	●	●	●	○	●	●	●	●	●	●
In	●	●	●	●	●	○	●	●	●	●	●	●
Li	●		○	●	●	◐					●	●
Mn	◐		●			○						○
Ni	●		●			○	○					○
Sn		●					◐					○
Te				●	●	◐	●				●	
Zn	○											○

• = high risk, ◐ = medium risk, ○ = low risk. When there is no categorization available, the risk has been considered high. In the case of the BGS [76] risk list, values from 4.8 to 6.5 have been considered low risk, 6.6 to 7.5 medium risk, and higher than 7.6 high risk.

Table 6
Current recycling rates, annual growth and 2050 recycling rate that would be needed to avoid constraints in the case of materials that belong to the medium risk category (where annual demand exceeds annual expected production).

	Current recycling rate	Annual growth	2050 recycling rate
Ag	30%	0.6%	37%
Cd	25%	1.3%	39%
Co	32%	1.8%	59%
Cr	20%	2.5%	47%
Dy	10%	0.9%	13.7%
In	37.5%	0.5%	44.7%
Li	1%	4.6%	4.8%
Mn	37%	0.1%	38%
Mo	33%	0.7%	42%
Nd	5%	0.1%	5.2%
Ni	29%	1%	41%
Se	5%	2%	10%
Sn	22%	0.1%	22.8%
Ta	17.5%	0.1%	18.2%

peaks usually appear before real ones [62]. Appendix C shows the Hubbert curves for those materials affected by this constraint.

In the cases of cobalt, neodymium and dysprosium, bottlenecks appear when both curves (production and demand) still have growing tendencies. For these cases, the bottleneck would be a problem of supply rather than scarcity, as it can be seen in the curves of Appendix C. Yet, it must be noted that other sectors demand has been considered constant and this assumption is especially conservative for the mentioned elements. Such metals are used to manufacture permanent magnets (neodymium and dysprosium) and NCA batteries (cobalt), used for other applications like electric bikes, hard disks for laptops or batteries for mobile phones whose demand is expected to significantly increase in the future [74,75].

In the case of tellurium, if the R2 accuracy is considered, the bottleneck could appear beyond 2050, but the accuracy is the lowest one (0.46). For this reason, projections regarding production have an important level of uncertainty with respect to other elements. Nevertheless, tellurium already falls in the very high risk category considering that cumulative demand surpasses resources, as it was shown in Fig. 6.

Noteworthy is the case of selenium, which is mainly used in CIGS PV technology. The theoretical peak is reached even before 2016, hence the bottleneck appears from that moment onwards. Yet it should be stated that, as it happens with tellurium, selenium is obtained as a by-product of copper extraction. Consequently, its production projections will depend on copper mineral extraction and hence Hubbert peak reliability is low.

3.5. Raw material constraints summary

Table 4 summarizes all the studied materials and their risk classification. The sole material with a very high identified availability risk is tellurium. At high risk are silver, cadmium, cobalt, chromium, copper, gallium, indium, lithium, manganese, nickel, tin and zinc. Finally, materials which only fall in the moderate future availability risk category are dysprosium, molybdenum, neodymium, selenium and tantalum, as their annual demand may exceed annual production before 2050.

It should be noted that cadmium, chromium, copper, gallium and zinc fall into the high risk but not into the medium risk category. This happens in those materials in which the difference between reserves and resources is notable. For the mentioned metals the ratios between proven resources and reserves are 2.4; 25; 4.2; 192 and 8.3, respectively. Accordingly, cumulative demand is greater than reserves but production projections based on available resources is always greater than expected demand. If projection demand had been assessed with reserves instead, all medium risk metals would fall in the high risk category.

Even if the main goal of this paper is not to create a list of critical materials, it is interesting to carry out a comparison between the list of elements that could generate bottlenecks in the development of green technologies with already published criticality assessment papers and reports (Table 5). All of the 13 identified elements with very high or high risk to generate bottlenecks have been classified as critical in some studies, but not all of them altogether. For instance, in the case of the risk list carried out by the British Geological Survey [76], all except tellurium are included, but the categorization is different for each element. The methodologies used in each criticality assessment usually take into account the same factors used by other authors [28,33,76–83] but with different weights, production concentration, recycling rates, technologies, substitutability, governance, environmental standards of the producing countries, among others. The main difference with the approach used in this paper is that we are considering not only the use of those elements in green technologies and in other sectors but also the geological availability using reserves and resources data compared to the estimated future production trends. Usually these aspects are not addressed in criticality assessment reports.

As an example, chromium, copper, nickel or zinc, which have been identified as presenting high risk in this paper, have low risk according to the BGS report. Additionally, silver and nickel have a high risk in this present study, but in Moss et al. [28] they both have a low overall risk. Copper is not usually classified as a critical element in any of these studies except in Angerer et al. [78] and Bae [77], but it is indeed used in all of the green technologies analyzed in this paper, and therefore very important to transition towards a low carbon economy. Noteworthy is the case of chromium, which was considered critical by the European Commission in 2014 [33] but not in their 2017 report [32]. Still, some of the elements that in this paper were identified to generate bottlenecks, such as cobalt, gallium and indium, are considered critical in almost all of the analyzed reports, emphasizing their relevance in this and in other sectors of the economy [84].

3.6. Recycling improvements

As stated before, a way to overcome supply bottlenecks is through increasing recycling rates. Note that recycling improvements to avoid high and very high risks are not calculated because in these cases, the problem is not caused by supply shortage but by geological scarcity. In such cases, if expected demand does not change, the most effective way to overcome bottlenecks is to invest in exploration to increase geological knowledge. This is because recycling can never achieve 100% efficiency due to second law of thermodynamics restrictions, and even if it were possible, exponential growth in demand makes that primary production will always be required to offset the rocketing demand.

Table 6 shows the growth in recycling rates that would be needed in order to avoid that annual demand surpasses annual production in a business as usual scenario (i.e. without considering substitution of technologies or materials and considering that reserves and resources do not increase). Table 6 also shows the current recycling rates and the values that would be reached in 2050 at this growing speed.

The highest growths correspond to lithium, chromium, cobalt and cadmium with annual growth rates of 4.6%, 2.5%, 1.8% and 1.3%, respectively. The case of lithium is of special relevance because of its notable future importance for storage systems and the low current recycling rate, which is below 1%. It is also noteworthy how relatively small recycling efforts could avoid the appearance of bottlenecks for certain materials such as manganese, neodymium or tin, which would require annual growths of around 0.1%, or silver or dysprosium, of less than 1%.

That said, recycling would be mainly based on minor metals recovery (cobalt, REE, lithium, tellurium, indium and silver among others). These minor metals began to be used in industrial applications only thirty years ago and there is a lack of information regarding recycling process efficiency [62]. Indeed, these metals have special properties which need complex recovery processes and when mixed, the recovery route of one set of metals may impede that of co-existing ones. Moreover, recycling processes have their own limits from a thermodynamic point of view, a fact that was named by Valero and Valero [62] as “entropic backfire”. This term describes how in all real processes the specific separation of components from a recyclate creates waste which is at each successive step, more difficult to salvage. Indeed, recycling never achieves 100% material recovery [86] and as a result there are unavoidable losses, as stated by the second law of thermodynamics, ending in landfills, dissolved or diluted in alloys in the case of metals [87].

Alternative solutions to recycling from the demand side are substitution, dematerialization or resource efficiency and most likely a combination of all, together with increases in reserves, will take place.

4. Discussion

Considering the green technologies analyzed, electric vehicles will probably demand the largest quantities of critical materials. Constraints are mainly focused on metals for battery manufacturing such as lithium, cobalt and nickel, which fall in high and medium risk categories. Additionally, there could be constraints regarding manufacturing of steel alloys that need chromium or molybdenum and with certain electric and electronic equipments, which require neodymium, dysprosium, silver, copper or tantalum.

In the case of solar photovoltaic, along with large quantities of silicon [88], an element not considered in this study, it will demand materials such as indium, silver, selenium, tin and tellurium. In these cases, the cumulative demand expected for 2016–2050 may exceed current reserves and in the case of tellurium, it may also exceed current resources. Still, the reliability of reserves and resources data of these commodities creates an important level of uncertainty. For instance, in the case of tellurium, further studies should be carried out focusing on increasing geological knowledge but also focusing on increasing recovery from existing copper producers [10].

As for CSP, it demands silver, copper, nickel and molybdenum, among others. Silver is used to build high performance solar glasses, while nickel and molybdenum are used for high strength steels and copper mainly for electric grids. These elements fall into the high risk category with the exception of molybdenum which is in the medium risk category.

Last, in the case of wind power, the highest risks are associated to the use of permanent magnets, as they require neodymium and dysprosium. Nevertheless, it must be taken into account that copper constraints could also affect this technology mainly for the demand needed to build electric distribution grids.

As stated before, in this study, demand in other sectors has been assumed constant until 2050. This is an optimistic scenario since if population grows to 9700 M inhabitants before 2050 [94], other sectors demand will most likely grow and even spiral up. This means that material constraints could appear sooner than expected, since green technologies will need to compete against other sectors whose demand will equally increase even at an exponential rate.

Still, some of these constraints might be partially overcome at least by substituting certain elements in each green technology. For instance, in the case of wind turbines, rather than using permanent magnets, wound-rotor generators can be used. Additionally, some research projects from all over the world are also trying to decrease the use of REE in green technologies or look for alternatives [89,90]. Indeed, this issue is also being considered by different companies. General Electric (GE) has developed their own methodology to identify materials that could present constraints throughout the production process in turbines engines [91]. In that study, rhenium used in super alloys, was used as a case study and measures related to the reduction of usage of rhenium, collecting scrap or recovery were analyzed. Further studies have been undertaken by other companies, such as Rolls-Royce or Volkswagen [92,93].

5. Conclusions

To reduce emissions and to move towards a complete low carbon economy, green technologies must be promoted. However, to manufacture them, many critical elements are needed and, as seen in this paper, raw material availability can produce restrictions and bottlenecks that should be avoided. Having a better understanding of what materials are used in each green technology might become critical from a supply side point of view and can favor the promotion of policies related to recycling, substitution, or material efficiencies able to prevent those bottlenecks.

Analyzing the materials used in the selected green technologies (solar photovoltaic, concentrated solar power, wind power and electric and hybrid vehicles) different constraints have been identified regarding material demand and available reserves, resources and future primary production.

Current green technologies depend on certain materials whose risks have been classified as very high, high or medium. Materials which present a very high risk are those where cumulative demand from 2016 to 2050 exceeds resources (tellurium). With high risk are those where cumulative demand surpasses reserves (silver, cadmium, cobalt, chromium, copper, gallium, indium, lithium, manganese, nickel, tin and zinc). Medium risk commodities are those whose demand might at some point exceed production before 2050 (silver, cobalt, indium, lithium, manganese, molybdenum, dysprosium, neodymium, nickel, selenium, tin, tantalum and tellurium). Technologies which are affected by these bottlenecks are solar photovoltaic, with indium, gallium, selenium, tellurium and silver requirements, electric vehicles, that need cobalt, lithium, molybdenum and gallium among others, wind power which demands permanent magnets (i.e. REE) and solar thermal power that requires silver and molybdenum.

Moreover, considering each specific green technology, it is noteworthy that not all available commercial products have the same impact on raw materials. For instance, for wind power, the demand of permanent magnets is lower in the case of turbines with gearbox. Additionally, in solar cells the demand of critical materials is lower in crystalline silicon technologies than in thin film technologies. In solar thermal power systems, a parabolic trough contain less “risk materials” than a central receiver system and so does PHEV with respect to BEV due to the lower material demand to manufacture batteries.

Therefore, if current material demands and recycling quotes continue in a business as usual scenario, the transition towards a low carbon economy will be threatened by the availability of certain commodities. This issue should be analyzed in depth to define appropriate strategies that avoid the mentioned bottlenecks.

These strategies might be focused on: (1) investments in geological exploration to increase current reserves and resources; (2) to invest in new technologies able to obtain commodities from unconventional sources, i.e. lithium extraction technologies from salt-lake brines and sea water using lithium ion-sieve (LIS) technology; (3) research in the design of green technologies with lower requirements of critical raw materials such as metal-air batteries, generators without permanent magnets or organic photovoltaic solar cells; (4) investing in recycling technologies that are able to recover critical materials based on environmental friendly processes; (5) a combination of all them by means of defining eco-design strategies that reduce the use of critical raw materials and also improve end of life material recovery. This last option would also prevent that critical raw materials end up in landfills, where their retrieval is considerably harder.

A proper strategy must bear in mind the own characteristics of materials and technical specifications of products and process. The thermodynamic limits of recycling, rebound effects in raw material demand caused by recycling improvements and the fact that substitutability between materials may decrease product performance, increase the price, or both, must not be forgotten.

Finally, as there are important gaps in the mineral statistics at world level, further studies must be made concerning evaluation and characterization of mineral deposits to have better assessments of available mineral resources. Having international standards that can be used by mining companies is a first approach, but other problems related with exploration and technology development must be solved.

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Appendix A. Recycling rates

Table A.1 shows the recycling rates used to estimate the amount of materials which come from recycling instead of from primary resources.

Table A.1
Recycling quotes from studied raw materials.
Source: [59].

Material	Recycling rate (%)	Material	Recycling rate (%)
Ag	30	Mg	33
Al	36	Mn	37
Cd	25	Mo	33
Ce	1	Nb	50
Co	32	Nd	5
Cr	20	Ni	29
Cu	30	Pd	50
Dy	10	Pr	5
Fe	50	Pt	50
Ga	25	Sn	22
Gd	5	Ta	17.5
Ge	35	Te	1
In	37.5	Ti	52
La	5	V	–
Li	1	Zn	22.5

Appendix B. Assumptions to assess green technologies material demand

Wind power

See Appendix Tables B.1–B.3.

Table B.1
List of materials used (in kg/MW) in wind turbines from different authors. Type 1 Doubled Fed Induction Generator and Type 2 Direct Drive Turbine.

Author	Cu	Fe	Al	Nd	Dy	Ni	Model[a]
[95]	–	–	–	150	14	–	2
[96]	1200	148,000	–	–	–	–	1
	5500	98,900					2
[97]	–	–	560	–	–	–	2
[36]	4700	–	–	200	13.3	–	2
[72]	–	120,000	–	195	13	–	2
[98]	1750	89,840	–	–	–	–	1
[82]	–	–	–	186[b]	18	–	2
[99]	2500	–	–	43.2	18	–	1
[100]	1408	–	830	–	–	–	1
[38]	–	–	–	–	–	111 (in steel)	1 and 2

[a] Model 1 with gearbox to transfer power from rotor to generator and Model 2 with a direct power transmission.

[b] 30% of permanent magnets mass.

Table B.2
Copper and iron demand (in kg/MW) in wind turbines, foundation and grid infrastructures.

Author	Material	On shore	Off shore
[101]	Cu	2700	11,500
[102]	Fe	–	120,000 more than on shore

Table B.3
Material requirements by type of turbine and installation (in kg/MW).

	Model 1		Model 2	
	On shore	Off shore	On shore	Off shore
Al	840	840	560	560
Cu	2700	11,500	7000	15,800
Fe	172,100	292,100	112,670	232,670
Nd	60.92	60.92	182.75	182.75
Dy	4.86	4.86	14.58	14.58
Ni	111	111	111	111

Solar thermal power

See Appendix Table B.4.

Table B.4
List of materials used in Solar Thermal Power installations (in ton/GW).
Source: [12].

Material	PT (ton/GW)	CRS (ton/GW)
Ag	13	16
Al	740	23,000
Cr	2200	3700
Cu	3200	1400
Fe	650,000	393,000
Mn	2000	5700
Mo	200	56
Ni	940	1800
Ti	25	0
V	2	2
Zn	650	1400

Solar photovoltaic

See Appendix Tables B.5–B.8.

Table B.5
c-Si material requirements (in kg/MW).

	Authors compilation				
	[28]	[37]	[38]	[103]	Average
Ag	24	19.2	355.9	–	133.0
Cd	–	6.1	–	–	6.1
Cu	2741	2194.1	7597.5	–	4177.5
Ga	–	0.1	–	–	0.1
In	–	4.5	–	–	4.5
Mg	53.5		–	–	53.5
Ni	–		1.1	–	1.1
Se	–	0.5	–	–	0.5
Si	3653		–	9000	6326.5
Sn	577	463.1	–	–	520.0
Te	–	4.70	–	–	4.7

Table B.6
CIGS material requirements (in kg/MW).

	Authors compilation						
	[37]	[38]	[104]	[105]	[106]	[107]	Average
Cd	–	–	–	–	–	1.8	1.8
Cu	21.0	–	–	–	–	16.9	19.0
Ga	2.3	5.0	–	7.5	5.0	5.0	4.9
In	18.9	27.4	15.5	22.5	27.4	27.4	23.2
Mo	–	–	–	–	–	94.3	94.3
Se	9.6	45.3		45.0	45.3	45.3	38.1
Zn	–	–	–	–	–	85.8	85.8

Table B.7
CdTe material requirements (in kg/MW).

	Authors compilation							
	[37]	[38]	[104]	[108]	[105]	[106]	[107]	Average
Cd	–	63.3	–	–	85.0	63.3	49.2	65.2
Cu	–	–	–	42.8	–	–	–	42.8
In	15.9	–	–	–	–	–	–	15.9
Mo	–	–	–	–	–	–	100.5	100.5
Sn	–	–	–	–	–	–	6.6	6.6
Te	–	61.9	55.0	–	97.5	–	47.2	65.4

Table B.8
a-Si material requirements (in kg/MW).

	Authors compilation				
	[38]	[104]	[106]	[107]	Average
Ge	6.9	42.0	6.9	3.4	14.8

Light duty vehicles

See Appendix Tables B.9–B.11.

Table B.9
Compilation of materials used in passenger car vehicles (in g per unit of vehicle) with the exception of Al, Cast Iron, Cu and Steel which are in kg.

Material	Authors compilation									
	[109]	[110]		[9]		[111]		[112]	[113]	[101]
	ICE	ICE[a]	PHEV[b]	PHEV	BEV[c]	ICE	BEV	ICE	ICE	PHEV
Al (kg)						50	200	88.45		
Cast Iron (kg)						50	20			
Ce	81	12.91	0.31							
Co										
Cu (kg)		27	60			25	150			67.5
Dy	27.45	1.96	129.66	210	336					
Er		0	0.18							
Eu	0.45	< 0.01	< 0.01							
Gd	0.36	< 0.01	< 0.01							
Ga		0.42	0.57	1.05	1.68					
Ge				0.05	0.08					
In		0.38	0.08	0.05	0.08					
La	8.1	0	6.68							
Li		1.36	6256.55							
Mo										
Nd	297	27.6	531.88	360	576					
Nb		89.81	109.14							
Pd		1.24	1.81		0.12					
Pt		7.85	5.51							
Pr	30.6	2.47	4.01	120	192					
Rh		< 0.01	< 0.01							
Sa	3.24	0.73	1.4							
Sc	1.13									
Ag		17,5	50	6	9.6					
Steel (kg)					730	790		975.22		
Sr										
Ta		6.99	10.83							
Te	0	0	19.86	21	34					

[a] With medium equipment level.
[b] With medium equipment level.
[c] Original values are published for a 50 kW motor. In the present study, values are adapted for 50 kW and 80 kW motors in PHEV and BEV, respectively.

Table B.10
Material demand for Li: ion NCA batteries (in g). Values adapted to an autonomy of 200 km.

	Authors compilation			
	[117]	[118]	[27]	Average
Li	9.01	7.2	9.3	8.50
Ni	57.40	46.5	58	53.97
Co	10.91	9	12	10.34

Table B.11
Studied materials in vehicles, contribution in mass (in g) per unit of vehicle analyzed.

Material	**Type of vehicle**	
	PHEV	**BEV**
Ag	28	30
Al	115,544	200,000
Ce	49.7	0.15
Co	2659	10,63
Cr	12,789	11,850
Cu	59,1	150
Dy	22.5	45
Fe	806,144	746,945
Ga	0.81	1.12
Gd	0.18	0.18
Ge	0.05	0.1
In	0.38	0.38
La	7.4	7.4
Li	2126	8504
Mn	5968	5530
Mo	3410	3410
Nb	426	426
Nd	553	749
Ni	17,864	58,026
Pd	0.94	0
Pr	51.5	98
Pt	5.51	0
Rh	0.01	0
Ta	10.8	10.8
V	852.6	790

For the assessment of materials used in batteries, it has been considered that current battery market situation is led by Li: ion batteries as demonstrated by the fact that both Nissan and Tesla are currently using Li: ion batteries in their vehicles [114,115]. Even if Toyota used NiMH batteries in their vehicles, last Prius PHEVs version is already using Li: ion depending on the equipment level [116]. Although Li: ion technology is expected to be the reference in the coming years, from a chemistry point of view there are different types of Li: ion batteries such as: NMC, NCA, LFP, Li/S or Li/air. This study considers only NCA (lithium nickel cobalt aluminum oxide) batteries because of their high energy density and because they are used in current Tesla vehicles.

Appendix C. Hubbert curves for medium risk materials

See Appendix Figs. C.1–C.13.

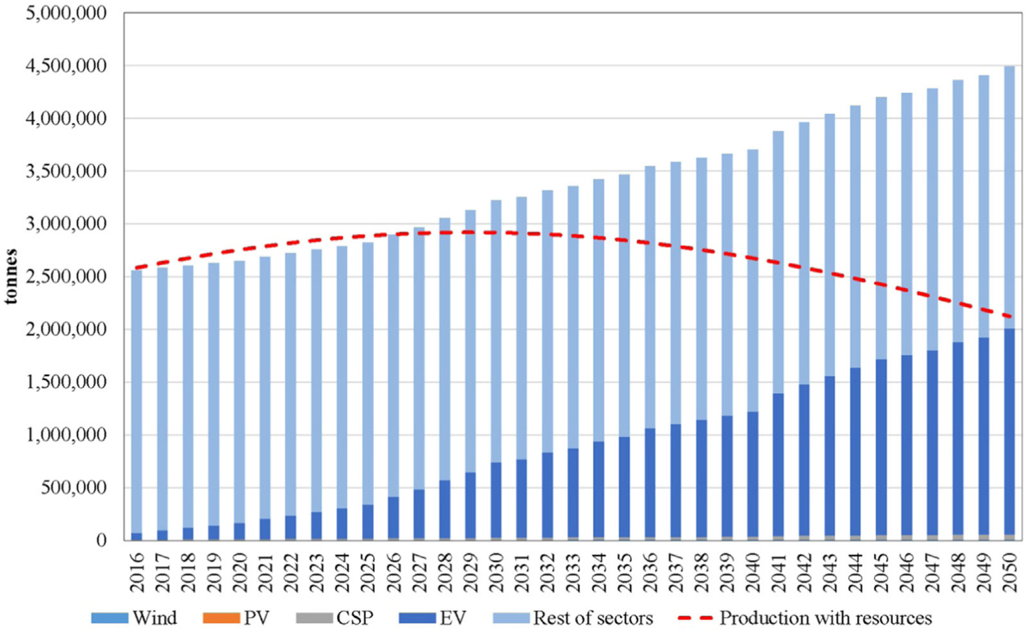

Fig. C.1. Expected demand and production assessed with Hubbert model for nickel.

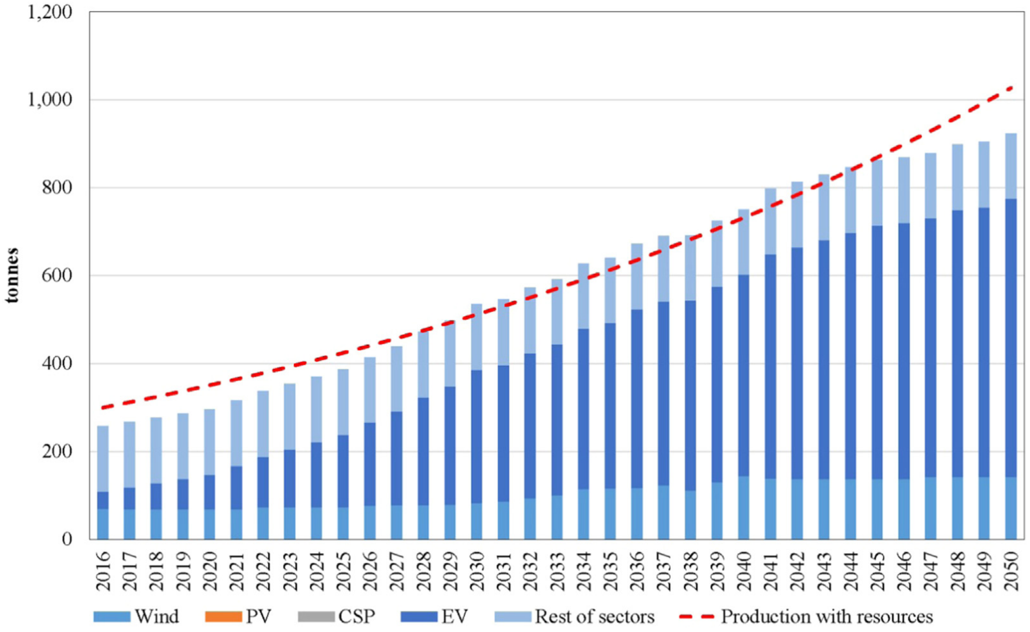

Fig. C.2. Expected demand and production assessed with Hubbert model for dysprosium.

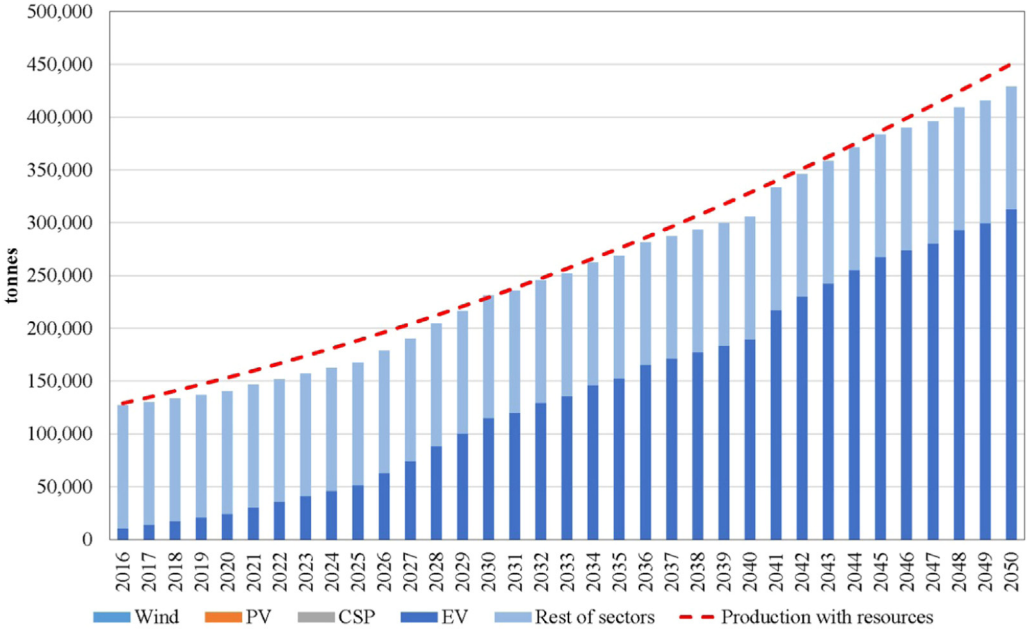

Fig. C.3. Expected demand and production assessed with Hubbert model for cobalt.

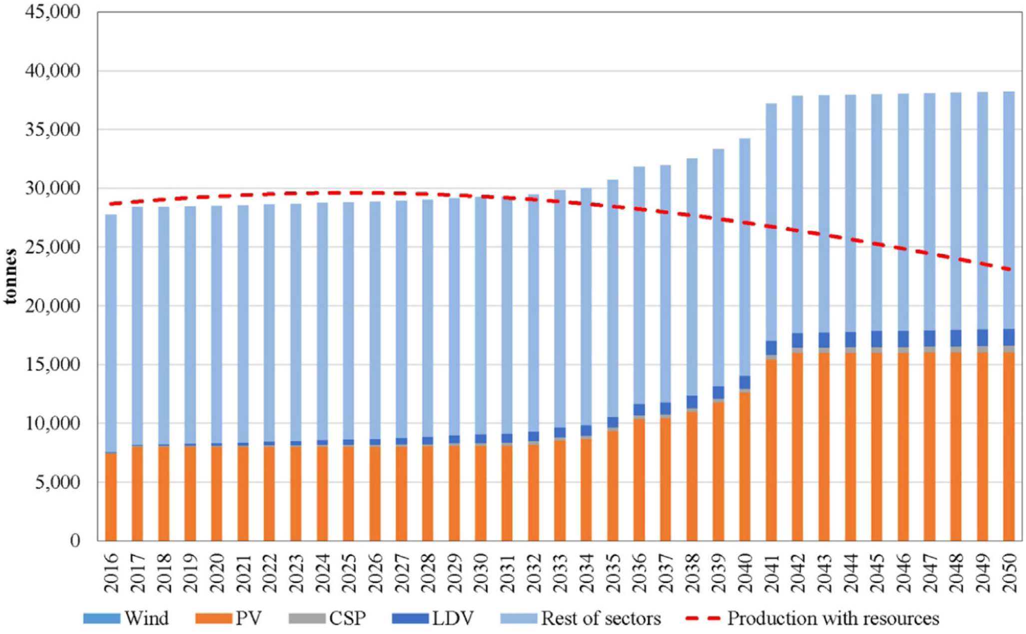

Fig. C.4. Expected demand and production assessed with Hubbert model for silver.

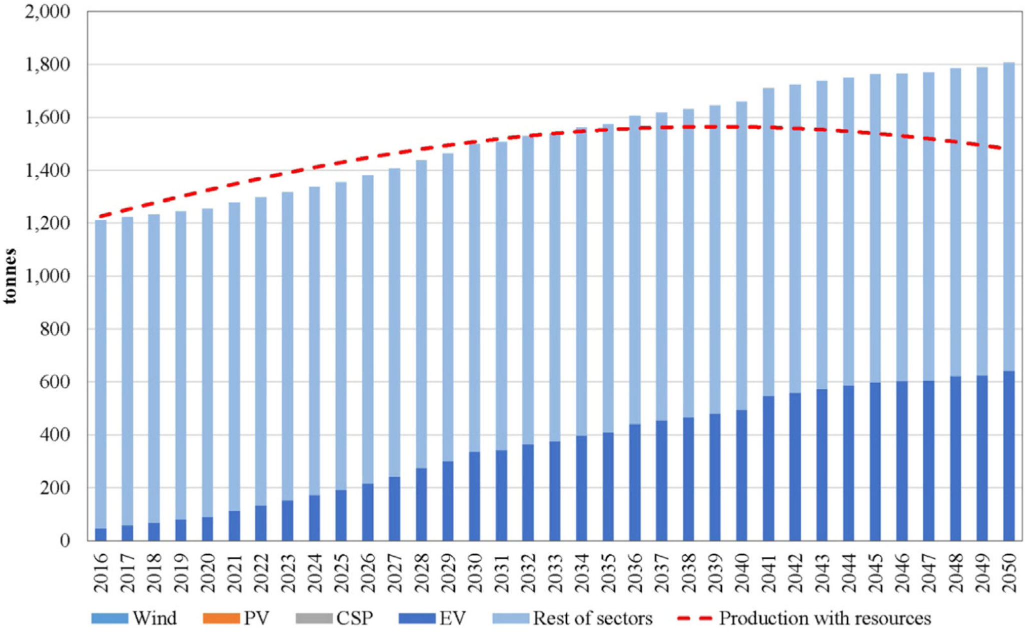

Fig. C.5. Expected demand and production assessed with Hubbert model for tantalum.

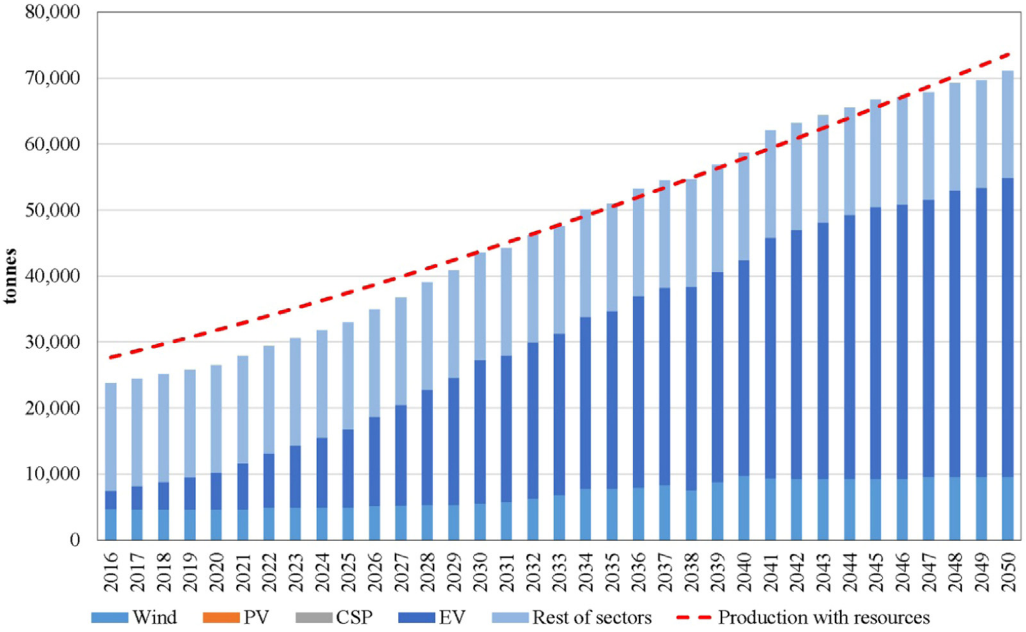

Fig. C.6. Expected demand and production assessed with Hubbert model for neodymium.

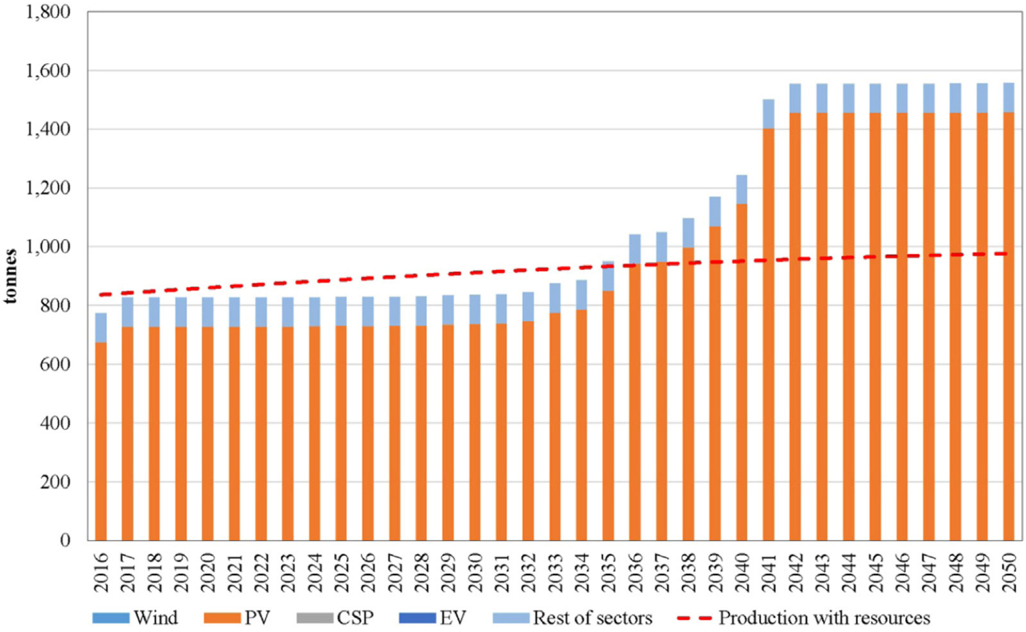

Fig. C.7. Expected demand and production assessed with Hubbert model for tellurium.

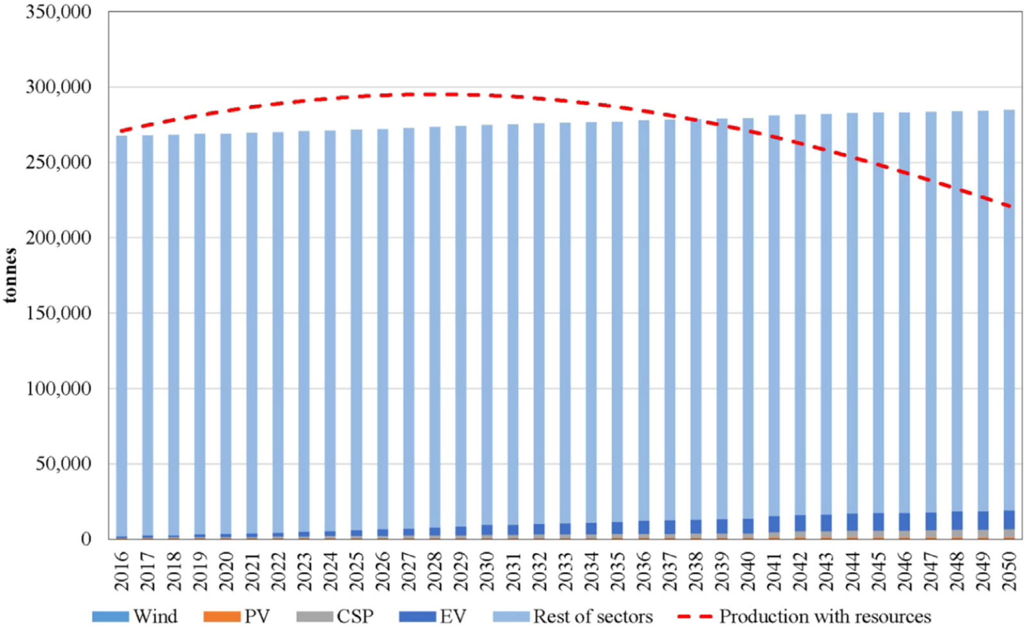

Fig. C.8. Expected demand and production assessed with Hubbert model for molybdenum.

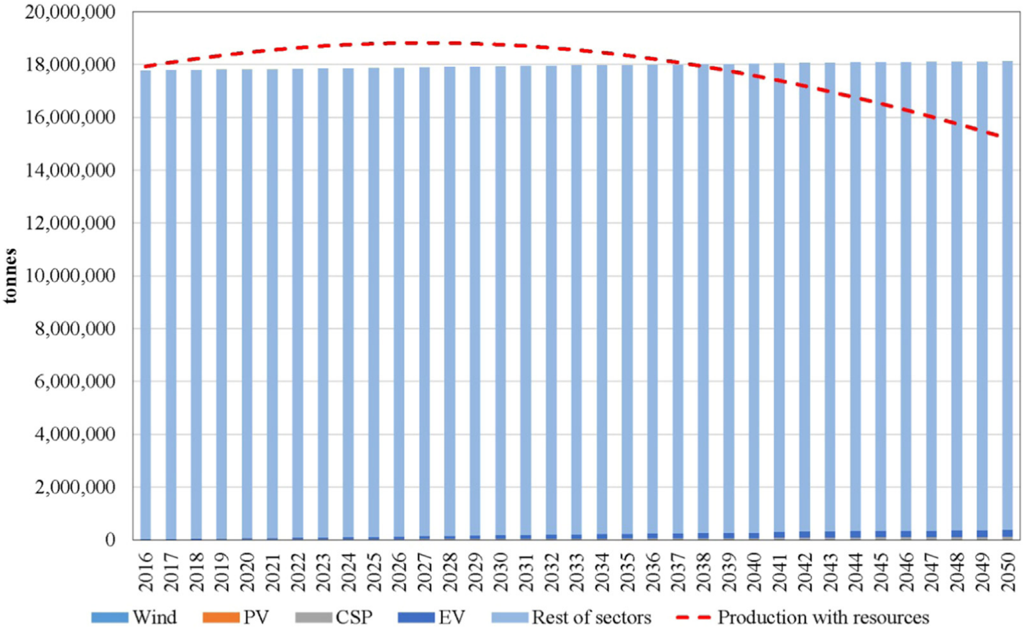

Fig. C.9. Expected demand and production assessed with Hubbert model for manganese.

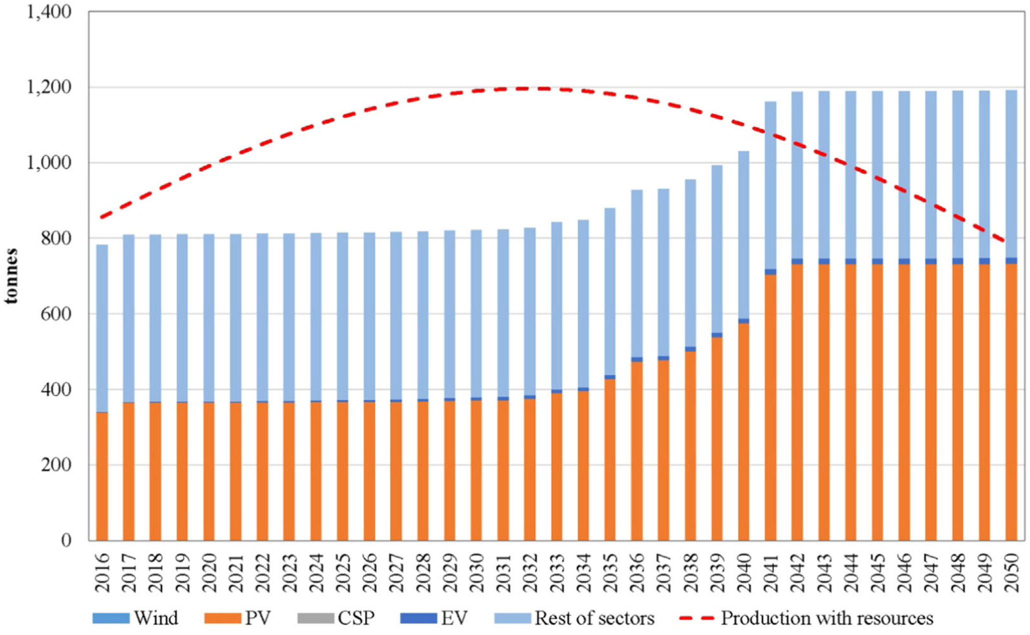

Fig. C.10. Expected demand and production assessed with Hubbert model for indium.

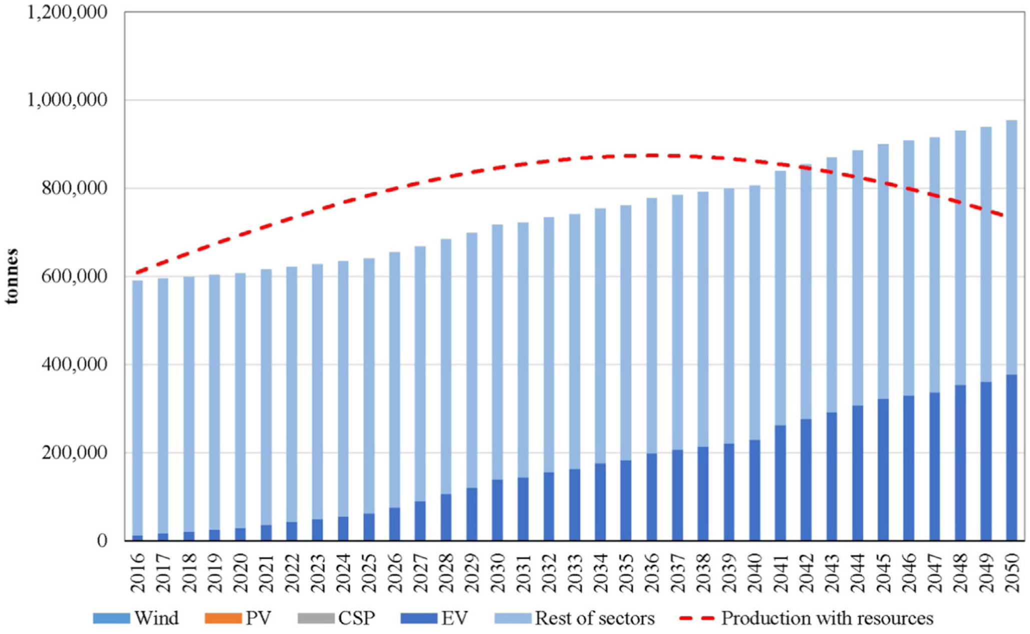

Fig. C.11. Expected demand and production assessed with Hubbert model for lithium.

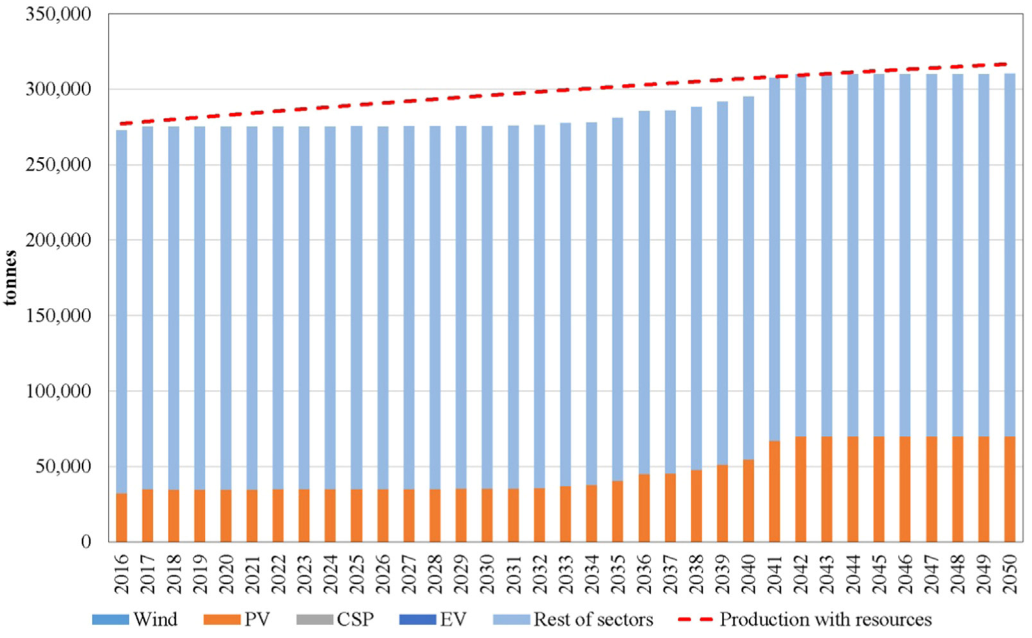

Fig. C.12. Expected demand and production assessed with Hubbert model for tin.

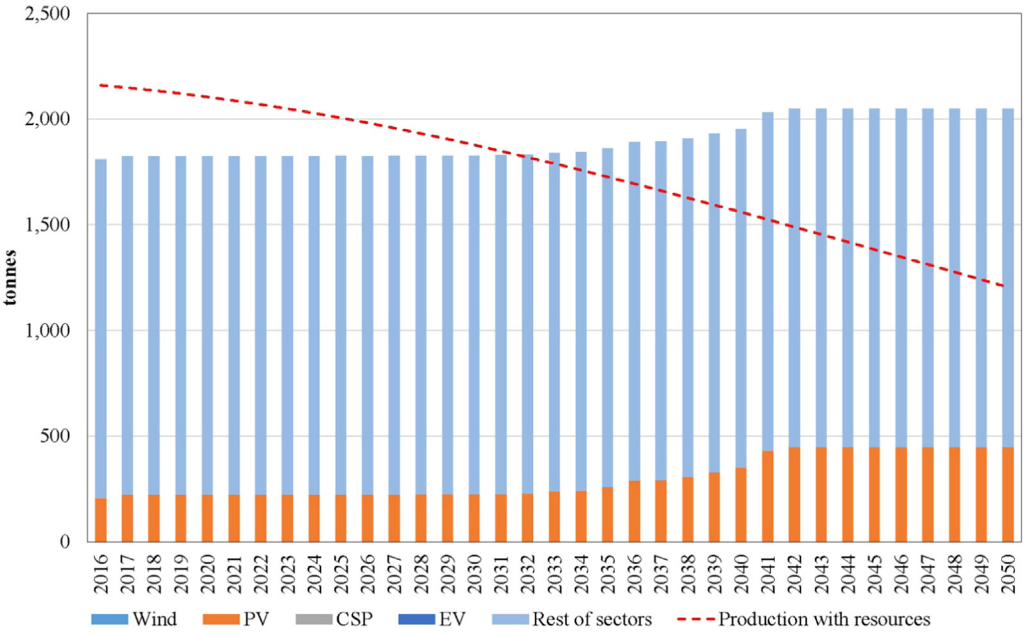

Fig. C.13. Expected demand and production assessed with Hubbert model for selenium.

References

[1] United Nations/FrameworkConvention on Climate Change. Paris agreement. In: Proceedings of the 21st conference parties; 2015, 3. 〈http://dx.doi.org/FCCC/CP/2015/L.9〉.

[2] European Climate Foundation. Power perspectives 2030. On the road to a decarbonised power sector. 2011 [Available at: 〈http://www.roadmap2050.eu/attachments/files/PowerPerspectives2030_FullReport.pdf〉, Accessed 12 April 2018].

[3] European Commission. 2050 low-carbon economy; 2015. Available at: 〈http://ec.europa.eu/clima/policies/strategies/2050/index_en.htm〉.

[4] European Commission. White paper. Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system. COM (2011) 144 final; 2011.

[5] International Energy Agency. Energy technology perspectives 2017. Catalysing energy technology transformations. International Energy Agency; 2017.

[6] Elshkaki A, Graedel TE. Dysprosium, the balance problem, and wind power technology. Appl Energy 2014;136:548–59.

[7] Chakhmouradian AR, Smith MP, Kynicky J. From "strategic" tungsten to "green" neodymium: a century of critical metals at a glance. Ore Geol Rev 2015:64. http://dx.doi.org/10.1016/j.oregeorev.2014.06.008.

[8] Alonso E, Sherman AM, Wallington TJ, Everson MP, Field FR, Roth R, et al. Evaluating rare earth element availability: a case with revolutionary demand from clean technologies. Environ Sci Technol 2012;46:3406–14. http://dx.doi.org/10.1021/es203518d.

[9] Grandell L, Lehtilä A, Kivinen M, Koljonen T, Kihlman S, Lauri LS. Role of critical metals in the future markets of clean energy technologies. Renew Energy 2016;95:53–62. http://dx.doi.org/10.1016/j.renene.2016.03.102.

[10] Ravikumar D, Malghan D. Material constraints for indigenous production of CdTe PV: evidence from a Monte Carlo experiment using India's National Solar Mission Benchmarks. Renew Sustain Energy Rev 2013;25:393–403. http://dx.doi.org/10.1016/j.rser.2013.04.030.

[11] Elshkaki A, Graedel TE. Solar cell metals and their hosts: a tale of oversupply and

undersupply. Appl Energy 2015;158:167–77. http://dx.doi.org/10.1016/j.apenergy.2015.08.066.

[12] Pihl E, Kushnir D, Sandén B, Johnsson F. Material constraints for concentrating solar thermal power. Energy 2012;44:944–54. http://dx.doi.org/10.1016/j.energy.2012.04.057.

[13] ANFAC. European motor vehicle parc; 2014.

[14] Riba J-R, López-Torres C, Romeral L, Garcia A. Rare-earth-free propulsion motors for electric vehicles: a technology review. Renew Sustain Energy Rev 2016;57:367–79. http://dx.doi.org/10.1016/j.rser.2015.12.121.

[15] Andersson M, Ljunggren Söderman M, Sandén BA. Are scarce metals in cars functionally recycled? Waste Manag 2017;60:407–16. http://dx.doi.org/10.1016/j.wasman.2016.06.031.

[16] Kushnir D, Sandén BA. The time dimension and lithium resource constraints for electric vehicles. Resour Policy 2012;37:93–103. http://dx.doi.org/10.1016/j.resourpol.2011.11.003.

[17] Scrosati B, Garche J. Lithium batteries: status, prospects and future. J Power Sources 2010;195:2419–30. http://dx.doi.org/10.1016/j.jpowsour.2009.11.048.

[18] Grosjean C, Miranda PH, Perrin M, Poggi P, Herrera Miranda P, Perrin M, et al. Assessment of world lithium resources and consequences of their geographic distribution on the expected development of the electric vehicle industry. Renew Sustain Energy Rev 2012;16:1735–44. http://dx.doi.org/10.1016/j.rser.2011.11.023.

[19] Schmidt T, Buchert M, Schebek L. Investigation of the primary production routes of nickel and cobalt products used for Li-ion batteries. Resour Conserv Recycl 2016;112:107–22. http://dx.doi.org/10.1016/j.resconrec.2016.04.017.

[20] Väyrynen A, Salminen J. Lithium ion battery production. J Chem Thermodyn 2012;46:80–5. http://dx.doi.org/10.1016/j.jct.2011.09.005.

[21] Redlinger M, Eggert R, Woodhouse M. Evaluating the availability of gallium, indium, and tellurium from recycled photovoltaic modules. Sol Energy Mater Sol Cells 2015;138:58–71. http://dx.doi.org/10.1016/j.solmat.2015.02.027.

[22] Wang X, Gaustad G, Babbitt CW. Targeting high value metals in lithium-ion battery recycling via shredding and size-based separation. Waste Manag 2016;51:204–13. http://dx.doi.org/10.1016/j.wasman.2015.10.026.

[23] Vikström H, Davidsson S, Höök M. Lithium availability and future production outlooks. Appl Energy 2013;110:252–66. http://dx.doi.org/10.1016/j.apenergy.2013.04.005.

[24] Richa K, Babbitt CW, Gaustad G, Wang X. A future perspective on lithium-ion battery waste flows from electric vehicles. Resour Conserv Recycl 2014:83. http://dx.doi.org/10.1016/j.resconrec.2013.11.008.

[25] Ortego A, Valero A, Valero A, Restrepo E. Vehicles and critical raw materials. A sustainability assessment using thermodynamic rarity. J Ind Ecol 2018. http://dx.doi.org/10.1111/jiec.12737.

[26] Silberglitt R, Bartis J, Chow B, An D, Brady K. Critical materials – present danger to US manufacturing. 2013. [〈http://dx.doi.org/978-0-8330-7883-4〉].

[27] U.S. Department of Energy. Critical material strategy. 2011 [Available at: 〈https://www.energy.gov/sites/prod/files/2016/12/f34/2011%20Critical%20Materials%20Strategy%20Report.pdf〉, Accessed 12 April 2018].

[28] Moss RL, Tzimas E, Kara H, Willis P, Kooroshy J. Critical metals in strategic energy technologies. 2011. http://dx.doi.org/10.2790/35600.

[29] Graedel TE, Harper EM, Nassar NT, Reck BK. On the materials basis of modern society. Proc Natl Acad Sci USA 2015:112. http://dx.doi.org/10.1073/pnas.1312752110.

[30] Alonso E, Gregory J, Field F, Kirchain R. Material availability and the supply chain: risks, effects, and responses. Environ Sci Technol 2007;41:6649–56. http://dx.doi.org/10.1021/es070159c.

[31] Achzet B, Helbig C. How to evaluate raw material supply risks—an overview. Resour Policy 2013;38:435–47. http://dx.doi.org/10.1016/j.resourpol.2013.06.003.

[32] European Commission. Study on the review of the list of Critical Raw Materials. Critical raw materials factsheets; 2017.

[33] European Commission. Report on critical raw materials for the EU. Report of the Ad hoc working group on defining critical raw materials. 2014 [Available at: 〈https://ec.europa.eu/growth/tools-databases/eip-raw-materials/en/system/files/ged/79%20report-b_en.pdf〉, Accessed 12 April 2018].

[34] Cox C, Kynicky J. The rapid evolution of speculative investment in the REE market before, during, and after the rare earth crisis of 2010–2012. Extr Ind Soc 2017. http://dx.doi.org/10.1016/J.EXIS.2017.09.002.

[35] Fernandez V. Rare-earth elements market: a historical and financial perspective. Resour Policy 2017;53:26–45. http://dx.doi.org/10.1016/J.RESOURPOL.2017.05.010.

[36] Habib K, Hamelin L, Wenzel H. A dynamic perspective of the geopolitical supply risk of metals. J Clean Prod 2016;133:850–8. http://dx.doi.org/10.1016/j.jclepro.2016.05.118.

[37] Moss RL, Tzimas E, Kara H, Willis P, Kooroshy J. The potential risks from metals bottlenecks to the deployment of strategic energy technologies. Energy Policy 2013;55:556–64. http://dx.doi.org/10.1016/j.enpol.2012.12.053.

[38] Elshkaki A, Graedel TE. Dynamic analysis of the global metals flows and stocks in electricity generation technologies. J Clean Prod 2013;59:260–73. http://dx.doi.org/10.1016/j.jclepro.2013.07.003.

[39] Sohn I. Long-term projections of non-fuel minerals: we were wrong, but why? Resour Policy 2006;30:259–84. http://dx.doi.org/10.1016/j.resourpol.2006.03.002.

[40] Emodi NV, Emodi CC, Murthy GP, Emodi ASA. Energy policy for low carbon development in Nigeria: a LEAP model application. Renew Sustain Energy Rev 2017;68:247–61. http://dx.doi.org/10.1016/j.rser.2016.09.118.

[41] Kuldna P, Peterson K, Kuhi-Thalfeldt R. Knowledge brokering on emissions modelling in strategic environmental assessment of Estonian energy policy with special reference to the LEAP model. Environ Impact Assess Rev 2015;54:55–60. http://dx.doi.org/10.1016/j.eiar.2015.06.001.

[42] Victor N, Nichols C, Balash P. The impacts of shale gas supply and climate policies on energy security: the U.S. energy system analysis based on MARKAL model. Energy Strategy Rev 2014;5:26–41. http://dx.doi.org/10.1016/j.esr.2014.10.008.

[43] Sverdrup HU, Ragnarsdottir KV, Koca D. On modelling the global copper mining rates, market supply, copper price and the end of copper reserves. Resour Conserv Recycl 2014;87:158–74. http://dx.doi.org/10.1016/j.resconrec.2014.03.007.

[44] Sverdrup HU. Modelling global extraction, supply, price and depletion of the extractable geological resources with the {LITHIUM} model. Resour Conserv Recycl 2016;114:112–29. http://dx.doi.org/10.1016/j.resconrec.2016.07.002.

[45] Sverdrup HU, Ragnarsdottir KV, Koca D. Aluminium for the future: modelling the global production, market supply, demand, price and long term development of the global reserves. Resour Conserv Recycl 2015;103:139–54. http://dx.doi.org/10.1016/j.resconrec.2015.06.008.

[46] Murray J, King D. Climate policy: oil's tipping point has passed. Nature 2012;481:433–5.

[47] Capellán-Pérez I, Mediavilla M, de Castro C, Carpintero Ó, Miguel LJ. Fossil fuel depletion and socio-economic scenarios: an integrated approach. Energy 2014;77:641–66. http://dx.doi.org/10.1016/j.energy.2014.09.063.

[48] Chapman I. The end of peak oil? Why this topic is still relevant despite recent denials. Energy Policy 2014;64:93–101. http://dx.doi.org/10.1016/j.enpol.2013.05.010.

[49] Calvo G, Valero A, Valero A. Assessing maximum production peak and resource availability of non-fuel mineral resources: analyzing the influence of extractable global resources. Resour Conserv Recycl 2017:125. http://dx.doi.org/10.1016/j.resconrec.2017.06.009.

[50] Höök M, Bardi U, Feng L, Pang X, Bardi U, Feng L, et al. Development of oil formation theories and their importance for peak oil. Mar Pet Geol 2010;27:1995–2004.

[51] USGS. Mineral commodity summaries 2015. United States Geological Service; 2015 [Available at: 〈https://minerals.usgs.gov/minerals/pubs/mcs/2015/mcs2015.pdf〉, Accessed 14 May 2018].

[52] Emsley J. Nature's building blocks: an A–Z guide to the elements. Oxford, England, UK: Oxford University Press; 2001.

[53] Frenzel M, Ketris MP, Seifert T, Gutzmer J. On the current and future availability of gallium. Resour Policy 2016;47:38–50. http://dx.doi.org/10.1016/j.resourpol.2015.11.005.

[54] Frenzel M, Ketris MP, Gutzmer J. On the geological availability of germanium. Miner Depos 2014;49:471–86.

[55] Sverdrup HU, Ragnarsdottir KV. Natural resources in a planetary perspective. Geochem Perspect 2014;3(2).

[56] Haque N, Hughes A, Lim S, Vernon C. Rare earth elements: overview of mining, mineralogy, uses, sustainability and environmental impact. Resources 2014;3:614–35.

[57] Hubbert MK. Nuclear Energy and the fossil fuels; 1956. Available at: 〈http://www.hubbertpeak.com/hubbert/1956/1956.pdf〉, [Accessed 12 April 2018].

[58] Hubbert MK. Energy resources: a report to the committee on natural resources of the National Academy of Sciences. Washington, D.C., USA; 1962.

[59] UNEP. Recycling rates of metals – a status report. A report of the working group of the global metal flows to the international resource panel. 2011.

[60] Geyer R, Kuczenski B, Zink T, Henderson A. Common misconceptions about recycling. J Ind Ecol 2016:20. http://dx.doi.org/10.1111/jiec.12355.

[61] Valero A, Valero A. Physical geonomics: combining the exergy and Hubbert peak analysis for predicting mineral resources depletion. Resour Conserv Recycl 2010;54:1074–83. http://dx.doi.org/10.1016/j.resconrec.2010.02.010.

[62] Valero Capilla A, Valero Delgado A. Thanatia: the destiny of the Earth's mineral resources: a cradle-to-cradle thermodynamic assessment. New Jersey: World Scientific; 2014.

[63] Raccurt O, Disdier A, Bourdon D, Donnola S, Stollo A, Gioconia A. Study of the stability of a selective solar absorber coating under air and high temperature conditions. Energy Procedia 2015;69:1551–7. http://dx.doi.org/10.1016/j.egypro.2015.03.107.

[64] EWEA. Wind energy´s frequently asked questions (FAQ) 2016. 2016 [Accessed 12 April 2018]. 〈http://www.ewea.org/wind-energy-basics/faq/〉.

[65] Bayod-Rújula AA, Ortego-Bielsa A, Martínez-Gracia A. Photovoltaics on flat roofs: energy considerations. Energy 2011;36:1996–2010. http://dx.doi.org/10.1016/j.energy.2010.04.024.

[66] EWEA. The European offshore wind industry – key trends and statistics 2015. 2016 [Available at: 〈https://windeurope.org/wp-content/uploads/files/about-wind/statistics/WindEurope-Annual-Offshore-Statistics-2016.pdf〉, Accessed 14 May 2018].

[67] International Energy Agency. Technology roadmap. Wind energy. 2013 [Available at: 〈https://www.iea.org/publications/freepublications/publication/Wind_2013_Roadmap.pdf〉, Accessed 12 April 2018].

[68] Greenpeace. Solar thermal electricity. Global outlook 2016. 2016 [Available at: 〈https://www.greenpeace.org/archive-international/Global/international/publications/climate/2016/Solar-Thermal-Electricity-Global-Outlook-2016.pdf〉, Accessed 12 April 2018].

[69] International Energy Agency. Technology roadmap. Solar thermal electricity. 2014 [Available at: 〈https://www.iea.org/publications/freepublications/publication/technologyroadmapsolarthermalelectricity_2014edition.pdf〉, Accessed 12 April 2018].

[70] International Energy Agency. Technology roadmap. Solar photovoltaic energy. 2014 [Available at: 〈https://www.iea.org/publications/freepublications/

publication/TechnologyRoadmapSolarPhotovoltaicEnergy_2014edition.pdf〉, Accessed 12 April 2018].

[71] Parrado C, Girard A, Simon F, Fuentealba E. 2050 LCOE (Levelized Cost of Energy) projection for a hybrid PV (photovoltaic)-CSP (concentrated solar power) plant in the Atacama Desert, Chile. Energy 2016;94:422–30. http://dx.doi.org/10.1016/j.energy.2015.11.015.

[72] Lacal-Arántegui R. Materials use in electricity generators in wind turbines – state-of-the-art and future specifications. J Clean Prod 2015;87:275–83. http://dx.doi.org/10.1016/j.jclepro.2014.09.047.

[73] Dulac J. Global transport outlook to 2050. International Energy Agency,; 2013 [Available at: 〈https://www.iea.org/media/workshops/2013/egrdmobility/DULAC_23052013.pdf〉, Accessed 12 April 2018].

[74] Hurst D, Gartner J. Global market opportunities, barriers, technology issues, and demand forecasts for E-bicycles, pedal-assist bicycles, and E-bicycle batteries and motors. 2013. p. 14.

[75] AvicenneENERGY. The worldwide battery market 2012 − 2025 33. 2013. p. 1–41.

[76] British Geological Survey. Risk list 2015. 2015 [Available at: 〈http://www.bgs.ac.uk/mineralsuk/statistics/risklist.html〉, Accessed 12 April 2018].

[77] Bae JC. Strategies and perspectives for securing rare metals in Korea. Critical elements for new energy technologies, an MIT energy initiative workshop report. 2000 [Available at: 〈http://web.mit.edu/miteicomm/web/reports/critical_elements/CritElem_Report_Final.pdf〉, Accessed 14 May 2018].

[78] Angerer DG, Marscheider-Weidemann F, Lüllmann A, Erdmann L, Scharp DM, Handke V, et al. Raw materials for emerging technologies. A report commissioned by the German Federal Ministry of Economics and Technology. 2009 [Accessed 14 May 2018]. 〈http://publica.fraunhofer.de/documents/N-111514.html〉.

[79] JOGMEC. The mineral resources policy of Japan. Tokyo: JOGMEC (Japan Oil, Gas and Metals National Corporation); 2010.

[80] Physics APS. Energy critical elements: securing materials for emerging technologies. A report by the APS panel on public affairs & the materials research society. 2011.

[81] Resnick Institute. Critical materials for sustainable energy applications. 2011 [Available at: 〈https://authors.library.caltech.edu/32727/1/ri_criticalmaterials_report.pdf〉, Accessed 15 May 2018].

[82] DOE, U.S. Department of Energy. Critical materials strategy. 2011 [Available at: 〈https://www.energy.gov/sites/prod/files/DOE_CMS2011_FINAL_Full.pdf〉, Accessed 15 May 2018].

[83] UKERC. Materials availability for low-carbon technologies: an assessment of the evidence. 2014 [Available at: 〈http://www.ukerc.ac.uk/asset/34D2BFC5%2D9C0D%2D4C07%2DBA6CD6D15BDE549A/〉, Accessed 15 May 2018].

[84] Calvo G, Valero A, Valero A. Thermodynamic approach to evaluate the criticality of raw materials and its application through a material flow analysis in Europe. J Ind Ecol 2017. http://dx.doi.org/10.1111/jiec.12624.

[85] European Commission. Critical raw materials for the EU. Report of the ad-hoc working group on defining critical raw materials. 2010.

[86] van Schaik A, Reuter MA. The use of fuzzy rule models to link automotive design to recycling rate calculation. Miner Eng 2007;20:875–90. http://dx.doi.org/10.1016/J.MINENG.2007.03.016.

[87] Amini SH, Remmerswaal JAM, Castro MB, Reuter MA. Quantifying the quality loss and resource efficiency of recycling by means of exergy analysis. J Clean Prod 2007;15:907–13. http://dx.doi.org/10.1016/J.JCLEPRO.2006.01.010.

[88] Davidsson S, Höök M. Material requirements and availability for multi-terawatt deployment of photovoltaics. Energy Policy 2017;108:574–82. http://dx.doi.org/10.1016/J.ENPOL.2017.06.028.

[89] Powell D. Sparing the rare earths: potential shortages of useful metals inspire scientists to seek alternatives for magnet technologies. Sci News 2011;180:18–21.

[90] LaMonica M DOE Opens Innovation Hub for Critical Materials | MIT Technology Review. MIT Technology Review; 2013. Available at: 〈http://www.technologyreview.com/view/509996/doe-opens-innovation-hub-for-critical-materials/〉, [Accessed 12 April 2018].

[91] Konitzer D, Duclos S, Rockstroh T. Materials for sustainable turbine engine development. Mater Res Soc Bull 2012;37:383–8.

[92] Lloyd S, Lee J, Clifton A, Elghali L, France C. Ecodesign through environmental risk management: a focus on critical materials. Des Innov Value Towar Sustain Soc 2012:374–9.

[93] Gaustad G, Krystofik M, Bustamante M, Badami K. Circular economy strategies for mitigating critical material supply issues. Resour Conserv Recycl 2017. http://dx.doi.org/10.1016/J.RESCONREC.2017.08.002.

[94] United Nations. World population projected to reach 9.7 billion by 2050. 2015 [Available at: 〈http://www.un.org/en/development/desa/news/population/2015-report.html〉, Accessed 14 May 2018].

[95] Habib K, Wenzel H. Exploring rare earths supply constraints for the emerging clean energy technologies and the role of recycling. J Clean Prod 2014;84:348–59. http://dx.doi.org/10.1016/j.jclepro.2014.04.035.

[96] Guezuraga B, Zauner R, Pölz W. Life cycle assessment of two different 2 MW class wind turbines. Renew Energy 2012;37:37–44. http://dx.doi.org/10.1016/j.renene.2011.05.008.

[97] Zimmermann T. Parametized tool site specif. LCAs wind power energy convert. Int J Life Cycle Assess 2013.

[98] Martínez E, Sanz F, Pellegrini S, Jiménez E, Blanco J. Life cycle assessment of a multi-megawatt wind turbine. Renew Energy 2009;34:667–73. http://dx.doi.org/10.1016/j.renene.2008.05.020.

[99] USGS. Wind energy in the USA and materials required for the land-based wind turbine industry. 2011 [Available at: 〈https://pubs.usgs.gov/sir/2011/5036/sir2011-5036.pdf〉, Accessed 14 May 2018].

[100] ELSAM. Life cycle assessment of offshore and onshore sited wind farms. 2004 [Available at: 〈https://www.vestas.com/~/media/vestas/about/sustainability/pdfs/lca_v80_2004_uk.ashx〉, Accessed 14 May 2018].

[101] García-Olivares A, Ballabrera-Poy J, García-Ladona E, Turiel A. A global renewable mix with proven technologies and common materials. Energy Policy 2012:561–74.

[102] Crown State. A guide to and offshore wind farm. 2012 [Available at: 〈https://www.thecrownestate.co.uk/media/5408/ei-a-guide-to-an-offshore-wind-farm.pdf〉, Accessed 12 April 2018].

[103] Kaneko. Recent status on electromagneting casting. In: Proceedings of the 16th work. cryst. silicon sol. cells modul. mater. process.; 2006.

[104] Fthenakis V. Sustainability of photovoltaics: the case for thin-film solar cells. Renew Sustain Energy Rev 2009;13:2746–50. http://dx.doi.org/10.1016/j.rser.2009.05.001.

[105] USGS. Byproduct mineral commodities used for the production of photovoltaics cell; 2010.

[106] Andersson BA, Jacobsson S. Monitoring and assessing technology choice: the case of solar cells. Energy Policy 2000;28:1037–49. http://dx.doi.org/10.1016/S0301-4215(00)00090-2.

[107] Candelise C, Speirs JF, Gross RJK. Materials availability for thin film (TF) PV technologies development: a real concern? Renew Sustain Energy Rev 2011;15:4972–81. http://dx.doi.org/10.1016/j.rser.2011.06.012.

[108] Berger W, Simon F-G, Weimann K, Alsema EA. A novel approach for the recycling of thin film photovoltaic modules. Resour Conserv Recycl 2010;54:711–8. http://dx.doi.org/10.1016/j.resconrec.2009.12.001.

[109] Alonso E, Wallington T, Sherman A, Everson M, Field F, Roth R, et al. An assessment of the rare earth element content of conventional and electric vehicles. SAE Int J Mater Manuf 2012;5:3–7.

[110] Cullbrand K, Magnusson O. The use of potentially critical materials in passenger cars. Department of Energy and Environment. Gothenburg, Sweden: Chalmers University of Technology; 2012〈http://publications.lib.chalmers.se/records/fulltext/162842.pdf〉 [Accessed 12 April 2018].

[111] González Palencia JC, Sakamaki T, Araki M, Shiga S. Impact of powertrain electrification, vehicle size reduction and lightweight materials substitution on energy use, CO_2 emissions and cost of a passenger light-duty vehicle fleet. Energy 2015;93:1489–504. http://dx.doi.org/10.1016/j.energy.2015.10.017.

[112] USGS. Aluminium stocks in use in automobiles in the United States. Fact sheet 2005–3145. 2006 Available at: 〈https://webarchive.library.unt.edu/eot2008/20081205144540/http://pubs.usgs.gov/fs/2005/3145/fs2005_3145.pdf〉, Accessed 14 May 2018].

[113] USGS.. Steel stocks in use in automobiles in the United States. Fact sheet 2005–3144. 2006 [Available at: 〈https://pubs.usgs.gov/fs/2005/3144/fs2005_3144.pdf〉, Accessed 14 May 2018].

[114] Nissan. Electric vehicle Lithium-ion battery; 2016. Available at: 〈http://www.nissan-global.com/EN/TECHNOLOGY/OVERVIEW/li_ion_ev.html〉, [Accessed 12 April 2018].

[115] TESLA. Tesla Gigafactory; 2014. Available at: 〈https://www.tesla.com/gigafactory〉, [Accessed 12 April 2018].

[116] Reuters. Toyota plans to increase lithium ion battery output-Nikkei; 2013. Available at: 〈http://www.reuters.com/article/toyota-battery-idUSL3N0E002O20130519〉, [Accessed 12 April 2018].

[117] Gaines L, Sullivan J, Burnham A, Bel. Life-cycle analysis for lthium-ion battery production and recycling. In: Proceedings of the transp. res. board 90th annu. meet.; 2010, 17. 〈http://dx.doi.org/10.1057/9781137332875.0027〉.

[118] Glöser S, Tercero Espinoza L, Gandenberger C, Faulstich M. Raw material criticality in the context of classical risk assessment. Resour Policy 2015;44:35–46. http://dx.doi.org/10.1016/j.resourpol.2014.12.003.

A.2 Paper II

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Scope: material and energy flows studies ('industrial metabolism'), technological change, dematerialization and decarbonization, life cycle planning, design and assessment, design for the environment, extended producer responsibility ('product stewardship'), eco-industrial parks ('industrial symbiosis'), product-oriented environmental, policy eco-efficiency.

Contribution to the work:

- To make a revision of scientific publications about the state of the art concerning the use of minor metals in vehicles.
- To make a revision about the composition of different kind of batteries: NMC, NCA and Ni-MH.
- To assess the Thermodynamic Rarity for the different types of vehicles.
- To disaggregate the results by vehicle components and studied metals.
- To compare the results by means of the mass and thermodynamic approaches.

Vehicles and Critical Raw Materials

A Sustainability Assessment Using Thermodynamic Rarity

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Supporting information is linked to this article on the *JIE* website

Summary

The changing material composition of cars represents a challenge for future recycling of end-of-life vehicles (ELVs). Particularly, as current recycling targets are based solely on mass, critical metals increasingly used in cars might be lost during recycling processes, due to their small mass compared to bulk metals such as Fe and Al. We investigate a complementary indicator to material value in passenger vehicles based on exergy. The indicator is called thermodynamic rarity and represents the exergy cost (GJ) needed for producing a given material from bare rock to the market. According to our results, the thermodynamic rarity of critical metals used in cars, in most cases, supersedes that of the bulk metals that are the current focus of ELV recycling. While Fe, Al, and Cu account for more than 90% of the car's metal content, they only represent 60% of the total rarity of a car. In contrast, while Mo, Co, Nb, and Ni account for less than 1% of the car's metal content, their contribution to the car's rarity is larger than 7%. Rarity increases with the electrification level due to the greater amount of critical metals used; specifically, due to an increased use of (1) Al alloys are mainly used in the car's body-in-white of electric cars for light-weighting purposes, (2) Cu in car electronics, and (3) Co, Li, Ni, and rare earth metals (La, Nd, and Pr) in Li-ion and NiMH batteries.

Introduction

Global car sales have more than doubled over the past 30 years, from about 29 million in 1980 to 65 million in 2014 (OICA 2016). The European Union (EU) passenger car fleet amounted to 250 million units in 2014, representing an increase of 5% in the last 5 years (ACEA 2014). Annually, end-of-life vehicles (ELVs) represent between 7 and 8 million tonnes of waste in the EU, which should be properly managed (European Commission 2016). Consequently, the EU Directive 2000/53/EC sets strict targets to prevent waste generation and to promote the reuse, recycling, and recovery of materials from ELVs. This directive establishes that, from 2015, the total mass percentage of materials reused and recovered with respect to the average car's weight must be equal to 95%, of which at least 85% must come from reuse and recycling. Reuse is understood as any operation by which components are "used for the same purpose for which they were conceived." Recovery means "any of the applicable operations provided for in Annex IIB of Directive 75/442/EEC," which in the case of vehicles can be: (1) fuel or energy generation, (2) recycling/reclamation of metals and metal compounds, and (3) recycling/reclamation of other inorganic materials (European Parliament and The Council 1975). Recycling, in turn, is the reprocessing of materials in "a

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production process for the original purpose or for other purposes, but excluding energy recovery" (*Directive 2000/53/EC of the European Parliament and of the Council on End of Life Vehicles*, 2000).

However, the future compliance with these recycling targets is challenged by two main factors: (1) the changing material composition of cars and (2) the thermodynamic limits of material production and recycling. Examples of the changing material composition over time are: the replacement of Fe by Al alloys for parts such as the engine, body-in-white, and wheels (Hatayama et al. 2012; Løvik et al. 2014; Van Schaik et al. 2002), increased use of plastics for the car's interior (Juska 2007), transition from conventional internal combustion engines to hybrid-electric and fully electric power trains (Eurostat 2015), and evolution from manual to automated control of vehicle functions provided by an increased number of car electronics (Restrepo et al. 2017). Regarding the thermodynamic limits of car recycling, Castro and colleagues (2004, 2007), Ignatenko and colleagues (2008), and Reuter and colleagues (2006), among others, have illustrated how the combination of materials, together with the intrinsic efficiency of the current recycling technologies, pose physical limits to the recycling of materials from ELVs. These limits are explained by the Second Law of Thermodynamics and have been discussed more generally by many authors, including Gutowski (2008), Gutowski and Dahmus (2005), Ignatenko and colleagues (2007), Nakajima and colleagues (2009), and Valero and Valero (2015). In short, according to the Second Law, there is an intrinsic irreversibility carried along with each production and recycling process, because part of the useful energy (exergy) of primary materials is inevitably transferred to the surroundings in the form of losses with each transformation process.

New developments in automobile design, triggered mainly by emission reduction policies and safety standards, have increased the number and amount of specialty metals that are used in a passenger car. For example, Nd is used in electric drive motors that replace internal combustion engines and Au is used in a variety of automotive controllers that help prevent road accidents. Most of these specialty metals are considered critical, due to their importance for future technologies, low substitutability, risks associated with their supply, and environmental impacts of production (European Commission 2014; Graedel et al. 2015).

According to Du and colleagues (2015) and Widmer and colleagues (2015), the majority of critical metals (CMs) used in passenger cars are found in the embedded electronics. After the current treatment of ELVs, most of these CMs end up in the automobile shredder residue (ASR) from which they are not recycled and, as reported by Andersson and colleagues (2017), from a total of 17 CMs investigated, only Pt from catalytic converters is functionally recycled in current ELV treatment systems. It is a fact that current ELV recycling targets by the EU favor the recycling of bulk metals, while overlooking most of the CMs that are used in smaller amounts. This is because metals such as Fe and Al still account for more than 90% of the car's mass (excluding plastics, rubber, and glass).

The objective of this study is to perform an assessment of the use of CMs in vehicles. This is achieved by: (1) establishing average compositions of several types of vehicles and (2) performing a thermodynamic rarity assessment of vehicles. To that end, we estimate the embedded exergy cost (rarities) of 17 CMs used in four different vehicle technologies: conventional passenger vehicles; plug-in hybrid electric vehicle (PHEV) with NiMH battery; PHEV with Li-ion battery; and battery electric vehicles (BEVs). A comparison of the mass of materials with their respective rarities unveils the hidden value of CMs with respect to bulk materials. This hidden value is effectively lost if recycling targets continue to be measured in terms of mass. We build upon previous work by Valero and Valero (2015) for the thermodynamic assessment through a complementary exergy-based indicator for material value in passenger cars and discuss the possible benefits of using it for setting ELV recycling targets in which the incentive for recycling CMs is made explicit.

Methodology

Technically, exergy is defined as the maximum amount of work that may theoretically be performed by bringing a resource into equilibrium with its surrounding environment by a sequence of reversible processes. The exergy of a system gives an idea of its evolution potential for not being in thermodynamic equilibrium or "dead state" with the reference environment. At the dead state, a system is at the temperature and pressure of its surroundings; it has no kinetic or potential energy and it does not react with the surroundings. All substances have a definable and calculable exergy content, with respect to a defined external environment. Once the environment is specified, exergy can be regarded as a property of the system.

A mineral deposit is a high-exergy resource that stands out from the surrounding environment, because of its specific chemical composition, cohesion degree, and concentration with respect to the average crust (Valero et al. 2012). The fact of having minerals concentrated in mines and not dispersed throughout the crust saves, in turn, huge amounts of extraction and beneficiation energy (Valero and Valero 2012)

A model for the average crust was developed by Valero and colleagues (2011), serving as the baseline for mineral exergy calculations. The model should represent an exhausted Earth (named Thanatia), where all mineral deposits have been extracted and dispersed and all fossil fuels have been burnt. The starting point to develop the model was the mineralogical composition proposed by Grigor'ev (2000), which was further improved considering the chemical composition in terms of elements proposed by Rudnick and Gao (2003). Accordingly, Thanatia's crust incorporates information regarding composition and crustal concentration of the nearly 300 most abundant minerals in the upper crust. With Thanatia as the reference environment, one can now calculate the exergy of a given by means of the concentration exergy (b_{ci}) as expressed in equation (1) (Faber and Proops 1991):

$$b_{ci} = -\overline{R}T^0 \left[lnx_i + \frac{(1 - x_i)}{x_i} ln(1 - x_i) \right]. \qquad (1)$$

Being *R* the universal gas constant (*8,314 kJ/kmolK*), T_0 is the temperature of the reference environment (*298.15 K*) and x_i is the concentration of substance *i*. The difference of the concentration exergy obtained with x_i being the ore grade of a given mine and with x_i being Thanatia's concentration of the mineral is called *replacement exergy* and represents the minimum energy (exergy) required to form the mineral from the concentration in the Earth's crust (x_c) to the concentration in the mineral deposits (x_m). In this way, the average exergy of different substances was obtained, considering global average ore grades (x_m), mainly derived from Cox and Singer (1992). It should be noted, however, that exergy only provides minimum values, which are far removed from societal perception of value. This is because, as per definition, it considers that processes are reversible. Yet man-made processes are very irreversible and, in reality, one would need k-times the minimum exergy (equation 2):

$$b_{ci}^{*} = k \cdot b_{ci} \tag{2}$$

Accordingly, instead of replacement exergy, we need to resort to exergy replacement costs, which are defined as the exergy required to concentrate a given mineral from Thanatia's dispersed conditions to the current concentration found in the mines with prevailing technology. Variable *k* is a constant called unit exergy cost. It is the ratio between (1) the real cumulative exergy required to accomplish the real process to concentrate the mineral from the ore grade x_m to the commercial grade x_r and (2) the minimum thermodynamic exergy required to accomplish the same process. An implicit assumption in the methodology is thus that the same technology applies for concentrating a mineral from x_m to x_r than from $_{xc}$ to x_m.

Exergy replacement costs can be seen as a hidden cost or "bonus" that nature provides for free for having minerals concentrated in mines and not dispersed throughout the crust. This bonus is related to mineral scarcity in nature. Note that scarcity is here referred as the relative low concentration of the given mineral in the crust, in contrast to the more anthropogenic definition by Van Oers and Guinée (2016, 7) where a specific mineral is scarce if "the amount available for use is, or will soon be, insufficient."

It should be stated that exergy replacement costs are an important part of the physical value of a substance, but not the only one. A mineral resource from which useful materials are obtained can be regarded as valuable from a physical point of view when (1) they are scarce in nature and/or (2) they are costly to obtain. The second part refers to the energy associated to extract, beneficiate, and refine the mineral to produce the useful element or commodity. In other words, the embodied exergy cost incurred by companies in mining and metallurgical processes. These costs increase as ore grades decline and so the Earth approaches to Thanatia.

From a life cycle assessment (LCA) point of view, this part corresponds to a cradle-to-gate approach, whereas exergy replacement costs to a grave-to-cradle approach as it is related to the exergy required to restore natural mines from the grave, that is, Thanatia (Valero and Valero 2013). Using embodied exergy and not embodied energy as commonly done in conventional LCA has an additional advantage: Cost allocation among simultaneously produced materials or energy flows is carried out according to the quality of the streams, that is, through exergy and not through tonnage or monetary costs. As demonstrated in Valero and colleagues (2013), exergy allocation brings the advantages of monetary allocation (resulting costs are close to societal perception of value) and those of tonnage allocation (stable and absolute value independent of market fluctuations).

The sum of the exergy replacement cost and the embodied exergy costs is what Valero and Valero (2015) named *thermodynamic rarity* of minerals. Thermodynamic rarity can be thus defined as the amount of exergy resources needed to obtain a mineral commodity from the ordinary rock (Thanatia), using the prevailing technology. Hence, it allows taking nature into account as it apprehends both ideas: (1) conservation, because it advices to preserve those minerals that are scarce through exergy replacement costs, and (2) efficiency, because embodied exergies indicate real energy expenditures that should be decreased in order to be cost-effective.

Note that if technology does not change, rarity can be assumed to be constant. Before effective mining appeared, mineral deposits were abundant and highly concentrated (the natural bonus was high and so the exergy replacement costs). In turn, it was very easy to mine and beneficiate minerals (embodied exergy costs were low). Throughout history, the low hanging fruits have been already mined, steadily resulting in exploitation of lower-ore grade mines. Currently, the mining industry needs to go deeper, further, and more energy intensively than before (the natural bonus has been decreased), that is, exergy replacement costs have been converted into embodied exergies. In some cases, technology improvements could partially offset decreasing ore grades (Swart and Dewulf 2013). Yet, as demonstrated by Calvo and colleagues (2016) for the case of copper, ore grades have generally declined throughout history leading to greater energy costs.

In summary, thermodynamic rarity is here proposed as an alternative unit of measure than mass for material assessment, as it gives a greater weight to those substances that are more valuable from a physical point of view. The methodology does not incorporate energy costs associated to the manufacturing and use phases of the products where the materials are contained, something that can be assessed through conventional LCA. It only focuses on the physical value of the substances per se. Other physical-based indicators that could eventually come into play are *the ecological footprint*, which consists of converting equivalent global hectares to the direct and indirect consumption of resources (Wackernagel and Rees 1996), or *emergy*, expressing the amount of direct and indirect solar energy needed to produce any product or service (Odum 1995). The problem with the first is that the environmental impact on mining is hardly measurable with biologically productive area and is consequently insensitive to depletion problems. The use of emergy, in turn, is questionable for mineral resource assessment, as the sun has not played a central role in their creation. One could also argue that price would be the better alternative.

This is because the price of a resource sometimes can be even regarded as a measure of its scarcity and societal value. Yet, prices are influenced by particular economic markets, national social conditions reflected in labor cost, the power of mining companies with a monopoly, the costs of identifying new reserves, etc. (Van Oers and Guinée 2016). Thermodynamic rarity, in turn, is a universal and much more stable unit of measure, reflecting physical criticality of mineral resources. It should be mentioned that such an exercise would be impossible with other criticality assessments such as the one defined by the European Commission (2014), based on supply risk or economic importance, since both indicators are dimensionless. This is why Calvo and colleagues (2017) proposed rarity as a new dimension in the criticality assessment of minerals.

It is important to state that rarity should not be confused with recyclability. Rarity measures in the exergy impact of materials contained in a component, considering the scarcity of these materials in nature, by means of the ore grade in mines and the exergy required to extract them from a hypothetical bare rock to postbeneficiation conditions. With this approach, one does not take into account how these materials are found in the specific component. Truly, it is not the same if Co is found homogeneously spread all over the vehicles, or if it is found almost pure in some components. This will not affect the results of the rarity assessment, but will affect recyclability significantly. Recyclability, in turn, depends on the components where materials are contained and hence for each metal a myriad of options appear. Values of exergy are included as Supporting Information available on the Journal's website (see table S1).

Results and Discussion

Materials Used by Type of Vehicle and Component

Table 1 shows the amount of metals considered by type of vehicle. More detailed information about considered assumptions regarding the types of vehicles analyzed according to sales projections and the specific weight of each metal by component and type of vehicle are included as Supporting Information on the Web (see tables S3 to S6).

Mass and Rarity Material Comparison

A comparison between the mass and rarity content of ICEV (internal combustion engine vehicle), PHEV, and BEV vehicles allow one to know the contribution of each metal with both approaches. Comparisons are presented individually for vehicles and batteries. This is because a vehicle's and a battery's end-of-life legislation are different. While ELVs are regulated by EU Directive 2000/53/EC, batteries are regulated by Directive 2006/66/EC, which establishes different mass recycling targets: 65% for lead based batteries, 75% for nickel-cadmium batteries, and 50% for the rest.

Comparison Considering the Vehicle without Batteries

Figure 1 and figure 2 present the contribution of each metal in terms of mass and rarity. Major metals are shown in figure 1, whereas those with a mass share below 0.1% are presented in figure 2. All values expressed in mass and exergy units for ICEVs, PHEVs, and BEVs are detailed as Supporting Information on the Web (see tables S10 to S12).

From figure 1, it becomes evident how iron, aluminum, and copper together account for over 95 wt% of the total amount of metals in the three cases (ICEV, PHEV, and BEV). This situation drastically changes when the assessment is carried out in rarity (rt) terms. Even if iron is the major metal used with mass shares greater than 75 wt%, the rarity share drops to around 15 rt%. On the contrary, aluminum's rarity share increases with respect to a mass assessment (40 rt% vs.12 wt%). This means that small quantities of aluminum used for a vehicle´s light-weighting purposes have a negative impact on the sustainability of the car from a rarity point of view. Aluminum contribution prevails over iron because of its higher embodied exergy associated to the Bayer process. The case of copper is also representative, since its rarity contribution doubles that of its mass contribution. Minor metals accounting for below 0.1 wt% have significantly greater contributions in rarity terms, that is, 34.1 rt%, 27.8 rt%, and 7.5 rt% for ICEVs, PHEVs, and BEVs, respectively. Figure 2 shows this fact in more detail. For instance, around 6 grams (g) of platinum and 1 g of palladium are used to build catalytic converters in ICEVs and PHEVs. Yet, considering their rarity values (per gram, the highest among all considered materials), they are as relevant as iron, aluminum, or copper, accounting for 22 and 7 rt%, respectively, for ICEVs and 15 and 5 rt% for PHEVs.

The importance of materials used in high-strength steel alloys becomes also more evident when using rarity as the unit of measure. Niobium passes from a share of 0.04 wt% to over 1 rt%, whereas vanadium passes from 0.09 wt% to 0.8 rt%. Something similar occurs to important materials demanded in electric and electronic components such as tantalum, neodymium, silver, or gallium. In BEVs, tantalum share increases from 0.001 wt% to over 3.5 rt% and neodymium from 0.08 wt% to 0.3 rt%, while gallium and silver pass from less than 0.01 wt% to around 0.6 rt% and 0.2 rt%, respectively.

As a summary, table 2 shows the metals where recycling efforts should be placed if the unit of measure in the European reuse and recycling target were mass (as it is now) or exergy through rarity indicator. The situation today is that the target can be achieved if iron and aluminum were fully recycled. Yet with rarity, at least platinum, palladium, and copper should be additionally considered depending on the type of vehicle. Note that this is a simplification, as complete recycling is impossible from a thermodynamic point of view (Reuter et al. 2006) and the maximum achievable recycling rates should be analyzed on a case-by-case basis. In fact, as Hagelüken and Meskers (2009) or Granata and colleagues (2011) state, certain high-tech metallurgical processes are capable to recover as by-products precious metals such as platinum group metals from automotive catalysts.

Table 1 Studied materials in vehicles (g) per unit of vehicle analyzed

		Type of vehicle		
Material	*ICEV*	*PHEV NiMH*	*PHEV Li:ion*	*BEV*
Ag	17.5	28.0	28.0	29.8
Al	110,544	115,544	141,370	200,000
Au	0	0.20	0.20	0.32
Ce	46.95	2,127	49.67	0.15
Co	0	8,313	2,712	9,330
Cr	6,510	6,510	6,510	6,031
Cu	28,500	43,481.92	59,166	150,000
Dy	14.70	165.72	165.72	224.63
Er	0	0.18	0.18	0.18
Eu	0.23	0.23	0.23	0.23
Fe	806,144	853,826	806,144	746,945
Ga	0.42	0.81	0.81	1.12
Gd	0.18	0.17	0.17	0.17
Ge	0	0.05	0.05	0.08
In	0.38	0.38	0.38	0.38
La	4.04	14,555	7.38	7.38
Li	1.36	1.36	2,242	7,709
Mn	5,968	5,968	5,968	5,530
Mo	260	260	260	260
Nb	426.30	426.30	426.30	426.30
Nd	162	2,631	552.79	749.30
Ni	1,780	82,832	16,049	55,724
Pb	5,850	5,850	5,850	5,850
Pd	1.24	0.94	0.94	0
Pr	16.53	2,129	51.48	98.00
Pt	7.85	5.51	5.51	0
Rh	0.01	0.01	0.01	0
Sm	1.98	2.32	2.32	3.15
Ta	6.99	10.83	10.83	10.83
Tb	0	13.62	13.62	26.93
V	852.61	852.61	852.61	790
Yb	0	0.08	0.08	0.16
Y	0.41	0.41	0.41	0.41
Weight analyzed (kg)	967	1,145	1,048	1,190
Weight analyzed (%)	82.5%	84.7%	80%	74.7%
Other mat. (kg)	206.1	206.1	263.1	402.4
Total weight (kg)	1,173	1,351	1,311	1,592

Note: "Other mat." refers to rubbers, plastics, glasses, and fluids.
g = grams; ICEV = internal combustion engine vehicle; PHEV = plug-in hybrid electric vehicle; BEV = battery electric vehicle; kg = kilograms.

Comparison in Batteries

Figure 3 represents the mass and rarity contribution for all metals required for batteries analyzed: lead based, NiMH, and Li:ion.

The case of lead batteries is straightforward, as its major component is lead. Hence, mass and rarity approaches provide similar results. For Li:ion, Co becomes very relevant in rarity terms, accounting for 46 rt% of the total with respect to the 4 wt%. The rarity share of Cu, in turn, drops from 26 wt% to only 8 rt%. Something similar occurs with iron in NiMH, which passes from 30 wt% to only 1 rt%, while cobalt prevails over the rest, with a 56 rt% rarity share (vs. 5 wt%).

With these results, one can now identify which would be the metals where more recycling efforts should be placed if EU reuse and recycling targets were rarity instead of mass based. This is presented in table 3. In lead batteries, both approaches provide the same results. Yet for NiMH and Li:ion, cobalt becomes the most relevant metal to be recycled.

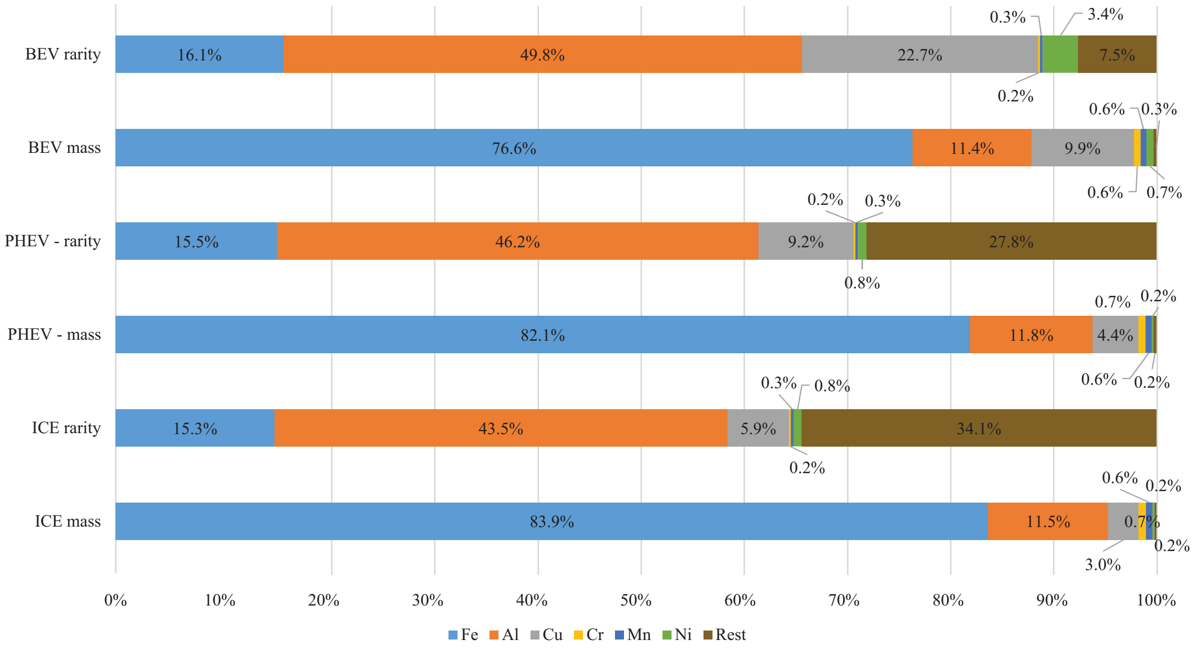

Figure 1 Mass and rarity for materials with a mass share greater than 0.1 wt%. BEV = battery electric vehicle; ICE = internal combustion engine; PHEV = plug-in hybrid electric vehicle.

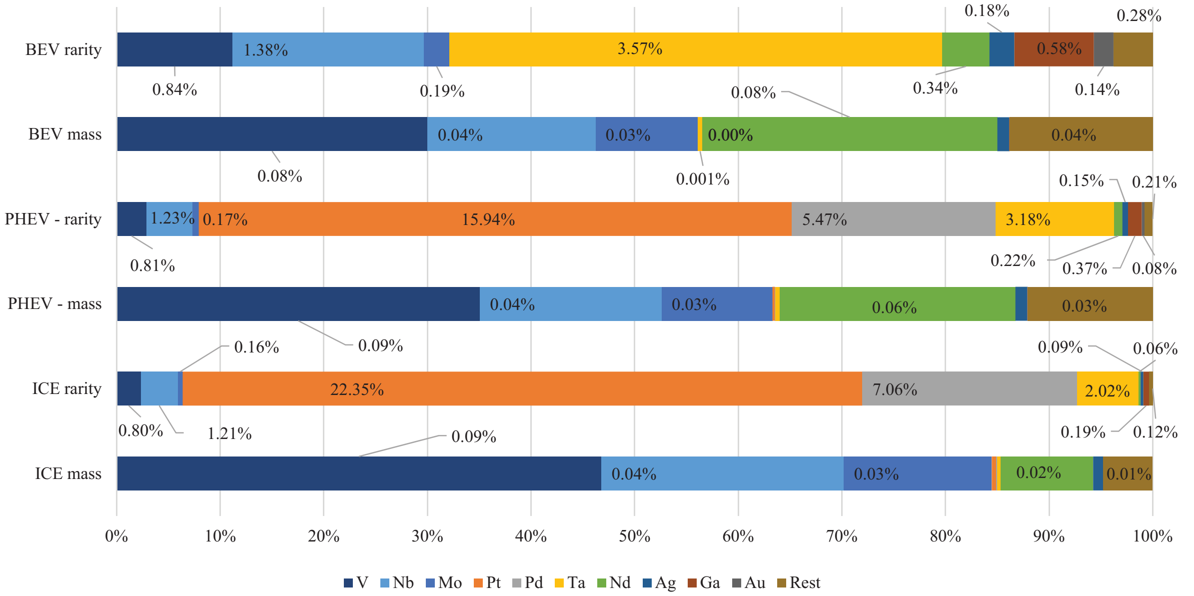

Figure 2 Mass and rarity for materials with a mass share below 0.1 wt%. BEV = battery electric vehicle; ICE = internal combustion engine; PHEV = plug-in hybrid electric vehicle.

Light-Duty Vehicle Components Comparison

One could go a step further and calculate thermodynamic rarity values by component and type of vehicle. By doing this, it would be easier to identify which are those car parts with the largest material rarity share, and thus advice for improving their eco-design and material recovery at the end of life. Rarity values are compared to the same results obtained using mass.

As can be seen in figure 4, both approaches point to the BEV as being the most material intensive from all types. While the heaviest parts (body, brakes, suspensions, and steering) are similar in the four analyzed cases, the BEV has an extra weight caused mainly by batteries and electronic components. It is also remarkable that PHEV weight grows from 1,048 to 1,145 kilograms (kg) if the NiMH instead of the Li:ion battery is used. This is because of the lower power density of

Table 2 Metal contribution to achieve EU Directive 2000/53/EC requirements under rarity and mass approaches

	Reuse and recycle 85%	
Type of vehicle	*Rarity*	*Mass*
ICEV	Al, Pt, Fe, Pd	Fe, Al
PHEV	Al, Pt, Fe, Cu	Fe, Al
BEV	Al, Cu, Fe	Fe, Al

Note: ICEV = internal combustion engine vehicle; PHEV = plug-in hybrid electric vehicle; BEV = battery electric vehicle.

Table 3 Metal contribution to achieve EU Directive 2006/66/EC requirements under rarity and mass approaches

	Recycling 65%	
Type of batteries	*Rarity*	*Mass*
Lead	Pb	Pb
NiMH	Co, Ni	Ni, Fe
Li:ion	Co, Al	Ni, Al, Cu

metallic hydrides with respect to Li:ion. Besides, electrical and electronic component's BEV weight is 68 kg on average, whereas that for the PHEV and ICEV it is only 44 and 28 kg, respectively.

Considered as a whole, an average BEV is around 220 and 140 kg heavier than an ICEV and PHEV, respectively. Such components are not only heavier, but contain critical materials with significant higher rarity contents. Figure 5 shows material contribution to the rarity value for each type of component and vehicle.

From a rarity point of view, even if BEVs are also the highest material-intensive vehicles, the distance to the other two types, especially to the ICEV, is far more pronounced. The rarity of a BEV is 2.2 times greater than that of the ICEV, yet it is only 22% heavier. With respect to the Li:ion-PHEV, the BEV has a rarity content that is 61% greater (but 13% heavier). Again, the differences among them are mainly caused by the contribution of batteries and electronic components, but also because of the greater aluminum use in the body's BEV for light-weighting purposes. Indeed, light-weighting constitutes an important challenge for electromobility because it is one effective way to increase a vehicle's autonomy. Nevertheless this is not without difficulties because battery autonomy heavily depends on their weight.

Battery autonomy is, in fact, the reason why this component is especially relevant for BEV, less so in the Li:ion-PHEV and almost insignificant for an ICEV. Nickel and cobalt account for more than 60 rt% of the battery's rarity in BEV and Li:ion-PHEV. Li in turn, accounts for around 3 rt% in both cases. The battery's rarity in the NiMH-PHEV case is 2.4 times greater than that of Li:ion-HEV and similar as in the BEV, although its autonomy is 4 times smaller. This is a consequence of the greater Ni and Co demand with respect to the Li:ion battery and the need for rarity intensive elements La, Pr, and Nd. Finally, in the case of ICEV, with a lead base battery, Pb demands most of the total rarity. All values expressed in mass and exergy terms for batteries are included as Supporting Information on the Web (see tables S13 to S16).

This unbalance is also very remarkable for the electric and electronic components. BEV and PHEV rarities are 2.2 and 1.7 times greater than in ICEV, respectively. This is mainly due to

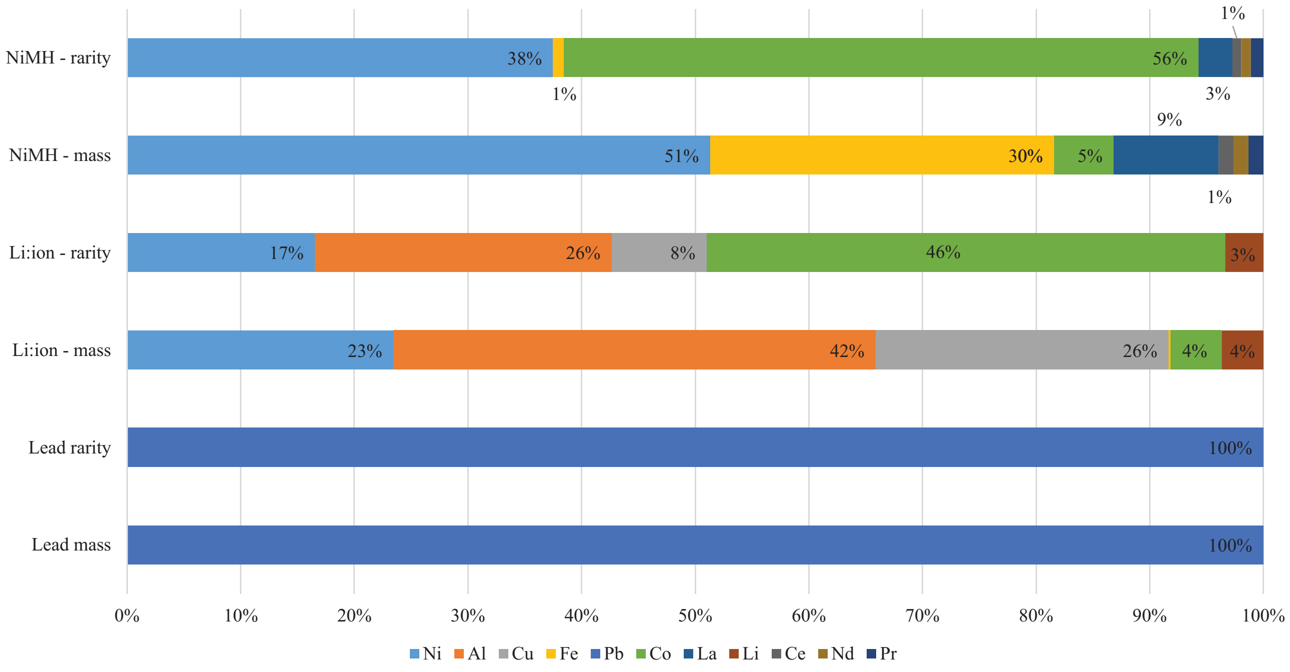

Figure 3 Mass and rarity comparison in different batteries.

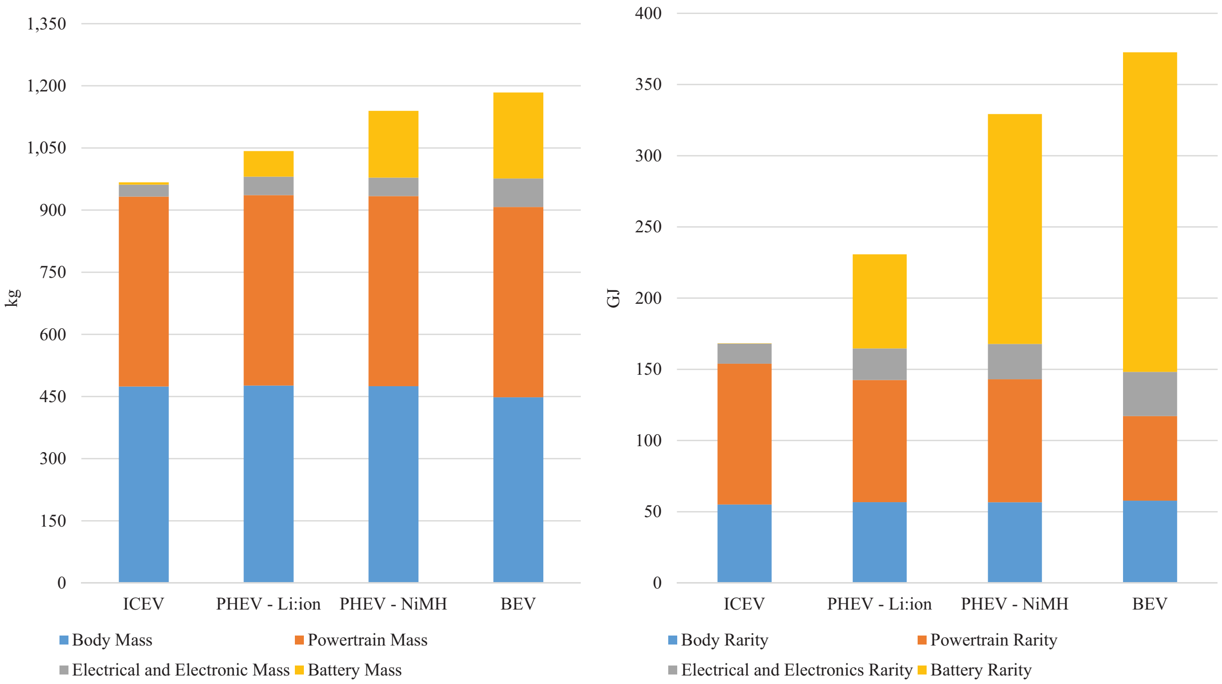

Figure 4 Mass and rarity by component and type of vehicle. BEV = battery electric vehicle; GJ = gigajoules; ICE = internal combustion engine; kg = kilograms; PHEV = plug-in hybrid electric vehicle.

the greater amount of Cu in the first vehicle types (i.e., Cu share for the BEV is near 80 rt%). That said, tantalum is also an important element, accounting for around 20 rt% of total electrical and electronic rarity. The most critical component in the ICEV and PHEV is the powertrain. This is because of the platinum and palladium content in the catalyzer, which are elements with the highest rarities per gram of all materials considered. Both account for more than 40 rt% of the powertrain's rarity in the ICEV and PHEV. Fortunately, such elements are also highly recovered, getting recycling shares of up to 90% (BASF 2012). The fact that they can be separated from the molten metal more easily than other elements for their metallurgical properties also helps to achieve the mentioned shares. It should be noted that even if BEVs do not contain catalyzers, the greater Al content in the powertrain with respect to the other two vehicles (with a contribution of 62 rt%), makes this component to have an important rarity's share. Not surprisingly therefore, Al is the material with the highest rarity contribution in the body, with 62 rt% to 68 rt% of the total share depending on the type of vehicle.

Not insignificant either are refractory metals used as steel alloys, such as Cr, Mn, Mo, Nb, Ni, and V, which account all together for 10 rt% of the body′s rarity in the case of the ICEV and PHEV and 15 rt% in the BEV. Niobium included in the steels of the ICEV, for instance, contributes to 4 rt% of the body′s rarity, but only 0.09 wt% to its mass, that is, 2 orders of magnitude more. While Fe is almost fully recovered as new Fe source through magnetic processes, other metals contained in the body become downcycled or lost. Today, there are more than nine types of steel containing less than 0.5% of critical elements, conferring special properties to the body and for satisfying safety standards and fuel efficiency requirements. Moreover, the future is moving toward the so-called "high-entropy" alloys. These consist of four, five, or more elements (such as Nb, Sc, Co, Cr, Ni, Ti, Fe, Al, or any other from the periodic table) mixed together in roughly equal ratios, leading to lighter and stronger materials than their conventional counterparts, while being much more resistant to corrosion, radiation, or severe wear (Lim 2016). As can be inferred from its name, recovering the elements from high-entropy alloys will be even more difficult than it is now. This is because today when the body goes to the fragmenting process, all steel types are mixed together, complicating the recovery of valuable materials such as Nb, Cr, Ni or V. In this respect, Ohno and colleagues (2014) demonstrated how around 60 wt% of Ni, Cr, and Mo contained in light-duty vehicles (LDVs) end unintentionally as an iron source in an electric arc furnace steel-making process and cannot be recovered. The case of Ni losses in shredding processes is so illustrative because approximately only 40 wt% of nickel contained in automobiles is reused for its nickel content in steel plate rolls, another 40 wt% is recycled into other metals and becomes unavailable to the nickel recycling loop, and, finally, around 20 wt% ends in landfills (Nickel Institute 2016).

For this reason, specific operations to dismantle components, recycle ASR, and reuse critical materials in vehicles must be urgently encouraged by European policies and implemented by the automotive industry. Particularly, separation of high-value components should be done in vehicles during the ELV treatment and before the shredding process.

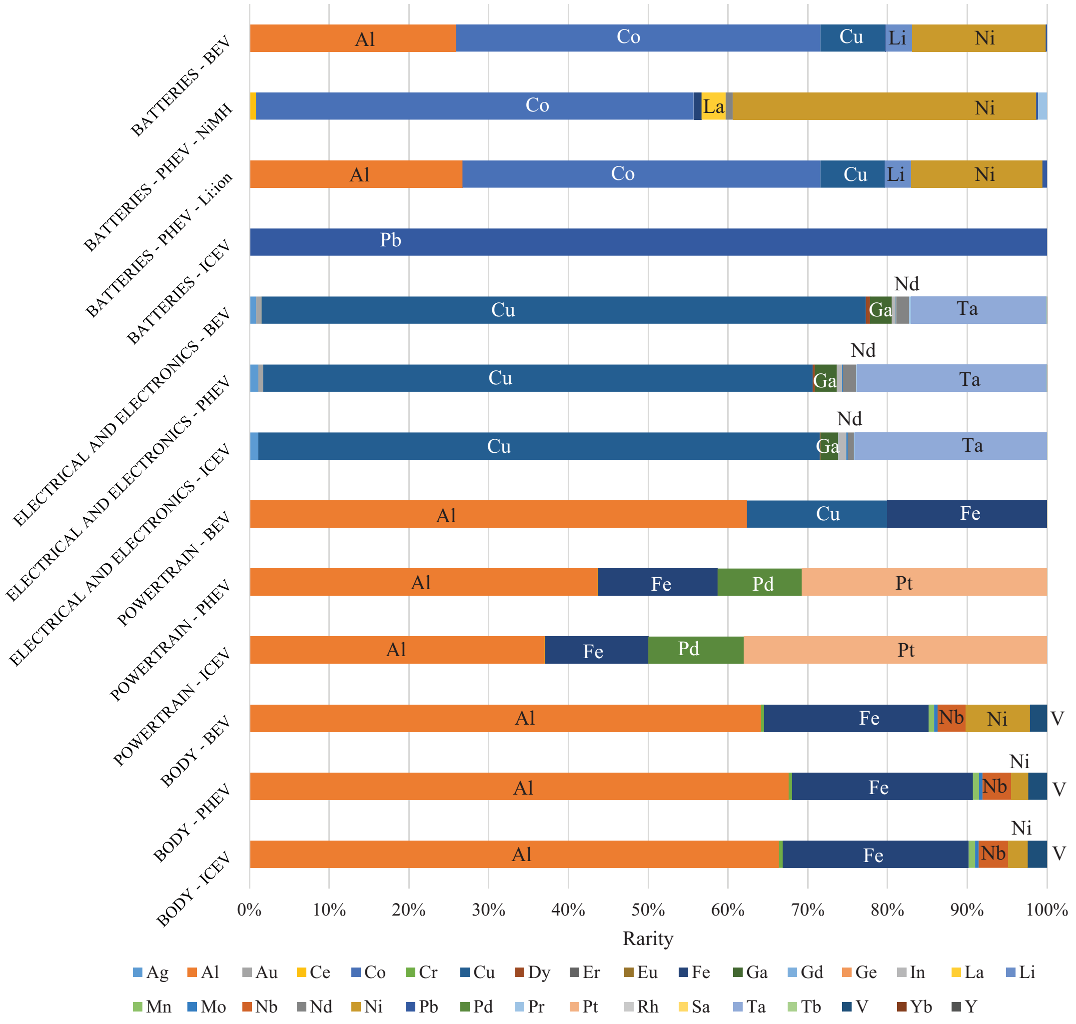

Figure 5 Rarity contribution in different types of vehicles. BEV = battery electric vehicle; ICE = internal combustion engine; PHEV = plug-in hybrid electric vehicle.

Nevertheless, it must be taken into account that metals are commonly spread in many vehicle parts (i.e., in a conventional LDV, the same metal can be present in more than 1,000 parts). This implies that disassembly by authorized treatment facilities of such rarity-intensive components (i.e., instrument panels, dashboards, capacitors, electronic control units, motors, wirings, sensors, or switchers) should be mandatory as it is done with catalytic converters, tires, fluids, or lead batteries. Moreover, and to guaranty the feasibility of the process, these parts should be designed to be disassembled quickly and easily.

In summary, considering the added value that rarity concept provides with respect to a conventional mass accounting, the following outcomes have been obtained:

- Although the weight increase in PHEVs and BEVs with respect to the ICEV is not remarkable, there is a substantial value increment related to those materials needed for electrical-electronic components and batteries. This means that from a thermodynamic rarity point of view, ICEV is better than the PHEV and BEV alternatives.
- If rarity per kilometer (km) of autonomy is assessed, it can be stated that NiMH batteries are worse from a thermodynamic rarity point of view than Li:ion batteries. NiMH has a rarity of 3.25 gigajoules (GJ)/km, while Li:ion has only 1.33 GJ/km.
- In the BEV and NiMH-PHEV and contrary to the other cases, electrical and electronic components and chemical storage devices together are even more important from a rarity point of view than the body and powertrain. Special attention should be paid to: Co, Ni, La, and Li (batteries) and Cu, La, Mo, and In (electrical and electronic components).
- The powertrain and the body contribute similarly in value in the three cases, yet the first is more critical than the latter. This is mainly due to the use of Al in powertrain components such as engine parts or suspensions. Refractory metals contained in steel alloys contribute substantially to the rarity of the body.

Conclusions

The application of the rarity approach allows not only to recognize the physical value of materials with a low-weight contribution, but also to quantify their specific importance in the vehicle as a whole. Particularly, it has been demonstrated that Al, Co, Cu, Ni, and La (used in chemical storage systems), Nb, Cr, Mo, and V (used in steel alloys), Ce, Pt, and Pd (used in catalytic converters) or Nd, In, Ga, and Ta (used in electrical and electronical applications), of which weight contribution in the vehicle as a whole is small, are not insignificant when considering their rarity. The demand of these materials will grow in the transition through zero emission vehicles, making PHEVs and BEVs worse from a thermodynamic rarity point of view than ICEVs. This situation will become even more acute in the future with the installation of sensors and connectivity devices in autonomous vehicles.

Therefore, if recycling policies use targets based on mass, even if they are ambitious, they fail in enhancing the recycling of the CM. This could be solved by using thermodynamic rarity as the unit of measure instead. Indeed, even if Fe, Al, and Cu account for more than 95 wt% of a vehicle's metal content, their relative thermodynamic contribution drops to less than 70 rt% in ICEV and PHEV cases, what would lead to recover other types of materials. For instance, a vehicle's recycling target should pass from 85 wt% (excluding plastics, rubber, and glass) to 90 wt% if Ta had to be recovered using rarity as the unit of measure.

The proposed approach also helps automobile manufacturers to quantify the impacts of using and not recovering a particular metal in their vehicles, serving as a guideline for ecodesign. For instance, with a detailed rarity analysis, it is possible to identify which parts of the car should be key to recover and hence find ways to improve disassembly times. Equally, it would allow to identify where to enhance more research on substitution materials. Substitution should especially be focused on those elements with higher rarities. As was seen, high-rarity materials are going to form part of the new generation of vehicles. This will probably lead to a future supply risk that may hinder the very development of the electric vehicle.

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References

ACEA. 2014. *Vehicle statistics*. http://www.acea.be/statistics/article/anfac-vehicles-in-use-report. Accessed 30 June 2016.

Andersson, M., M. Ljunggren Söderman, and B. A. Sandén. 2017. Are scarce metals in cars functionally recycled? *Waste Management* 60: 407–416.

BASF. 2012. *Typical ceramic auto catalyst processing and refining*. Lincoln Park, MI, USA: BASF Corporation.

Calvo, G., A. Valero, and A. Valero. 2017. Thermodynamic approach to evaluate the criticality of raw materials and its application through a material flow. *Journal of Industrial Ecology*. https://doi.org/10.1111/jiec.12624.

Calvo, G., G. Mudd, A. Valero, and A. Valero. 2016. Decreasing ore grades in global metallic mining: A theoretical issue or a global reality? *Resources* 5(4): 36.

Castro, M. B. G., J. A. M. Remmerswaal, J. C. Brezet, and M. A. Reuter. 2007. Exergy losses during recycling and the resource efficiency of product systems. *Resources, Conservation and Recycling* 52(2): 219–233.

Castro, M., J. Remmerswaal, M. Reuter, and U. Boin. 2004. A thermodynamic approach to the compatibility of materials combinations for recycling. *Resources, Conservation and Recycling* 43(1): 1–19.

Cox, D. P. and D. A. Singer. 1992. *Grade and tonnage model of distal disseminated Ag- Au, in Bliss, J.D., ed.* Directive 2000/53/EC of the European Parliament and of the Council on End of Life Vehicles (2000). Mineral Deposit Models, Vol. US Geological Survey Bulletin 1693 (US Geological Survey). http://pubs.usgs.gov/bul/b1693/. Accessed January 2014.

Du, X., E. Restrepo, R. Widmer, and P. Wäger. 2015. Quantifying the distribution of critical metals in conventional passenger vehicles using input-driven and output-driven approaches: A comparative study. *Journal of Material Cycles and Waste Management* 17(2): 218–228.

European Commission. 2014. *Report on Critical Raw Materials for the EU*. Report of the Ad-hoc Working Group on defining critical raw materials. Brussels: European Commission.

European Commission. 2016. End of life vehicles—Waste—Environment—European Commission. European Parliament and The Council. Directive 75/442/EEC on Waste (1975). Brussels: European Commission.

European Parliament and The Council, 1975. Directive 75/442/EEC on Waste.

Eurostat. 2015. Passenger cars in the EU—Statistics explained. Eurostat Data Base. New registrations of passenger cars by type of motor energy. http://ec.europa.eu/eurostat/web/transport/data/database. Accessed 30 November 2016.

Faber, M. and J. Proops. 1991. *Ecological Economics: The Science and Management of Sustainability National Accounting, Time and the Environment*. (C. University, Ed.), *Ecological Economics: The Science and Management of Sustainability National Accounting, Time and the Environment*. New York: Columbia University.

Graedel, T., E. Harper, N. Nassar, P. Nuss, and B. K. Reck. 2015. Criticality of metals and metalloids. *Proceedings of the National Academy of Sciences of the United States of America* 112(14): 4257–4262.

Granata, G., E. Moscardini, G. Furlani, F. Pagnanelli, and L. Toro. 2011. Automobile shredded residue valorisation by hydrometallurgical metal recovery. *Journal of Hazardous Materials* 185(1): 44–48.

Grigor'ev, N. A. 2000. The average mineral composition of the upper continental crust. *Ural Geology* 3: 3–21.

Gutowski, T. G. 2008. Thermodynamics and recycling: A review. In *IEEE International Symposium on Electronics and the Environment. In Absolute versus Relative Environmental Sustainability: What can the Cradle-to-Cradle and Ecoefficiency Concepts Learn from Each Other*, 321–332. San Francisco. 19–22 May 2008. 2008 IEEE International Symposium on Electronics and the Environment.

Gutowski, T. G. and J. B. Dahmus. 2005. Mixing entropy and product recycling. In *Electronics and the Environment, 2005. Proceedings of the 2005 IEEE International Symposium on*, 72–76. New York: IEEE.

Hagelüken, C. and C. Meskers. 2009. Technology challenges to recover precious and special metals from complex products. *R'09 World Congress, Davos, . . .*, 6. http://ewasteguide.info/system/files/Hageluecken_2009_R09.pdf.

Hatayama, H., I. Daigo, Y. Matsuno, and Y. Adachi. 2012. Evolution of aluminum recycling initiated by the introduction of next-generation vehicles and scrap sorting technology. *Resources, Conservation and Recycling* 66: 8–14.

Ignatenko, O., A. van Schaik, and M. A. Reuter. 2007. Exergy as a tool for evaluation of the resource efficiency of recycling systems. *Minerals Engineering* 20(9 special issue): 862–874.

Ignatenko, O., A. van Schaik, and M. A. Reuter. 2008. Recycling system flexibility: The fundamental solution to achieve high energy and material recovery quotas. *Journal of Cleaner Production* 16(4): 432–449.

Juska, C. 2007. *Moving toward sustainable plastics*. Ann Arbor, MI, USA: The Ecology Center.

Lim, X. 2016. Metal mixology. *Nature* 533: 306–307.

Løvik, A. N., R. Modaresi, and D. B. Müller. 2014. Long-term strategies for increased recycling of automotive aluminum and its alloying elements. *Environmental Science & Technology* 48(8): 4257–4265.

Nakajima, K., O. Takeda, T. Miki, and T. Nagasaka. 2009. Evaluation method of metal resource recyclability based on thermodynamic analysis. *Materials Transactions* 50(3): 453–460.

Nickel Institute. 2016. Recycling of nickel-containing materials in automobiles. Toronto, ON, Canada: Nickel Institute.

Odum, H. 1995. *Environmental accounting. Emergy and environmental decision making*. New York: Wiley.

Ohno, H., K. Matsubae, K. Nakajima, S. Nakamura, and T. Nagasaka. 2014. Unintentional flow of alloying elements in steel during recycling of end-of-life vehicles. *Journal of Industrial Ecology* 18(2): 242–253.

OICA (International Organization of Motor Vehicle Manufacturers). 2016. Sales statistics. www.oica.net/category/sales-statistics/. Accessed 15 July 2016.

Restrepo, E., A. N. Løvik, P. Wäger, R. Widmer, R. Lonka, and D. B. Müller. 2017. Stocks, flows and distribution of critical metals in embedded electronics in passenger vehicles. *Environmental Science & Technology* 51(3): 1129–1139.

Reuter, M. A., A. van Schaik, O. Ignatenko, and G. J. De Haan. 2006. Fundamental limits for the recycling of end-of-life vehicles. *Minerals Engineering* 19(5): 433–449.

Rudnick, R. L. and S. Gao. 2003. Vol. 3 The Crust, 3.01—The composition of the continental crust. In *Treatise on geochemistry*, edited by H. D. Holland and K. K. Turekian. Oxford, UK: Elsevier-Pergamon, 1–64.

Swart, P. and J. Dewulf. 2013. Modeling fossil energy demands of primary nonferrous metal production: The case of copper. *Environmental Science & Technology* 47(24): 13917–13924.

Valero, A. and A. Valero. 2012. Exergy of comminution and the Thanatia Earth's model. *Energy* 44(1): 1085–1093.

Valero, A. and A. Valero. 2013. From grave to cradle: A thermodynamic approach for accounting for abiotic resource depletion. *Journal of Industrial Ecology* 17: 43–52.

Valero, A., A. Valero, and J. B. Gómez. 2011. The crepuscular planet. A model for the exhausted continental crust. *Energy* 36(1): 694–707.

Valero, A., A. Valero, and P. Vieillard. 2012. The thermodynamic properties of the upper continental crust: Exergy, Gibbs free energy and enthalpy. *Energy* 41(1): 121–127.

Valero, A. and A. Valero Delgado. 2015. *Thanatia: The destiny of the Earth's mineral resources: A cradle-to-cradle thermodynamic assessment*. Hackensack, NJ, USA: World Scientific.

Valero, A., A. Valero Delgado, and A. Dominguez. 2013. Exergy replacement cost of mineral resources. *Environmental Accounting and Management* 1(2): 147–158.

Van Oers, L. and J. Guinée. 2016. The abiotic depletion potential: Background, updates, and future. *Resources* 5(1): 16.

Van Schaik, A., M. A. Reuter, U. M. J. Boin, and W. L. Dalmijn. 2002. Dynamic modelling and optimisation of the resource cycle of passenger vehicles. *Minerals Engineering* 15(11): 1001–1016.

Wackernagel, M. and W. Rees. 1996. *Our ecological footprint: Reducing human impact on the earth*. Gabriola Island, British Columbia, Canada: New Society.

Widmer, R., X. Du, O. Haag, E. Restrepo, and P. A. Wäger. 2015. Scarce metals in conventional passenger vehicles and end-of-life vehicle shredder output. *Environmental Science & Technology* 49(7): 4591–4599.

Supporting Information

Supporting information is linked to this article on the *JIE* website:

Supporting Information S1: This supporting information provides documentation used for the calculations in the main article. The information is presented in the following sections: (1) thermodynamic rarity values used; (2) compilation of critical materials used in passenger cars; (3) material composition of studied vehicles by metal and component; (4) material composition of batteries; rarity and mass approaches in vehicles; and (5) rarity and mass approaches in batteries.

A.3 Paper III

Ortego. A, Valero. Al, Valero. A, Calvo. G, Villacampa. M, Iglesias. M. Strategic metals ranking in the automobile sector. *13th Sustainable Development Energy Water and Environmental Systems Conference. Palermo, Italy.* **4th October 2018.**

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Scope: The 13th Conference on Sustainable Development of Energy, Water and Environment Systems - SDEWES Conference is dedicated to the improvement and dissemination of knowledge on methods, policies and technologies for increasing the sustainability of development by de-coupling growth from natural resources and replacing them with knowledge-based economy, taking into account its economic, environmental and social pillars. Among its areas are included the followings: Smart transport systems and policy; Green economy and better governance; Sustainability comparisons and measurements; Transport management.

Contribution to the work:

- To develop the method to define the metal ranking by means of combining physical and non-physical approaches.
- To define scenarios.
- To calculate the metal ranking.
- To assess the reliability of the thermodynamic approach by comparing the results.

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Strategic Metals Ranking in the Automobile Sector

Abel Ortego, Alicia Valero, Antonio Valero, Guiomar Calvo, Mar Villacampa, Marta Iglesias*

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at the **13th Conference on Sustainable Development of Energy, Water and Environment Systems - SDEWES**
held from September 30 - October 4, 2018 in Palermo, Italy.

Prof Zvonimir Guzović
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Strategic metals ranking in the automobile sector

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ABSTRACT

A conventional passenger vehicle demands more than 50 different types of metals, some of them such as tantalum, indium, niobium or rare earths elements (REE), are considered critical by the European Commission. Besides this, their functional recycling is practically absent. Moreover, the transition to fully electric vehicles will require more electrical and electronic devices, motors and batteries that will need an increasing amount of critical metals.

With the aim to identify possible future metal supply constraints, an own methodology has been developed and applied to the automobile manufacturing industry. This approach defines a variable called Strategic Metal Index (SMI) which is calculated for each metal. The SMI is the result of combining the following parameters: (1) Automobile sector demand with respect to world production; (2) Available reserves; (3) Known resources; (4) Metal production capacity; (5) Economic importance and (6) Supply risk. Together with another methodology called thermodynamic rarity developed by the authors, they should provide a holistic decision support tool for raw material strategic planning in the automobile sector.

The SMI has been applied to 50 metals used by different types of vehicle powertrains. The assessment covers metal demand from 2018 to 2050 according to vehicle sales projections for five different scenarios.

This assessment reflects as main possible constraints: Ni, Li, Co and Mn (batteries); Nd and Dy (permanent magnets); Pt (catalytic converters); Tb (lighting and fuel injectors); Sb (steel alloys and paintings); Au, Ag and Ta (electronics); In (screens); Te (steel alloys and electronics) and Se (sensors and glasses).

KEYWORDS

Material bottlenecks; Strategic raw materials; Resource efficiency; Electric vehicle; Passenger vehicles; Strategic decision tool.

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INTRODUCTION

The vehicle manufacturing sector is one of the largest raw material consumers and the tendency is that this demand will continue growing in the future [1]. Global vehicle sales have doubled in the last 30 years [2] and as a result vehicle world fleet has grown exponentially [3]. For instance, only in the European Union, passenger car fleet has grown by 5% annually in the last 5 years [4] and projections indicate that it will keep growing in the coming years [5]. This evolution in vehicle sales has caused in parallel an increase in raw material demand to manufacture them [6].

Besides, automobile manufacturers are directing their efforts to comply with the environmental protection legislation [7] because stricter regulations are continuously being introduced [8]. As an example, according to the European transport White Paper, before 2050 urban mobility will not be allowed to conventional fueled vehicles [9] and some cities such as Paris, Barcelona, Milan or London have even committed to more ambitious targets to procure that a major area of their cities is zero emissions by 2030 [10]. These cleaner vehicles need more different types of metals and as a consequence in the last years not only the quantity of vehicles has grown but also the number of different raw materials necessary to manufacture them has changed [11]. Some examples of this change is the fact that some steel parts such as engine head, suspension arms or wheels are being substituted by aluminum alloys for light weighting purposes [12–14]. It is also remarkable that more permanent magnets such as neodymium or dysprosium are being demanded to manufacture hybrid or fully electric powertrains [15,16]. Moreover, some metals such as lithium, cobalt or rare earths are being used to manufacture batteries [17] and others like silver, indium, tantalum or lanthanum to make electronic components [18]. As a result, nowadays a conventional vehicle needs around 50 different types of metals [11]. Furthermore, some of these metals such as light rare earth elements, cobalt, gallium, indium, magnesium, niobium, tantalum, or vanadium are considered critical due to potential supply risk problems and economic importance [19–25] or have other associated problems such as the case of rare earths production and the associated thorium accumulation [26].

One solution to guarantee a sustainable use of critical metals is the improvement of recycling processes at the end of life of the product. In the case of ELV, the EU Directive 2000/53/EC sets strict targets to promote the reusing, recycling and recovering of materials (from 2015, the total mass percentage of materials reused and recovered with respect to the average car's weight must be equal to 95%, of which at least 85% must come from reuse and recycling). However ELV recycling operations are mainly focused on recycling major metals such as steel and aluminum alloys [18] and many others are not functionally recycled [11]. Nevertheless, these scarce materials may be recycled, but in reality only a very small proportion is ever recycled back into cars. The vast majority are downcycled into less technically demanding applications or indeed simply thrown away [27]. As it was demonstrated by Andersson et al [18], from a total of 17 metals investigated, only Pt from catalytic converters is functionally recycled. Other examples are the cases of nickel, chromium and molybdenum, which approximately 60% unintentionally ending as the iron source in steel-making process [28].

It is also remarkable the case of nickel, as only 40% of its content in automobiles is reused for its nickel content in steel plate rolls, being the rest downcycled or ending up in landfills [29]. As a result current functional recycling rates of some of these materials are almost negligible because sometimes recycling processes are more expensive than primary raw material costs, as it happens in the cases of indium, gallium, cadmium and tellurium [30]. Indeed, and even if it has been demonstrated that recycling has a huge improving potential by including pre-recycling processes to recover the metals, current recycling rates are still very low [31]. For instance, less than 3 % of the lithium contained in a battery is currently recycled [32] and only 42 % of the total battery waste mass can be recycled with current available technology [33]. As a consequence, the concern regarding raw material availability is becoming an important issue for countries which aim to guarantee their sustainability [22,34–37].

This is why a number of studies have analyzed this specific issue in the car industry. Focusing on the components that use critical metals, Field et al. [38] assessed the use of several critical and minor metals used in a Ford Fiesta, Ford Focus and F-150. They realized that strategic metals were mainly used in electrical, drivetrain and suspension systems. Du et al. [39] quantified the use of critical metals in conventional vehicles by means of an hybrid approach (input and output) and compared the results of previous studies for 25 metals. As a main conclusion it was stated that the comparison among different studies is quite difficult because there are no standard nomenclatures to define vehicle subsystems. Restrepo et al. [40] evaluated the use of critical metals in electronic components used in passenger vehicles. It was demonstrated that REE are mainly found in electric motors (alternator, starters, steering motor, etc…) and drive motors (in hybrid and electric ones). This is why they suggest dismantling strategies for these components before entering shredding processes.

Henbler et al. [41] presented the ESSENZ method that compared a Mercedes-Benz C-Class with different powertrains (petrol, diesel and plug-in hybrid). The method shows that more different materials are used in PHEV and that combustion engines perform better than PHEV in the category of abiotic resource depletion of metals.

Regarding the future availability of raw materials, Simon et al. [17] researched the impact of different types of lithium ion batteries in lithium, cobalt, nickel and manganese supply. The assessment was limited to European passenger vehicle fleets and metal resources. It was identified that a possible shortage in European lithium and nickel reserves might be expected around 2025. Grandell et al. [35] assessed the role of critical metals in clean technologies, including electric vehicles. The paper identified several constraints in the future for Ag, Te, In, Dy, La, Co, Pt and Rh.

In this respect, a new methodology called Thermodynamic Rarity was proposed to assess the use of scarce and critical metals from a thermodynamic perspective [42]. Rarity measures in exergy terms, the impact of materials contained in a component, considering the scarcity of these materials in Nature, by means of the ore grade in mines and the exergy required to extract them from a hypothetical bare rock, to post-beneficiation conditions. Thermodynamic Rarity can be considered as a new dimension to assess metal criticality and it complements other common non-physical assessment dimensions like supply risk or economic importance which are used by the European Commission [43]. This approach has been applied to identify more critical vehicle components for different powertrain vehicles [11] and to calculate the loss of mineral capital in current End of Life Vehicle (ELV) recycling processes [44]. The application of the rarity approach, allows not only to recognize the physical value of materials with a low contribution in mass terms, but also to quantify their specific importance in the vehicle as a whole. This is because scarce and difficult to obtain metals have a higher rarity than abundant ones (i.e. platinum vs. iron). This approach is objective and universal because it is only based on physical parameters. However it is well known that there are non-physical factors that could also provoke metal supply constraints to a given industry such as the specific dependency for these metals, the unavailability of substitution alternatives, the existence of other industries that also demand or compete for the same metal, the future expected demand for emerging technologies or the concentration of mining activity in politically unstable countries. For these reasons the physical point of view must be also complemented with another method that also considers socio-economic parameters.

To advance in scientific knowledge regarding metal availability and importance for the automobile industry, this paper proposes a complementary index to thermodynamic rarity to identify possible raw material supply constraints in the vehicle manufacturing industry until 2050. This method is based on: (1) expected material demand; (2) available reserves; (3) known resources; (4) metal capacity production; (5) supply risks and (6) economic importance. It must be noted that the author's intention is not to propose a new critical metal list but to make a list of strategic metals and to show what vehicle components demand these metals and hence are advised to be eco-designed to avoid future raw material supply risks.

MATERIAL AND METHODS

Strategic Metal Index

An index named Strategic Metal Index (SMI) has been defined in order to rank raw materials in the automobile sector according to different criteria. The SMI index ranges from 0 to 100 and is calculated considering the following variables:

- A: Automobile manufacturing sector demand of each metal with respect to total production. It is calculated by dividing the cumulative demand (2018 – 2050) of automobile manufacturing sector and the total cumulative demand (2018 – 2050) of all sectors for each studied metal. It gives an idea of the importance of the automobile sector in the world capacity production of this metal.
- B: Available reserves with respect to cumulative demand (from 2018 to 2050) of this metal. It is calculated by dividing the total cumulative demand (2018 – 2050) and the available reserves. It gives an idea of the directly geological availability of this commodity.
- C: Metal known resources with respect to cumulative demand (from 2018 to 2050) of this metal. It is calculated by dividing the total cumulative demand (2018 to 2050) and the current known resources. As in the previous case it gives an idea of the geological availability of each commodity but based on resources instead of reserves (i.e. not necessarily economically feasible at the time of determination).
- D: Production capacity and annual demand ratio for each metal (from 2018 to 2050). It is useful because it compares for each studied year the expected demand with the production capacity. To do it, the production capacity is modeled by means of the Hubbert theory. This model is explained in section 2.3.
- E: Economic Importance. Value taken from the Critical Raw Material report published by the European Commission [45]. This index ranges from 0 to 10 and so it can be used in SMI by extrapolating it to a 0 to 100 scale. This variable complements the A variable, and offers an idea of the economic dependency of a given metal.
- F: Supply risk. Value taken from the Critical Raw Material report published by the European Commission [45]. This index ranges from 0 to 10 and so to use it in the SMI index it is extrapolated to a 0 to 100 scale. It offers a geopolitics vision of dependency for each commodity.

The SMI is calculated as the sum of the six described variables (A – F) by means of using weighting coefficients for each one, as follows (equation 1):

$$SMI = \alpha * A + \beta * B + \gamma * C + \delta * D + \varepsilon * E + \zeta * F \qquad \text{Eq. 1}$$

Where: $\alpha + \beta + \gamma + \delta + \varepsilon + \zeta = 1$

Once the SMI is assessed for each metal, all of them can be ranked. Nevertheless at this stage the challenge is to calculate the required variables. In the next sections the assessment methods to calculate reserves data, resources data, metal production capacity and metal demand for each year from 2018 to 2050 are explained.

Reserves and Resources

As extraction is ultimately limited by the amount of minerals present in the crust with sufficient concentration, it is important to know raw material availability in terms of reserves and resources.

Resources (RES) are concentrations of naturally occurring materials on the Earth's crust in such form that economic extraction is feasible, currently or at some future time. Reserves (RSV) in turn are the portion of resources which can be economically extracted or produced at the time of determination. Reserves are thus lower than resources and more dynamic, since identified resources can be reclassified as reserves when commodity prices rise or a decrease in production costs takes place. Different sources have been compared and those considered more accurate have been used for the methodology [46–50]. Information regarding reserves and resources of rare earth elements (REE) comes from [51] and [46].

Variables B and C from equation 1 are calculated by means of dividing resources and reserves by cumulative demand respectively. Appendix A shows the Reserves and Resources values used.

Metal production

As annual production rates need to be synchronized with the rising demand of materials, projections regarding future raw material production are equally required. In this paper it is assumed that material production will follow the Hubbert peak model. Hubbert [52,53] showed that trends in fossil fuels production always followed the same pattern. The curve of production started slowly before rising steeply and tending towards an exponential increase over time. This trend goes on until reaching an inflection point, upon which the curve starts to decrease, generating a bell-shaped curve of normal distribution. The area below the curve depends on the combination of the available reserves or resources and the historic production data of the commodity. Production of commodity pa in year t is given by Equation 2:

$$p_a(t) = \frac{R}{b_0\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{t-t_0}{b_0}\right)^2} \qquad \text{Eq. 2}$$

Where R are the reserves (RSV) or resources (RES) of the commodity and the parameters b_0 and t_0 are the unknowns. The function's maximum is given by parameter t_0, and it verifies that:

$$p_a(t_0) = \frac{R}{b_0\sqrt{2\pi}} \qquad \text{Eq. 3}$$

With this approach, the maximum production peak of the commodity can be obtained, meaning the year when production starts to decrease. Additionally, future yearly projections of production can be obtained using a business-as-usual scenario. It is presumed that production will continue rising with an exponential trend, as it has been the case for most commodities. Yet geological availability in form of reserves or resources prevents at some point this continuing growth.

The variable D from equation 1 is calculated by means of identifying the possible year in which metal production can be smaller than metal expected demand. It is assessed by means of a lineal interpolation, where a bottleneck in 2050 or later has null value and a bottleneck in 2018 has a figure of 100. The model has uncertainty, for this reason the coefficient of determination (R2) for each metal production capacity has been calculated. This coefficient is used to correct the value of the lineal interpolation always extending the maximum capacity year and thus keeping the criteria of a best case scenario. By means of this method those values with a small reliability will not contribute too much in variable D from equation 1.

Metal demand

Metal demand for each type of vehicle has been assessed. Metal composition data for combustion vehicles (petrol and diesel) comes from an automobile manufacturer and in the cases of PHEV and BEV from a scientific paper revision. The metal compositions for each type of vehicle and the assumptions are included in Appendix B. Regarding material demand, it was considered that a certain amount of raw materials comes from secondary sources (recycling processes). As the available information on recycling rates is usually very aggregated or general, the recycling rates used in this study come from the United Nations Environmental Program [54], and are listed in Appendix C. Eq. 4 shows how material demand in the studied vehicles is calculated for a given year for each commodity:

$$d_{a\_tv} = [N * M * (1 - r)] \qquad \text{Eq. 4}$$

Where d_{a_tv} is the quantity of primary material a demanded for the analyzed type of vehicle (tv) during a given year; N is the number of yearly manufactured units of each type of vehicle; M is the quantity of material a demanded by each type of vehicle to manufacture one functional unit - FU (FU=1 vehicle); r is the share of material which comes from recycling.

The impact of recycling on primary production is assumed as one to one displacement because reprocessing does not change material properties. It should be stated though that as Geyer et al. demonstrated [55], this approach is not a rule because rebound effects in demand could appear, so robust models to predict the impact of recycling in primary demand must be yet developed. As the projections presented in this study go until 2050 and the vehicle lifetime is lower, material demand from fleet renovation must be considered. This effect is taken into consideration using Equation 5.

$$N = N_{nv} + N_{rv} \qquad \text{Eq. 5}$$

Where N_{nv} is the number of new vehicles which are added to the global fleet and N_{rv} is the number of vehicle to renew old ones.

Nevertheless, it must be also considered that automobile manufacturing industry will need to compete for materials with many sectors, such as construction, chemicals, metal industry or electronics and with other disruptive sectors such as renewable energy technologies. Unfortunately, for the rest of the sectors the information on material consumption is scattered and in many cases unavailable. This is why in this paper it is assumed that material demand for other sectors (d_{a_os}) will be kept constant until 2050 and equal to the difference between total material production in 2018 $(P_a)_{2018}$ and material demand for vehicles for the same year $(d_{a\_v})_{2018}$ (Eq. 6). Obviously, this is a very conservative assumption as historically material demand for other sectors has usually increased year by year. That said, this assumption allows us to identify the lower bound for potential material constraints regarding material competition of automobile manufacturing sector with other sectors.

$$d_{a\_os} = (P_a)_{2018} - (d_{a\_v})_{2018} \qquad \text{Eq. 6}$$

Accordingly, total demand for a given commodity a in year t (d_{a_T}) is calculated by means of Eq. 7, whereas the total cumulative material demand for commodity a (D_{a_T}) from 2018 to 2050 is obtained through Eq. 8.

$$(d_{a\_T})_t = (d_{a\_v})_t + (d_{a\_os})_t \qquad \text{Eq. 7}$$

$$D_{a\_T} = \sum_{t=2018}^{t=2050} \left[(d_{a\_T})_t\right] \qquad \text{Eq. 8}$$

RESULTS AND DISCUSSION

Vehicle stock and sales projections

The demand projections for each type of vehicle are represented in Figure 1. In the case of annual sales (left) it must be taken into consideration that fleet renovation effect is included. The lifetime considered for all types of vehicles is 17 years according to data published by the Spanish ELV recycling management system [56]. Projections of sales and world fleet evolution are built using data from International Energy Agency roadmaps and the International Organization of Automobile Manufacturers [2,57].

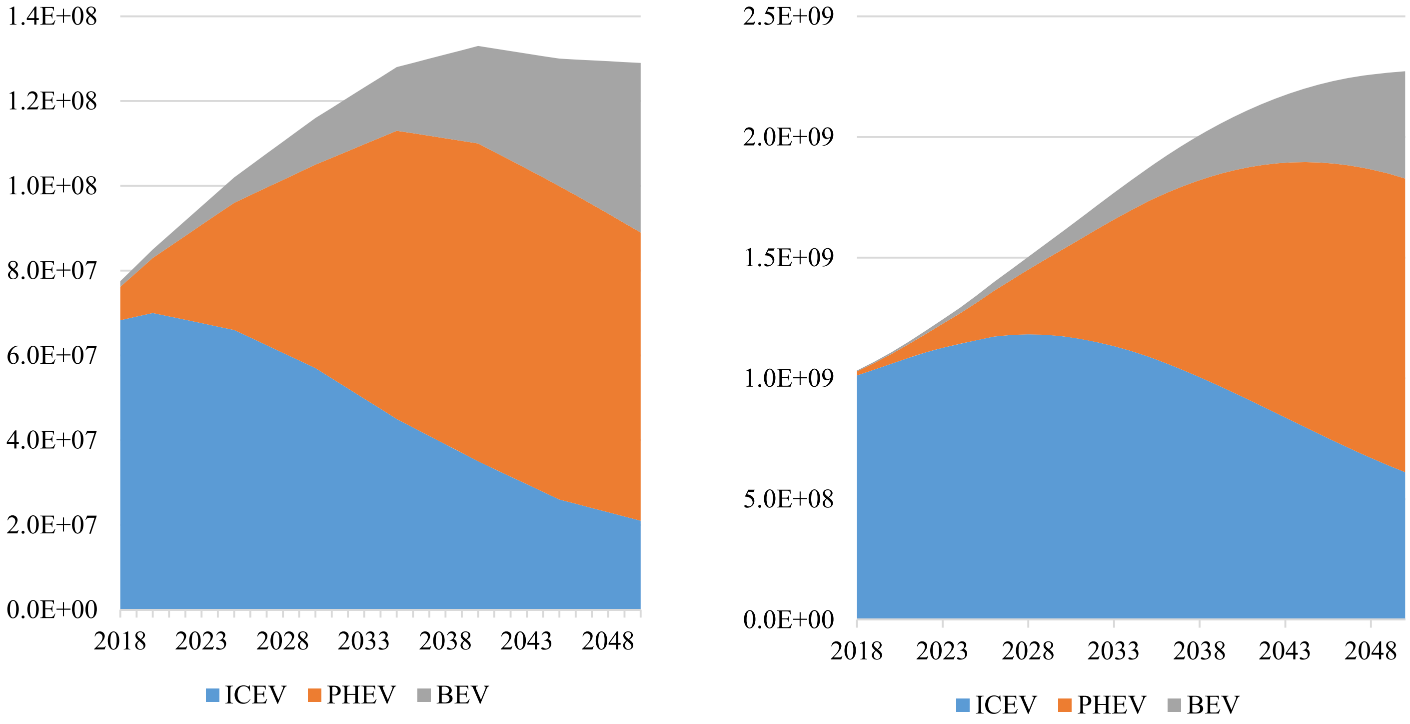

Figure 1: World vehicle sales projection (left) and world fleet evolution (right)

According to the above, world fleet would increase to more than 2,200 million of vehicles in 2050 from which 26 %, 53 % and 19 % will be ICEV, PHEV and BEV respectively. On the other hand, it stands that PHEV and BEV sales would surpass those from ICEV in 2032 and 2044 respectively. Regarding sales it can be observed that beyond 2020 ICEV world sales will decrease.

Metal demand, resources and reserves

Through sales projections, annual material demand by type of vehicle and demand for the rest of sectors for each metal is assessed. These demands are compared to resources and reserves data to calculate B and C parameters of equation 1. In Figure 2, demand, reserves and resources data for each metal are shown.

It can be highlighted that cumulative demand exceeds reserves values for silver, arsenic, gold, cadmium, cobalt, copper, gallium, mercury, indium, nickel, lead, antimony, tin, strontium, tellurium and zinc. However, when comparing the demand with resources it only happens in the case of tellurium. It is important to note that reserves and resources data for tellurium are usually inaccurate or incomplete as it is a byproduct mainly produced during the copper and lead-zinc refining processes.

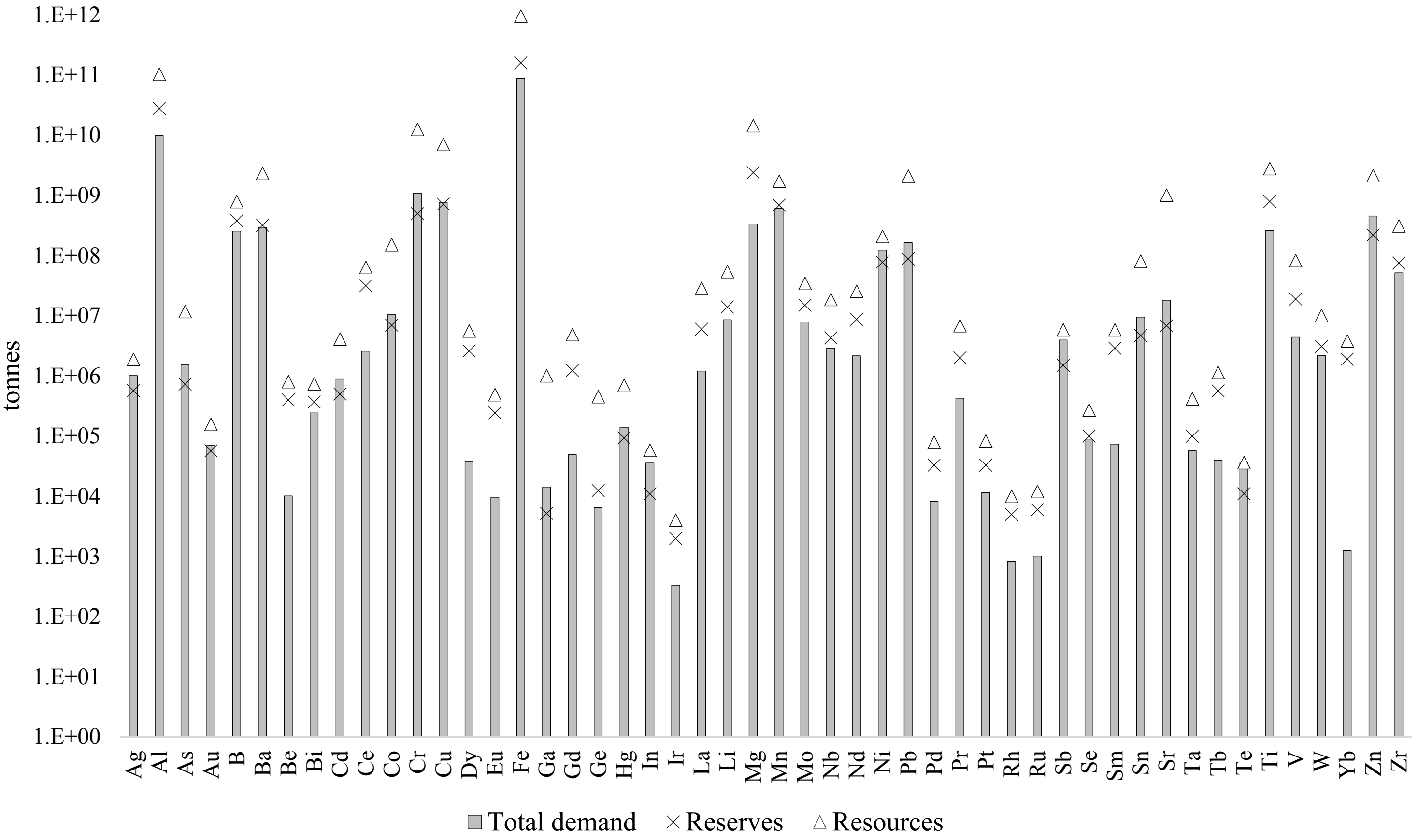

Figure 2: Total demand, resources and reserves for each metal

Annual capacity production comparison with annual demand

Through a combination of metal capacity production and metal demand explained in sections 2.3 and 2.4, respectively, the data of maximum production peaks have been calculated. Table 1 shows those metals where demand may exceed capacity production before 2050, with their regression factors R2 of the Hubbert model applied. The information concerning possible bottlenecks represents the latest possible year considering the reliability or R2.

Table 1: Metals where demand may exceed production before 2050

Metal	R2	Peak production	Possible bottleneck
Ag	0.71	2026	≤ 2040
Au	0.78	2018	≤ 2042
B	0.91	2030	≤ 2047
Co	0.90	>2050	≤ 2026
Dy	0.95	>2050	≤ 2020
Li	0.94	>2050	≤ 2020
Mn	0.84	2027	≤ 2048
Nd	0.96	>2050	≤ 2021
Ni	0.94	2029	≤ 2025
Pt	0.95	>2050	≤ 2023
Sb	0.71	2018	≤ 2040
Se	0.95	2028	≤ 2040
Tb	0.95	>2050	≤ 2019

It can be observed that for Co, Dy, Li, Nd, Pt and Tb the demand and production intersections are achieved before the metal production peak. This means that for these metals the problem is not availability but an excessive expected demand because production and demand intersect along the growing tendency. Tellurium, despite a bottleneck being identified, is not included in the table because R2 is too low to be considered reliable (only 0.35).

Figure 1 presents the case of selenium. According to the Hubbert methodology, a possible production peak may be achieved in 2028. Considering the evolution of the expected demand, the possible bottleneck could arrive in 2035. If the reliability of the model is considered through the R2 value (i.e. 0.95), the maximum capacity production increases and hence the bottleneck is displaced to 2040.

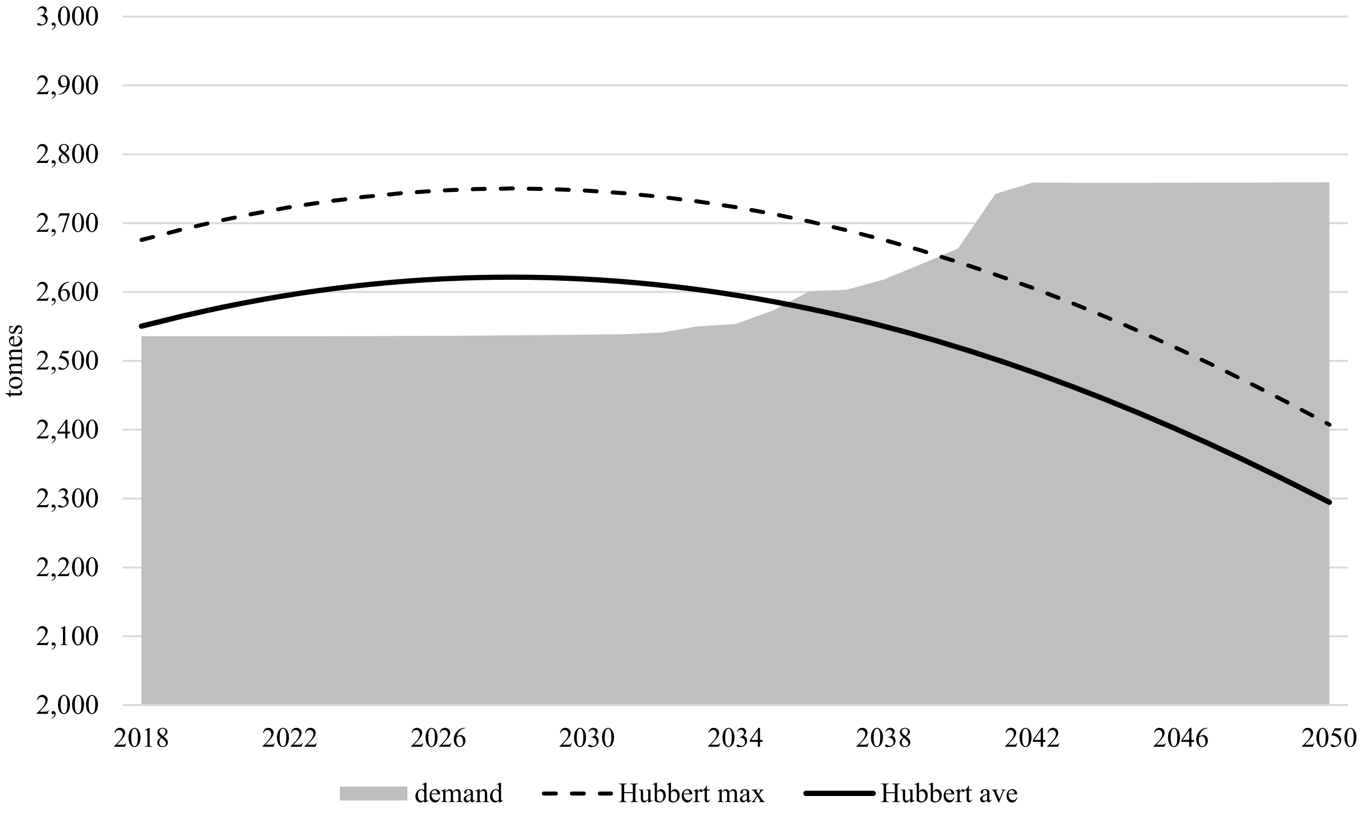

Figure 3: Estimated production and demand for selenium case

Metal strategic Ranking

As different variables are needed to calculate the SMI, several scenarios are presented to assess it under different possible situations. The following scenarios have been defined:

- **Geo:** The higher weight (0.6 over 1) is given to metal geological availability variables (B, C and D). The rest of variables are equitably weighted.
- **EU:** The higher weight (0.6 over 1) is given to the variables defined by the European Commission (E and F). The rest of variables are equitably weighted.
- **Ams:** The higher weight (0.6 over 1) is given to the automobile demand with respect to total demand (A). The rest of variables are equitably weighted.
- **Equi:** All variables have the same weight.
- **Exp:** It is a scenario based on the common criteria between the authors of this paper and the car manufacturer.

The values used for the weighting coefficients are presented in Table 2.

Table 2: Weighting coefficients used for the different scenarios

Scenario	α	B	γ	δ	E	ζ
Geo	0.13	0.2	0.2	0.2	0.13	0.13
EU	0.1	0.1	0.1	0.1	0.3	0.3
Ams	0.6	0.08	0.08	0.08	0.08	0.08
Equi	0.16	0.16	0.16	0.16	0.16	0.16
Exp	0.3	0.1	0.1	0.1	0.2	0.2

The selection of these scenarios allows us to have a range of values in the SMI calculation. Figure 4 represents the SMI ranking and the uncertainty range for each case. Metals are ranked through the SMI value calculated for an Average scenario. The average scenario is calculated as the average SMI value obtained for each metal from the scenarios shown in Table 2. The SMI for the Average scenario is represented with crosses. Color scale means: Red (SMI ≥ 35); Orange (35 > SMI ≥ 20); Green (SMI < 20). The most critical metals under the SMI approach (those which SMI ≥ 50) are Ni (61), Li (57), Tb (56), Co (55), Dy (51) and Sb (51). These metals are followed by Nd (47), Pt (44), Au (40), Ag (40) and Te (40).

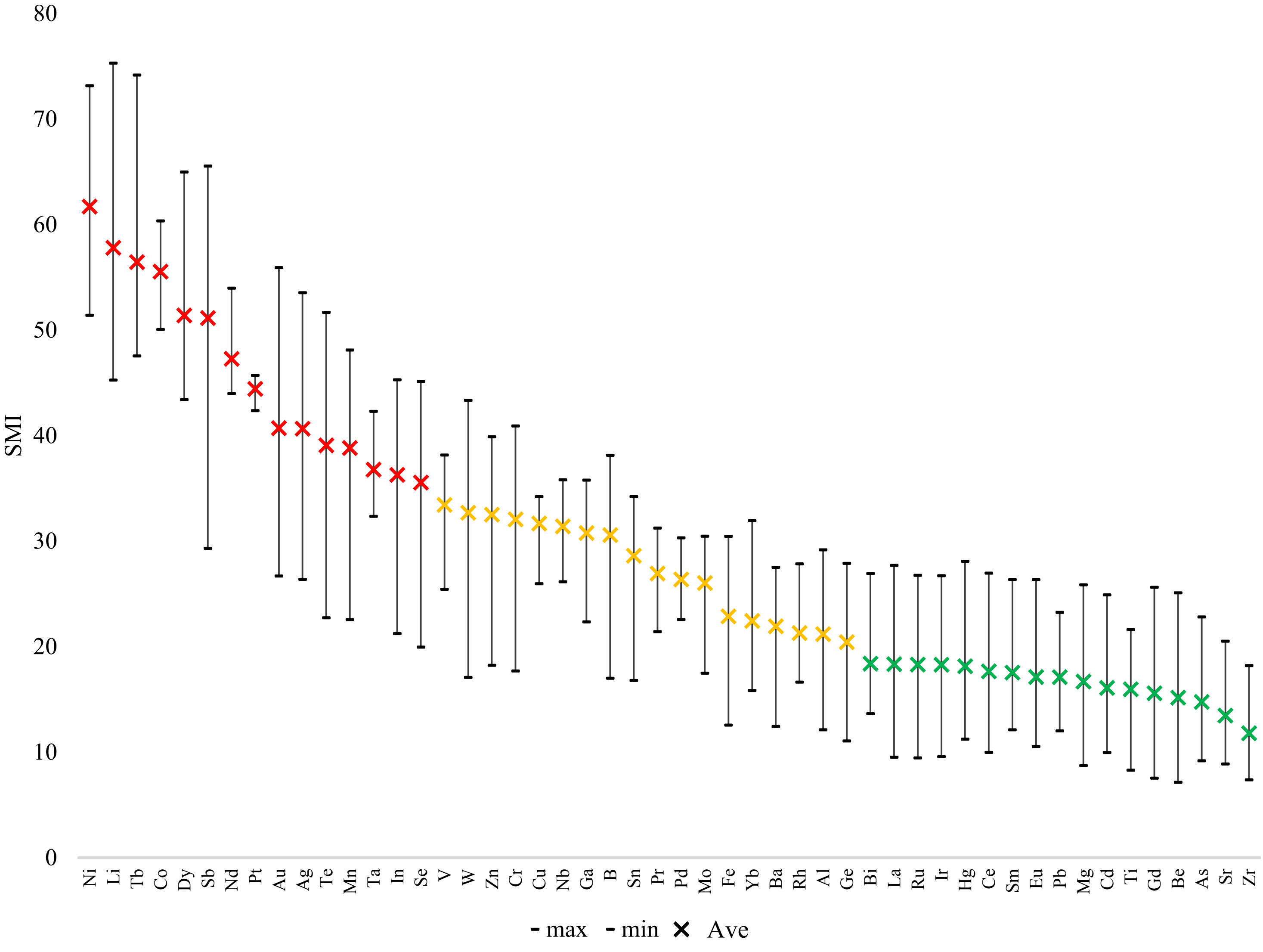

Figure 4: Metal strategic ranking

Considering the possible range of results among the studied metals and scenarios, the lowest corresponds to the Ams scenario for most cases. This scenario assigns the highest impact to the automobile sector demand with respect to the total demand. The opposite case corresponds for Geo and EU scenarios. In Appendix D all SMI values for each metal and scenario are shown.

It must be underlined that the SMI should only serve as a strategic ranking tool for metals in cars. It is not a criticality list of metals because, contrary to general criticality lists such as the one by the European Commission, the SMI reflects material shortages from the perspective of the automobile industry. Obviously, certain metals that are critical by the EC but do not appear in cars are not considered in this approach, i.e. tungsten, hafnium or scandium. However, this does not mean that they might appear in the future, if these metals are demanded in future cars.

Most strategic metals and vehicle applications

The next step is to identify the most critical parts considering the metals with an SMI greater than 35 for the Exp scenario. Table 3 contains this information, showing that the most affected components are batteries, which mainly use Ni, Li Co and Mn, all of these metals with an average SMI value higher than 40 and in the case of Ni, Li and Co even higher than 55.

Moreover, the case of Tb stands out, which is mainly used in lightings and fuel injectors. Lighting equipment can be subject to Se shortages, an element that is also used for glazing manufacturing. Permanent magnets are also included among the most affected components. Dy and Nd have SMI values of 51 and 47, respectively. High strength steel alloys can be also affected, as Sb and Te are ranked between the most strategic metals. Catalytic converters used to treat combustion gases will be also at risk due to their critical metals content. This is mainly because of their Pt content, which has an average SMI of 44. Finally, electronic components that demand Au and Ag for contacts and welding can be subjected also to the possible shortage of Ta to manufacture capacitors or In, which is mainly used in the screens of combi instruments and infotainment units.

Table 3: Main strategic metals and vehicle applications

Metal	SMI range	Applications
Ni	From 51.4 to 73.1	Batteries (NMC and NCA) and steel alloys
Li	From 45.2 to 75.3	Batteries (NMC)
Tb	From 47.5 to 74.1	Lighting and fuel injectors
Co	From 50.0 to 60.3	Batteries (NMC and NCA) and steel alloys
Dy	From 43.4 to 64.9	Permanent magnets
Sb	From 29.3 to 65.5	Steel alloys and paintings
Nd	From 43.9 to 53.9	Permanent magnets
Pt	From 42.3 to 45.7	Catalytic converters
Au	From 26.7 to 55.9	Electronics (contacts coating)
Ag	From 26.4 to 53.5	Electronics (contacts coating)
Te	From 22.7 to 51.7	Steel and lead alloys and electronics
Mn	From 22.6 to 48.1	Batteries (NMC) and steel alloys
Ta	From 32.3 to 42.3	Electronics (capacitors)
In	From 21.2 to 45.3	Screens
Se	From 19.9 to 45.1	Lighting sensors and glasses

CONCLUSIONS

The SMI is presented as a useful index to rank materials demanded to manufacture vehicles according to their possible future strategic importance to the sector and so guide in the formulation of possible ecodesign alternatives. The SMI is calculated through a holistic approach considering physical variables such as reserves and resources and non-physical ones such as supply risks and economic importance of raw materials within and outside the sector.

The SMI should not be understood as a quantitative variable for measuring metal scarcity or criticality. If the SMI value of metal A doubles that of metal B, it does not mean that the former is twice as critical or scarce as the latter. This is for instance the case of aluminum and germanium where the SMI for Al (21.2) is slightly higher than that of Ge (20.4). But in fact germanium is scarcer in the crust than aluminum, and contrary to the latter, due to its global economic importance and supply risks, germanium is considered critical by the European Commission. The SMI rather reflects how scarcity and criticality of a given metal may affect the automotive sector.

Moreover, and contrary to the Thermodynamic Rarity indicator proposed by the authors in previous studies (which uses exergy as the unit of measure to value minerals according to their specific physical features in the crust and mining energy intensities), the assumptions considered implicitly in this method, make that the SME cannot be considered either as a universal numeraire of metal sustainability in the automobile sector. Such assumptions are: (1) the vehicle composition is considered constant throughout the analyzed years; (2) future mineral reserves discoveries are not considered; (3) the possible growth in the metal demand of other sectors is not considered; (4) Metal production capacity is modeled using a Hubbert approach, which is theoretical; (5) Supply risk and economic importance by the EC might change over time (6) the weighting factors used for each category composing the SMI is arbitrary.

Nevertheless, the SMI complements the thermodynamic approach because it provides a different dimension for the potential identification of raw material shortages in the automotive sector. This dimension incorporates non-physical parameters such as supply risk, sector dependency or economic importance which are indeed key for the automobile industry.

Particularly, in this paper we have obtained through the SMI that the main identified shortages are those concerning the manufacturing of batteries in electric vehicles (Ni, Co, Li and Mn), permanent magnets for motors (Nd and Pr), electronic components (Ag, Au, Ta, Te and In), catalytic converters (Pt), fuel injectors (Tb) and paintings (Sb). In fact these same components were also identified as the most relevant when the assessment was carried out from a thermodynamic point of view in a previous research [11] what ensures that the thermodynamic approach at least in the automobile case can be considered as self-sufficient. Yet this may not be the case for other sectors and this is why both approaches are always recommended to have a holistic view of the problem.

For the identified components, automobile manufactures should encourage ecodesign strategies to reduce the demand of these strategic metals, to find substitutes or to increase their functional recyclability. This is why, based on the obtained results, in a future paper, the authors will propose specific ecodesign measures in vehicles.

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NOMENCLATURE

BEV: Battery Electric Vehicle
CRM : Critical raw materials
d: material demand
D: cumulative material demand
ELV: End of Life Vehicle
FU: Functional Unit
GHG: Greenhouse gas
ICEV: Internal Combustion Engine Vehicle
m: studied technologies
N: manufactured units
Nns: new units added to the global market
Nrn: units manufactured to renew installations
PHEV: Plug Hybrid Electric Vehicle
R: reserves or resources
r: material share from recycling
Re: recycling quote
REE: Rare Earth Element
RES: resources
RSV: reserves
SMI: Strategic Metal Index
t: studied years

REFERENCES

[1] Wells P. Automotive materials: the challenge of the globalization and technological change. Cardiff 1998:185.

[2] OICA. Sales statistics 2016. http://www.oica.net/category/sales-statistics/ (accessed July 15, 2016).

[3] Palencia JCG, Otsuka Y, Araki M, Shiga S. Impact of new vehicle market composition on the light-duty vehicle fleet CO2 emissions and cost. Energy Procedia 2017;105:3862–7. doi:10.1016/J.EGYPRO.2017.03.790.

[4] ACEA. Vehicle statistics. 2014.

[5] Simic V, Dimitrijevic B. Resources , Conservation and Recycling Risk explicit interval linear programming model for long-term planning of vehicle recycling in the EU legislative context under uncertainty 2013;73:197–210.

[6] Hernandez M, Messagie M, De Gennaro M, Van Mierlo J. Resource depletion in an electric vehicle powertrain using different LCA impact methods. Resour Conserv Recycl 2017;120:119–30. doi:10.1016/j.resconrec.2016.11.005.

[7] ACEA. EURO standards 2018. http://www.acea.be/industry-topics/tag/category/euro-standards (accessed February 6, 2018).

[8] Singh S, Kennedy C. Estimating future energy use and CO2emissions of the world’s cities. Environ Pollut 2015;203:271–8. doi:10.1016/j.envpol.2015.03.039.

[9] European Commission. White paper. 2011.

[10] C40 cities. mayors of 12 pioneering cities commit to create green and helthy streets 2017. http://www.c40.org/press_releases/mayors-of-12-pioneering-cities-commit-to-create-green-and-healthy-streets (accessed February 6, 2018).

[11] Ortego A, Valero A, Valero A, Restrepo E. Vehicles and critical raw materials. A sustainability assessment using thermodynamic rarity. Ind Ecol 2017.

[12] Hatayama H, Daigo I, Matsuno Y, Adachi Y. Evolution of aluminum recycling initiated by the introduction of next-generation vehicles and scrap sorting technology. Resour Conserv Recycl 2012;66:8–14. doi:10.1016/j.resconrec.2012.06.006.

[13] Løvik AN, Modaresi R, Müller DB. Long-term strategies for increased recycling of automotive aluminum and its alloying elements. Environ Sci Technol 2014;48:4257–65. doi:10.1021/es405604g.

[14] Van Schaik A, Reuter MA. Dynamic modelling and optimisation of the resource cycle of passenger vehicles. Miner Eng 2002;15:1001 1016.

[15] Eurostat. Passenger cars in the EU - Statistics Explained 2015. http://ec.europa.eu/eurostat/web/waste/key-waste-streams/elvs.

[16] Riba J-R, López-Torres C, Romeral L, Garcia A. Rare-earth-free propulsion motors for electric vehicles: A technology review. Renew Sustain Energy Rev 2016;57:367–79. doi:10.1016/j.rser.2015.12.121.

[17] Simon B, Ziemann S, Weil M. Potential metal requirement of active materials in lithium-ion battery cells of electric vehicles and its impact on reserves: Focus on Europe. Resour Conserv Recycl 2015;104:300–10. doi:10.1016/j.resconrec.2015.07.011.

[18] Andersson M, Ljunggren Söderman M, Sandén BA. Are scarce metals in cars functionally recycled? Waste Manag 2016. doi:10.1016/j.wasman.2016.06.031.

[19] Alonso E, Gregory J, Field F, Kirchain R. Material availability and the supply chain: Risks, effects, and responses. Environ Sci Technol 2007;41:6649–56. doi:10.1021/es070159c.

[20] Achzet B, Helbig C. How to evaluate raw material supply risks—an overview. Resour Policy 2013;38:435–47. doi:10.1016/j.resourpol.2013.06.003.

[21] European Commission. Report on critical raw materials for the EU. Report of the Ad hoc working group on defining critical raw materials. 2014.

[22] Moss RL, Tzimas E, Kara H, Willis P, Kooroshy J. Critical Metals in Strategic Energy Technologies. 2011. doi:10.2790/35600.

[23] Moss RL, Tzimas E, Kara H, Willis P, Kooroshy J. The potential risks from metals bottlenecks to the deployment of Strategic Energy Technologies. Energy Policy 2013;55:556–64. doi:10.1016/j.enpol.2012.12.053.

[24] Graedel T, Harper E, Nassar N, Nuss P, Reck BK. Criticality of metals and metalloids. Proc Natl Acad Sci 2015;112:4257–62.

[25] Greenfield A, Graedel TE. The omnivorous diet of modern technology. Resour Conserv Recycl 2013;74:1–7. doi:10.1016/j.resconrec.2013.02.010.

[26] Kamei T. Preliminary Study of Development of the Organization of Rare-Earth Exportation Countries. J Sustain Dev Energy, Water Environ Syst 2013;1:1–13. doi:10.13044/j.sdewes.2013.01.0001.

[27] Wells P. Sustainable business models and the automotive industry: A commentary. IIMB Manag Rev 2013;25:228–39. doi:10.1016/j.iimb.2013.07.001.

[28] Ohno H, Matsubae K, Nakajima K, Nakamura S, Nagasaka T. Unintentional flow of alloying elements in steel during recycling of end-of-life vehicles. J Ind Ecol 2014;18:242–53. doi:10.1111/jiec.12095.

[29] Nickel Institute. Recycling of nickel-containing materials in automobiles 2016.

[30] Redlinger M, Eggert R, Woodhouse M. Evaluating the availability of gallium, indium, and tellurium from recycled photovoltaic modules. Sol Energy Mater Sol Cells 2015;138:58–71. doi:10.1016/j.solmat.2015.02.027.

[31] Wang X, Gaustad G, Babbitt CW. Targeting high value metals in lithium-ion battery recycling via shredding and size-based separation. Waste Manag 2016;51:204–13. doi:10.1016/j.wasman.2015.10.026.

[32] Vikström H, Davidsson S, Höök M. Lithium availability and future production outlooks. Appl Energy 2013;110:252–66. doi:10.1016/j.apenergy.2013.04.005.

[33] Richa K, Babbitt CW, Gaustad G, Wang X. A future perspective on lithium-ion battery waste flows from electric vehicles. Resour Conserv Recycl 2014;83:63–76. doi:10.1016/j.resconrec.2013.11.008.

[34] Silberglitt R, Bartis J, Chow B, An D, Brady K. Critical Materials - Present Danger to US Manufacturing. 2013. doi:978-0-8330-7883-4.

[35] Grandell L, Lehtilä A, Kivinen M, Koljonen T, Kihlman S, Lauri LS. Role of critical metals in the future markets of clean energy technologies. Renew Energy 2016;95:53–62. doi:10.1016/j.renene.2016.03.102.

[36] U.S. Department of Energy. Critical material strategy. 2011.

[37] Graedel TE, Harper EM, Nassar NT, Reck BK. On the materials basis of modern society. Proc Natl Acad Sci U S A 2015;112:6295–300. doi:10.1073/pnas.1312752110.

[38] Field FR, Wallington TJ, Everson M, Kirchain RE. Strategic Materials in the Automobile: A Comprehensive Assessment of Strategic and Minor Metals Use in Passenger Cars and Light Trucks. Environ Sci Technol 2017;51:14436–44. doi:10.1021/acs.est.6b06063.

[39] Du X, Restrepo E, Widmer R, Wäger P. Quantifying the distribution of critical metals in conventional passenger vehicles using input-driven and output-driven approaches: a comparative study. J Mater Cycles Waste Manag 2015:218–28. doi:10.1007/s10163-015-0353-3.

[40] Restrepo E, Løvik AN, Wäger P, Widmer R, Lonka R, Müller DB. Stocks, flows and distribution of critical metals in embedded electronics in passenger vehicles. Submitt to Environ Sci Technol 2016. doi:10.1021/acs.est.6b05743.

[41] Henßler M, Bach V, Berger M, Finkbeiner M, Ruhland K. Resource Efficiency Assessment—Comparing a Plug-In Hybrid with a Conventional Combustion Engine. Resources 2016;5:5. doi:10.3390/resources5010005.

[42] Valero A, Valero A. Thermodynamic accounting of the global depletion mineral capital on earth. A proposal to the U.N. 12th Biannu. Jt. Eur. Thermodyn. Conf., Brescia: 2013.

[43] Calvo G. Thermodynamic Approach to Evaluate the Criticality of Raw Materials and Its Application through a Material Flow 2017;0. doi:10.1111/jiec.12624.

[44] Ortego A, Valero A, Iglesias M. Downcycling in automobile recycling process: a thermodynamic assessment. Resour , Conserv Recycl 2018.

[45] Comisión Europea. ES. Bruselas: 2014.

[46] USGS. Mineral Commodity Summaries 2015. United States Geological Service. 2015.

[47] Sverdrup HU, Ragnarsdottir KV. Natural resources in a planetary perspective. Geochemical Perspectives, volume 3, number 2; 2014.

[48] Emsley J. Nature's Building Blocks: An A–Z Guide to the Elements. Oxford, England, UK: Oxford University Press. 2001.

[49] Frenzel M, Ketris MP, Seifert T, Gutzmer J. On the current and future availability of gallium. Resour Policy 2016;47:38–50. doi:10.1016/j.resourpol.2015.11.005.

[50] Frenzel M, Kertris MP, Gutzmer J. On the geological availability of germanium. Miner

Depos 2014;49:471–86.

[51] Haque N, Hughes A, Lim S, Vernon C. Rare Earth Elements: Overview of Mining, Mineralogy, Uses, Sustainability and Environmental Impact. Resources 2014;3:614–35.

[52] Hubbert MK. Energy Resources. Washington: 1962.

[53] Hubbert MK. Nuclear Energy and the fossil fuels. 1956.

[54] UNEP. Recycling rates of metals. A status report. 2011.

[55] Geyer R, Kuczenski B, Zink T, Henderson A. Common Misconceptions about Recycling. J Ind Ecol 2016;20:1010–7. doi:10.1111/jiec.12355.

[56] SIGRAUTO. Age of ELV treatments 2018. http://www.sigrauto.com/estaantig.htm (accessed February 5, 2018).

[57] International Energy Agency. Energy Technology Perspectives: Scenarios & Strategies To 2050. 2010. doi:10.1049/et:20060114.

[58] Valero A, Ortego A, Calvo G, Iglesias M, Villacampa M. Weighting coefficients for SCI 2017.

[59] Valero A, Valero A. Thanatia: the destiny of the Earth's mineral resources: a cradle-to-cradle thermodynamic assessment. New Jersey: World Scientific; 2015.

[60] Cullbrand K, Magnusson O. The Use of Potentially Critical Materials in Passenger Cars. 2012.

[61] González Palencia JC, Sakamaki T, Araki M, Shiga S. Impact of powertrain electrification, vehicle size reduction and lightweight materials substitution on energy use, CO2 emissions and cost of a passenger light-duty vehicle fleet. Energy 2015;93:1489–504. doi:10.1016/j.energy.2015.10.017.

[62] García-Olivares A, Ballabrera-Poy J, García-Ladona E, Turiel A. A global renewable mix with proven technologies and common materials. Energy Policy 2012;41:561–74. doi:10.1016/j.enpol.2011.11.018.

[63] Nissan. Electric vehicle Lithium-ion battery 2016. http://www.nissan-global.com/EN/TECHNOLOGY/OVERVIEW/li_ion_ev.html (accessed October 20, 2016).

[64] TESLA. Tesla Gigafactory 2014. https://www.tesla.com/gigafactory (accessed October 20, 2016).

[65] Reuters. Toyota plans to increase lithium ion battery output-Nikkei 2013. http://www.reuters.com/article/toyota-battery-idUSL3N0E002O20130519 (accessed October 20, 2016).

[66] Gaines L, Sullivan J, Burnham A, Bel. Life-Cycle Analysis for Lithium-Ion Battery Production and Recycling. Transp Res Board 90th Annu Meet 2010:17. doi:10.1057/9781137332875.0027.

[67] Glöser S, Tercero Espinoza L, Gandenberger C, Faulstich M. Raw material criticality in the context of classical risk assessment. Resour Policy 2015;44:35–46. doi:10.1016/j.resourpol.2014.12.003.

APPENDIX A – RESERVES AND RESOURCES DATA

Table A. 1: Reserves and Resources data (in tonnes)

Metal	Reserves	Resources	Metal	Reserves	Resources
Ag	570,000	1,308,000	**Mn**	690,000,000	1,030,000,000
Al	28,000,000,000	75,000,000,000	**Mo**	15,000,000	19,400,000
As	730,000	11,000,000	**Nb**	4,300,000	14,328,483
Au	57,000	100,000	**Nd**	8,750,000	16,700,000
B	380,000,000	410,000,000	**Ni**	78,000,000	130,000,000
Ba	320,000,000	2,000,000,000	**Pb**	88,000,000	2,000,000,000
Be	400,000	400,000	**Pd**	33,000	46,000
Bi	370,000	370,000	**Pr**	2,000,000	4,800,000
Cd	500,000	3,600,000	**Pt**	33,000	50,000
Ce	31,700,000	31,700,000	**Rh**	5,000	5,000
Co	7,000,000	145,000,000	**Ru**	6,000	6,000
Cr	500,000,000	12,000,000,000	**Sb**	1,500,000	4,300,000
Cu	720,000,000	6,350,000,000	**Se**	100,000	172,000
Dy	2,600,000	2,980,000	**Sm**	2,900,000	2,900,000
Eu	244,333	244,333	**Sn**	4,700,000	76,200,000
Fe	160,000,000,000	800,000,000,000	**Sr**	6,800,000	1,000,000,000
Ga	5,200	1,000,000	**Ta**	100,000	317,060
Gd	1,235,000	3,622,143	**Tb**	566,104	566,104
Ge	12,500	440,000	**Te**	11,080	25,000
Hg	94,000	600,000	**Ti**	794,000,000	2,000,000,000
In	11,000	47,100	**V**	19,000,000	63,000,000
Ir	2,000	2,000	**W**	3,100,000	7,000,000
La	6,000,000	22,600,000	**Yb**	1,900,000	1,900,000
Li	14,000,000	40,000,000	**Zn**	220,000,000	1,900,000,000
Mg	2,400,000,000	12,000,000,000	**Zr**	75,000,000	235,029,851

APPENDIX B – VEHICLE COMPOSITION

Table B. 1: Compilation of materials used in passenger car vehicles PHEV and BEV (in g) per unit of vehicle with the exception of Al, Cast Iron, Cu and Steel which are in kg.

	[60]	[35]		[61]	[62]
	PHEV[2]	PHEV	BEV[3]	BEV	PHEV
Al (kg)				200	
Cast Iron (kg)				20	
Ce	0.31				
Co					
Cu (kg)	60			150	67.5
Dy	129.66	210	336		
Er	0.18				
Eu	<0.01				
Gd	<0.01				
Ga	0.57	1.05	1.68		
Ge		0.05	0.08		
In	0.08	0.05	0.08		
La	6.68				
Li	6,256.55				
Mo					
Nd	531.88	360	576		
Nb	109.14				
Pd	1.81		0.12		
Pt	5.51				
Pr	4.01	120	192		
Rh	<0.01				
Sa	1.4				
Sc					
Ag	50	6	9.6		
Steel (kg)				790	
Sr					
Ta	10.83				
Te	19.86	21	34		

For the assessment of materials used in batteries, it has been considered that current battery market situation is led by Li:ion batteries as demonstrated by the fact that both Nissan and Tesla are currently using Li:ion batteries in their vehicles [63,64]. Even if Toyota used NiMH and Li:ion batteries in their vehicles, last Prius PHEVs version is already using Li:ion depending on the equipment level [65]. This is why materials considered to be demanded for batteries in vehicles are those demanded by Li:ion batteries.

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[2] With medium equipment level.

[3] Original values are published for a 50 kW motor. In the present study, values are adapted for 50 kW and 80 kW motors in PHEV and BEV, respectively.

0006-19Table B. 2: Material demand by type of battery in g. Values adapted to a battery autonomy of 200 km.

	Authors compilation			
	[66]	[67]	[36]	**Average**
Li	9.01	7.2	9.3	8.50
Ni	57.40	46.5	58	53.97
Co	10.91	9	12	10.34

Table B. 3 contains the metal composition for each type of vehicle. In ICEV petrol and diesel cases, information comes from SEAT Leon model (segment C).

Table B. 3: Metal composition (in gr) for each type of vehicle

	ICEV Diesel	**ICEV Petrol**	**PHEV**	**BEV**
Ag	10.19	19.47	28	29.80
Al	61,103	78,343	141,370	200,000
As	0.14	1.30	0	0
Au	3.15	3.65	0.20	0.32
B	23.76	26.37	0	0
Ba	832.55	777.66	0	0
Be	0.03	0.02	0	0
Bi	8.81	8.84	0	0
Cd	0.15	0.12	0	0
Ce	2.67	0.37	49.67	0.15
Co	9.72	8.06	2,712	9,330
Cr	5,041	5,566	6,510	6,031
Cu	15,584	15,376	59,166	150,000
Dy	0.19	0.48	13.81	18.73
Eu	0	0.0001	0.23	0.23
Fe	701,095	653,524	806,140	746,945
Ga	0.27	0.27	0.81	1.12
Gd	0.0005	0.0005	0.17	0.17
Ge	0.0036	0.003	0.05	0.08
Hf	0.0027	0.008	0	0
Hg	0.047	0.001	0	0
In	0.216	0.21	0.38	0.38
Ir	0.018	0	0	0
La	0.341	0.40	7.38	7.38
Li	22.06	4.63	2,242	7,709
Mg	13,622	3,565	0	0
Mn	4,333	4,211	5,968	5,530
Mo	240.03	187.97	260	260
Nb	154.20	145.57	426.30	426.30
Nd	23.71	18.84	552.79	749.30
Ni	1,590	2,993	16,049.57	55,724
Pb	12,527	11,535	9,750	9,750
Pd	1.99	1.84	0.94	0
Pr	0.066	0.08	51.48	98
Pt	3.79	0.13	5.51	0

Rh	0.12	0.09	0.01	0
Ru	0.012	0.013	0	0
Sb	15.70	35.36	0	0
Se	0.013	0.02	0	0
Sm	0.21	0.33	2.32	3.15
Sn	208.53	234.61	0	0
Sr	148.84	144.08	0	0
Ta	4.65	6.53	10.83	10.83
Tb	0.01	0.02	13.62	26.93
Te	0.20	0.18	0	0
Ti	541.41	536.41	0	0
V	92.81	86.62	852.61	790
W	9.24	3.17	0	0
Y	0.07	0.13	0.41	0.41
Yb	0.0003	0.0002	0.08	0.16
Zn	6,614	6,502	0	0
Zr	12.50	78.42	0	0

APPENDIX C – METAL RECYCLING VALUES

Table C. 1: Metal recycling values [54]

Metal	Recycling rate	Metal	Recycling rate
Ag	30%	**Mn**	37%
Al	36%	**Mo**	33%
As	1%	**Nb**	50%
Au	30%	**Nd**	5%
B	0%	**Ni**	29%
Ba	1%	**Pb**	51%
Be	17.5%	**Pd**	50%
Bi	0%	**Pr**	5%
Cd	25%	**Pt**	50%
Ce	1%	**Rh**	40%
Co	32%	**Ru**	55%
Cr	20%	**Sb**	17%
Cu	30%	**Se**	5%
Dy	10%	**Sm**	1%
Eu	1%	**Sn**	22%
Fe	50%	**Sr**	0%
Ga	25%	**Ta**	17.5%
Gd	5%	**Tb**	1%
Ge	35%	**Te**	1%
Hf	0%	**Ti**	52%
Hg	37.5%	**V**	0.5%
In	37.5%	**W**	46%
Ir	17.5%	**Y**	0%
La	5%	**Yb**	0%
Li	1%	**Zn**	22.5%
Mg	33%	**Zr**	5%

APPENDIX D – STRATEGIC METAL INDEX AND SCENARIOS

Table D. 1: SMI values for each metal and scenario

	Exp	EU	Geo	Equi	Ams
Ag	35.60	39.82	53.55	47.95	26.39
Al	21.79	29.18	20.84	22.04	12.13
As	11.44	11.42	22.83	18.95	9.19
Au	34.60	37.33	55.92	48.99	26.70
B	27.87	34.46	38.14	35.43	17.02
Ba	19.91	24.36	27.52	25.46	12.44
Be	16.98	25.11	11.99	14.66	7.15
Bi	14.80	13.66	26.94	22.68	13.88
Cd	12.46	12.46	24.91	20.68	9.97
Ce	19.31	26.98	14.82	17.26	9.99
Co	54.67	50.07	56.99	55.65	60.35
Cr	31.32	40.93	35.32	35.10	17.71
Cu	30.82	33.94	34.23	33.44	25.97
Dy	54.29	47.88	43.42	46.35	64.99
Eu	19.09	26.35	13.43	16.22	10.55
Fe	22.89	30.47	23.97	24.50	12.57
Ga	30.25	35.79	32.84	32.62	22.35
Gd	17.44	25.63	12.30	15.02	7.55
Ge	20.70	27.91	20.83	21.64	11.07
Hg	14.05	14.05	28.10	23.33	11.24
In	32.99	39.96	45.30	41.94	21.24
Ir	19.21	26.73	17.17	18.76	9.59
La	19.64	27.71	16.41	18.47	9.54
Li	57.94	45.26	55.63	54.91	75.30
Mg	18.18	25.86	14.25	16.50	8.73
Mn	35.48	43.28	48.12	44.75	22.56
Mo	25.22	30.47	28.80	28.21	17.49
Nb	31.66	35.82	31.39	31.97	26.16
Nd	48.01	43.98	44.92	45.49	53.98
Ni	57.09	58.95	73.17	67.92	51.40
Pb	14.45	12.03	23.25	19.97	15.91
Pd	28.08	30.32	22.58	24.72	26.21
Pr	29.33	31.24	21.43	24.34	28.37
Pt	43.93	42.37	45.42	44.73	45.72
Rh	22.71	27.86	18.64	20.63	16.65
Ru	19.19	26.77	17.28	18.83	9.47
Sb	45.77	55.13	65.55	59.94	29.33
Se	32.04	39.13	45.14	41.53	19.96
Sm	19.71	26.37	13.27	16.25	12.13
Sn	27.25	34.22	32.98	31.86	16.81
Sr	10.55	10.31	20.53	17.11	8.89
Ta	38.49	36.55	32.35	34.21	42.31
Tb	59.57	50.41	47.55	50.55	74.18
Te	34.25	40.26	51.69	46.47	22.75
Ti	15.98	21.62	16.79	17.18	8.31

	Exp	EU	Geo	Equi	Ams
V	36.77	37.42	25.45	29.38	38.17
W	32.34	43.35	35.18	35.52	17.10
Yb	25.56	31.96	15.85	19.91	18.98
Zn	31.13	39.89	37.17	36.16	18.24
Zr	9.16	9.12	18.22	15.13	7.39

A.4 Paper IV

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Scope: The journal emphasizes the transformation processes involved in a transition toward more sustainable production and consumption systems. Emphasis is upon technological, economic, institutional and policy aspects of specific resource management practices, such as conservation, recycling and resource substitution, and of "systems-wide" strategies, such as resource productivity improvement, the restructuring of production and consumption profiles and the transformation of industry.

Contribution to the work:

- To make a revision of scientific publications about the state of the art of recycling processes.
- To identify improvement measures through field work visiting ELV installations.
- To develop a method to assess downcycling in vehicles.
- To obtain values from smelters about steel and aluminum scrap compositions which come from ELV treatment centers.
- To obtain the composition of all types of steel and aluminum alloys used in a passenger vehicle.
- To apply the method in a case study.
- To define recommendations for reducing downcycling.

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Full length article

Downcycling in automobile recycling process: A thermodynamic assessment

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ABSTRACT

Current metal recycling techniques for end-of-life vehicles (ELV) are based on mechanical treatments to mainly recover steel, aluminum, copper, and zinc alloys. Such techniques facilitate compliance with the ELV European Directive (2000/53/EC) target of achieving recyclability quotes of up to 85%. However, a vehicle can use more than 60 metals, some of them considered critical by international institutions, which end up downcycled as part of alloys or ultimately in landfills. This paper undertakes an assessment of the downcycling degree of minor metals in conventional vehicles using a SEAT Leon III model as a case study. Downcycling is assessed from a thermodynamic point of view using thermodynamic rarity, an indicator that is used as a weighting factor for the metals used in the car. The thermodynamic rarity of metals is a function of the quality of the minerals from which they stem, considering their relative abundance in Nature and the energy intensity required to extract and process them. The results demonstrated that, even if the quantity of downcycled metals only represents 4.5% of the total metal weight of the vehicle, in rarity terms, this figure increases to approximately 27%. This indicates that an important portion of high-quality metals becomes functionally lost. The most downcycled vehicle subsystems are in order: (1) accessories, (2) electrical and electronic equipment, (3) exhaust system, and (4) engine. Further, the most downcycled parts are: speed sensor, control unit, antenna amplifier, airbag circuit, temperature and rain sensors, front pipe, particle filter, and turbo parts.

1. Introduction

At present, the vehicle sector generates approximately 5% of the world's industrial waste, either from vehicles or the plants that produce them (Zorpas and Inglezakis, 2012). Each year in Europe, end-of-life vehicles (ELV) generate between 7 and 9 million tonnes of waste (European Commission, 2017a) and hence, the treatment of ELV and the impact of discarding their residues are subjects of worldwide concern (Simic and Dimitrijevic, 2012). As stated by Arda et al. (2017), a stable supply of raw materials is crucial for the transition to a sustainable and circular economy. This becomes even more important considering that, by 2030, up to 1.85 billion vehicles are expected to be added to the current fleet (Simic and Dimitrijevic, 2013), requiring massive amounts of raw materials (Hernandez et al., 2017).

In order to reduce waste originating from ELVs and increase their recyclability, in 2000, the EU enforced the ELV Directive (2000/53/EC). It aims to reduce the waste generated by ELVs and also to protect the environment by promoting the reuse and recycling of ELV components. According to the ELV Directive, from January 1, 2015, recovery requirements should achieve the target of at least 95% (with a maximum energy recovery of 10%) and a minimum of 85% of the total material has to be reusable and recyclable. Consequently, nowadays, a common vehicle has recyclability rates higher than 85% for any equipment version (Millet et al., 2012).

However, the future compliance of these recycling targets is challenged by the changing material composition of cars (Ortego et al., 2017). Examples of the changes in vehicle material composition over time are: the replacement of Fe by Al alloys for parts such as the head cylinder or gearbox case, body-in-white, and wheels (Hatayama et al., 2012; Løvik et al., 2014; Van Schaik et al., 2002); the increased use of plastics for the interior of the car (Juska, 2007); the transition from conventional internal combustion engines to hybrid-electric and fully electric powertrains (Eurostat, 2015); the evolution from manual to automated control of vehicle functions owing to an increased number of car electronics (Restrepo et al., 2016). Current vehicles require more electrical and electronic devices, which demand an increasing amount of different metals such as Li, Co, Mn, Ni, and different rare earths to manufacture batteries (Simon et al., 2015); Nd, Pr, and Dy to build permanent magnets (Riba et al., 2016); Ag, In, Ta, or La to manufacture electronic components (Andersson et al., 2016). As a result of this

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vehicle evolution, currently, more than 60 metals are used in a vehicle (Ortego et al., 2017).

Furthermore, some of these metals such as light rare earth elements (REE), Co, Ga, In, Mg, Nb, Ta, or V are also considered critical from several perspectives such as vulnerability, economic importance, supply, or ecological risks (Achzet and Helbig, 2013; Alonso et al., 2007; European Commission, 2014, 2017b). Critical metals in passenger vehicles are mainly found in the embedded electrical and electronic devices (Du et al., 2015; Widmer et al., 2015). Moreover, critical metals are also used as alloying elements in aluminum and steel alloys constituting the body-in-white and powertrain of the vehicle (Løvik et al., 2014). The number of embedded electrical and electronic devices and the alloy types depend on characteristics such as vehicle equipment, power source, and model, which define the vehicle type (Modaresi and Müller, 2012). Moreover, the future widespread adoption of electrical powertrains will encourage the development of large-capacity batteries, which will also increase the demand for some metals such as lithium (Grosjean et al., 2012; Kushnir and Sandén, 2012; Scrosati and Garche, 2010) or cobalt (Schmidt et al., 2016; Väyrynen and Salminen, 2012).

Focusing on ELV recycling processes, they are typically aimed at isolating hazardous content, selling spare parts, recovering and recycling some regulated parts such as batteries, tires, or catalytic converters, and recycling the metallic compounds existing in the largest quantities such as steel and aluminum alloys (Andersson et al., 2016). Focusing only on ELV metals, recycling plants (shredders) are mainly designed to separate ferrous (steel) and non-ferrous (aluminum, copper and zinc) fractions, which are subsequently sent to smelters as secondary sources. Such an operation entails the loss of most alloy elements (Ohno et al., 2015) either because they are downcycled or because they end up in the automobile shredder residue (ASR), ultimately becoming landfilled.

The concept of downcycling is understood as *"to recycle something in such a way that the resulting product is of a lower value than the original item"* (Merriam-Webster, 1995). Metal downcycling in ELV processes is a topic of concern; as demonstrated by Andersson et al. (2016) from a total of 17 metals investigated, only Pt from catalytic converters is functionally recycled. Moreover, as demonstrated by Ohno et al. (2014), approximately 60% of Ni, Cr, and Mo contained in light duty vehicles unintentionally ends up as the metal source in steel-making process.

As a result, these metals are lost during smelting; dissolved in the molten metal during smelting; or diluted as contaminants when they exceed the maximum content allowed for a specific alloy (Amini et al., 2007).

Another example is the case of nickel—only 40% of its content in automobiles is reused for its nickel content in steel plate rolls; another 40% is downcycled into other metals and becomes unavailable to the nickel recycling loop; finally, approximately 20% ends up in landfills (Nickel Institute, 2016). This occurs because metals are recycled in open/cascade recycling loops where dilution and quality losses occur (Maurice et al., 2017).

Indeed, and as demonstrated by Van Schaik and Reuter (2007), commercial recycling systems never achieves 100% material recovery during physical separation, high temperature metal production or thermal processing. These losses are intrinsic to any process and many of them are unavoidable as stated by the second law of thermodynamics (Valero and Valero, 2015). The physical limitations posed by the combination of materials, together with the intrinsic efficiency of the current recycling technologies have been analyzed by different authors including Castro et al. (2004, 2007); Reuter et al. (2006); Ignatenko et al. (2007, 2008); Gutowski and Dahmus (2005) or Gutowski (2008). According to Reuter (2016), one of the key drivers of a true circular economy is metallurgy and recycling and the understanding of entropy in each of its facets.

It should be stressed that recyclability assessments are intricate and work intensive because products are complex combinations of materials changing rapidly and continuously over time and that have an effect on the metals and other materials obtained after their recycling (Meskers et al., 2008; Van Schaik et al., 2003). This is why, considering that a car is made up of over 1000 different car parts, it is advisable to rank them according to the intrinsic value of the materials contained in the given component. Once ranked, recyclability assessments can be subsequently performed to those car parts selected as more valuable from a material point of view and so find ways to improve the eco-design of the product.

In depth recyclability assessments of vehicles have been performed by Van Schaik et al. (2002, 2003), and Van Schaik and Reuter (2007), who developed dynamic and fuzzy rule models to predict the liberation behavior and therefore the quality of e.g. recyclates as a function of design choices. This in turn provides a technology based feedback to the designer on the consequences of material combinations, connections and joints as defined in the design stage of the product. A useful software to undertake such analyses is HSC Sim 9 simulator (Outotec, 2017), which also allows to quantify the environmental impact via Life Cycle Assessments as well as through exergy.

This paper uses a methodology based on an indicator called thermodynamic rarity that allows to assess the physical value of systems based on their material contents. It must be noted that this methodology does not take into account the chemical relationships among metals, which affects the recyclability of the system. That said, with the method we can provide a quantitative number of the material losses that take place in ELV recycling processes, considering not only the quantity but also the quality of the materials. It also allows to identify those car components where deeper recyclability analysis and subsequent eco-design efforts should be placed. The methodology is applied to a segment A vehicle (SEAT Leon III) to which a hypothetical conventional ELV recycling operation is applied.

2. Research framework

As demonstrated by Ortego et al. (2017), a mass-based assessment of metal content in a vehicle excludes minor but very valuable elements that are increasingly gaining importance in the automotive sector. In order to overcome this deficiency, an alternative indicator based on the second law of thermodynamics was proposed. The aim of the new indicator, called "thermodynamic rarity," is to allocate a physical value to minerals and subsequently to metals according to their relative abundance in Nature and the energy intensity required to extract and process them to obtain the refined raw material. Consequently, commodities of precious metals such as platinum or gold are several orders of magnitude greater in terms of rarity than common metals such as iron, aluminum, or lead. Thermodynamic rarity combines the advantage of mass-based approaches—in that it is an indicator strictly based on the physical aspects of the commodity and hence is universal, objective, and stable—and that of monetary-based approaches, in that mineral rarities are closer to the societal perception of value.

The methodology is based on the recognition that the physical value of minerals is mainly due to their chemical properties and their degree of scarcity in the crust. The scarcer a resource, the greater its extraction costs and these, in turn, increase exponentially as the ore grades become depleted (Valero and Valero, 2015). Thermodynamic rarity incorporates two aspects. The first and the most evident one is the exergy cost (kJ) required to extract and process a given mineral from the cradle to the gate (i.e., until it becomes a raw material for the manufacturing industry). The second is the hypothetical exergy cost required if the given mineral must be restored to its initial conditions of composition and concentration in the original mines from a completely dispersed state (Valero and Valero (2015)). The latter is named exergy replacement cost, whereas the former is named embodied exergy cost. Notably, as minerals become depleted, exergy replacement costs decrease, indicating that the "bonus" granted by Nature for having minerals concentrated in mines and not dispersed reduces, indicating that real

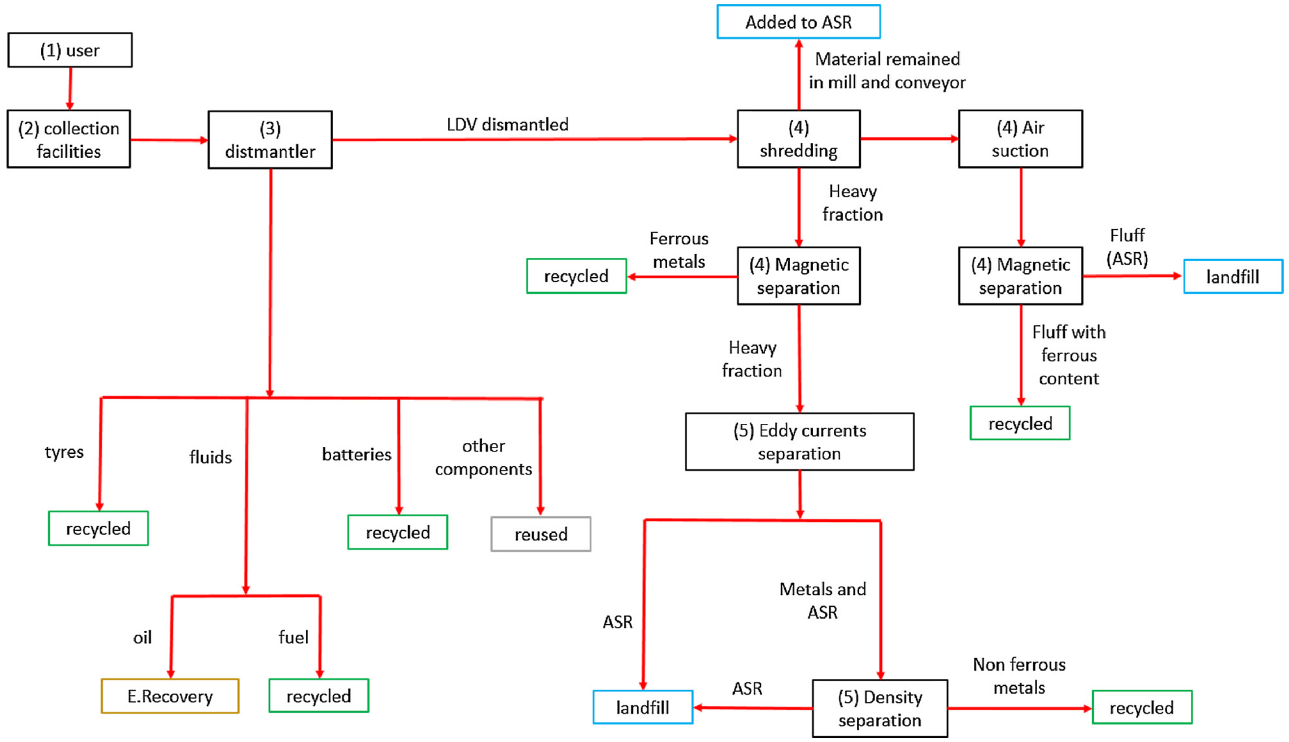

Fig. 1. Vehicle recycling scheme. (1) operations performed by users; (2) operations performed by collection facilities; (3) operations performed by dismantlers; (4) operations performed by shredding plants, and (5) operations performed by post-shredding plants.

mining costs necessarily increase. Both approaches, cradle-to-gate and grave-to-cradle, are equally important, as the first apprehends 1) efficiency, because embodied exergies indicate real energy expenditures that should be decreased in order to be cost-effective and 2) conservation, because it suggests the preservation of minerals that are scarce via exergy replacement costs.

Embodied exergy costs are obtained from the literature, assuming the average values of prevailing technologies for each commodity. In order to calculate exergy replacement costs, one should first define a baseline reference with which the current state of mineral deposits will be compared. That reference should be assimilated to a dead state of "zero utility" and as universal and stable as possible. Valero et al. (2011) proposed "Thanatia" as the baseline, which represents a resource-exhausted Earth where all mineral deposits have been extracted and dispersed. The so-called crepuscular crust is composed of approximately the 300 most abundant minerals in the upper crust, with relative compositions and concentrations. For the current state of mineral deposits, the average weighted values of ore grades across the world were obtained, mainly derived from Cox and Singer (1992). Considering that each element is obtained from a single type of ore (e.g., for copper: chalcopyrite), and knowing the concentration of the given mineral in Thanatia (x_c) and that in the average mines (x_m), the exergy replacement cost for mineral i (b_{ci}*) is calculated as:

$$b_{ci}^{*} = k \bullet \Delta b_{ci}$$

$$\Delta b_{ci} = b_{ci}(x = x_c) - b_{ci}(x = x_m) \qquad (1)$$

$$b_{ci} = -RT_0\left[lnx_i + \frac{(1-x_i)}{x_i}\ln(1-x_i)\right]$$

Starting with the last equation, b_{ci} is the concentration exergy and represents the exergy required to separate a given substance from a mixture. In our case, a given mineral from the ore. In the equation, R is the universal gas constant (8314 kJ/kmol K), T_0 is the temperature of the reference environment (298,15 K), and x_i is the concentration of the analysed mineral i, measured in grams of mineral per gram of ore. The difference between the concentration exergy obtained with x_i being Thanatia's concentration of the mineral (x_c) and with x_i being the ore grade of a given mine (x_m) is called "*replacement exergy*", denoted Δb_{ci},and it represents the minimum energy (exergy) required to convert the mineral from the concentration in the Earth's crust (x_c) to the concentration in the mineral deposits (x_m). As exergy considers that processes are reversible and hence only provides minimum values, which are far removed from the societal perception of value, we must resort to exergy replacement costs (b_{ci}*). Hence, man-made processes that are irreversible require k-times the minimum exergy. Variable k is a constant called unit exergy cost. It is the ratio between a) the real cumulative exergy required to accomplish the process of concentrating the mineral from the ore grade x_m to the commercial grade x_r and b) the minimum thermodynamic exergy required to accomplish the same process. An implicit assumption in the methodology is, thus, that the same technology applies for concentrating a mineral from x_m to x_r as from x_c to x_m. Once exergy replacement costs of minerals are obtained (i.e. for chalcopyrite), those of the element (i.e. for Cu) are calculated through their corresponding molecular weights.

It is important to stress that thermodynamic rarity does not consider the distribution of materials in specific components. Materials can be homogenously spread throughout the whole vehicle or found in almost the pure form in several components. This fact would certainly affect the recyclability of the vehicle, but the rarity would remain the same. Thus, rarity only measures in terms of energy, the impact of using those raw materials in a vehicle or any other application, by means of the ore grade in mines and the exergy required to extract them from a hypothetical bare rock to post-beneficiation conditions. Thermodynamic rarity values are given in Appendix A (Supplementary material).

3. Materials and methods

3.1. ELV recycling process

Fig. 1 illustrates the ELV recycling process where red arrows represent the material flow of a recycling operation, blue boxes show the destiny in a landfill, green boxes show the output of recycled material, the yellow boxes show the output to an energy recovery process and the grey box shows reusing. There are mainly five entities involved: (1) users who must deliver their vehicle to collection facilities (Vidovic et al., 2011); (2) collection facilities i.e., dealers or repair garages, which collect the ELVs; (3) authorized ELV treatment companies, which remove hazardous parts of vehicles that cannot be depolluted in landfills such as fuel, oil, tires, batteries, or air conditioning cooling gas, and remove reusable parts (called in Fig. 1 "other components") such as starters, suspensions or engines; (4) shredding plants, which receive decontaminated ELVs and shred them to separate them into three fractions: ferrous metals, non-ferrous metals, and the rest (a mix of rubber, foam, and plastics called ASR) using magnetic processes; (5) post-shredding plants, which receive the non-ferrous metal fraction from shredding plants and apply eddy current and density processes to separate mainly aluminum, zinc, and copper.

The scrap resulting from (4) and (5) is sent to smelters to produce steel or aluminum from secondary sources. The ASR resulting from (4) and (5) usually ends up in landfill or energy recovery plants, although the latter option is more complex owing to the heterogeneity of ASR composition, which contains a small fraction of metals that often hinders energy recovery.

Consequently, in a conventional vehicle recycling process, no specific operations to recycle minor but valuable metals is present. This fact was corroborated by several technical visits to and interviews with different Spanish ELV recycling actors including vehicle manufacturers, recycling associations, authorized ELV treatment centers, shredding plants, post-shredding plants, and smelter plants.

3.2. Data gathering and downcycling assessment

Downcycling is calculated in this paper as the additional quantity of virgin metals that would be required to manufacture a complete vehicle if the starting point were scrap coming from ELV recycling facilities. According to this definition, it is assumed that all metals become diluted in one of the different scrap types from ELV recycling facilities. This is an idealization, since in reality and as was previously explained, a portion of metals (usually below 5% end also in landfill). Yet this approach allows us to identify those components that are more critical from a downcycling point of view and thus provide automobile manufacturers and policy makers with valuable information to improve resource efficiency. It should be stated that this hypothesis is not very far removed from current approaches used by automobile manufacturers. In the homologation of vehicles, manufacturers need to assess the recyclability degree of the new car so as to ensure that they meet the ELV directive. To that end, it is considered that all metals incorporated in a vehicle are recycled.

Following the definition provided, downcycling assessment methodology follows the scheme illustrated in Fig. 2. The starting point is to determine the number of vehicle parts and the metal composition of each part. Therefore, it is necessary to disaggregate components into as small parts as possible, provided that the composition of each given component is known. This activity is performed using two information technology (IT) systems belonging to SEAT S.A. The first one includes a list of vehicle parts and the latter assesses the metal composition of each part (1). The selected parts are those that incorporate any kind of metal, having excluded those made exclusively of plastic, foam, glasses, or rubbers. The battery, catalytic converter and tires are also excluded since they are disassembled before shredding.

Owing to the large amount of parts constituting a vehicle, they are aggregated into larger subsystems for facilitating the assessment of results (2). The used subsystems classification is: engine, fuel tank and exhaust system, transmission, front axle, rear axle, wheel-brakes, selector mechanism, body, electrical equipment, and accessories. Subsequently, each part is also classified depending on the type of metal alloy used (3). The metal alloy classifications are: steel, aluminum, copper, and zinc alloys. These groups are used because shredding and post-shredding operations are almost exclusively designed to recycle these metals. It must be noted that magnesium has not been considered because it is typically fed into a second lifecycle as a secondary alloy, thus becoming a part of the aluminum cycle (Ehrenberger and Friedrich, 2013). Once the composition of vehicle parts is known, the subsequent step is to determine the composition of the steel, aluminum, copper, and zinc scraps of the ELV obtained after the recycling process (4). These scraps will be used as the input metal in steel, aluminum, copper, or zinc smelting plants. Starting from the scrap metal composition, all the vehicle parts are virtually manufactured, considering that the final weight and composition of each part must be the same as the corresponding original pieces (5). As the composition of scrap (7) differs from that used in original vehicle parts (6), new material has to be added. This difference, which represents the downcycling degree (8), is calculated not only by weight, but also in terms of thermodynamic rarity for each part. Downcycled parts and metals are finally ranked to identify those for which eco-design should be enhanced (9).

In the case of components manufactured with metals different from those used in steel, aluminum, copper, or zinc alloys such as Ag, Au, Co, Li, Sn, or Ta, the loss is assumed to be 100%, as these metals either become completely downcycled in minor quantities in alloys, thus completely losing the functionality for which they were produced, or are landfilled.

Notably, by using this method, the thermodynamic rarity of the scrap (7) for some vehicle parts is greater than that of the required metal composition. This occurs with parts made of low-quality alloys that do not require certain elements or require them in lower quantity than those that have been trapped in the scrap. An example of this is martensitic steel whose alloy elements (Al, Nb, Ti) are significantly lower than others such as ultra-high strength steel. In the methodology, when this occurs, the rarity of the metals not required to manufacture a certain part from scrap is assumed to be zero, since this addition, although valuable is unintentional and does not confer new properties to the given part.

To perform the rarity assessment, the first step is to obtain the metal composition for each part of the vehicle. Subsequently, the thermodynamic rarity of each part is calculated by means of Eq. (2).

$$R\,(A) = \sum_{i=1}^{n} m(i)\cdot R(i) \tag{2}$$

Where:

R = thermodynamic rarity, expressed in kJ/g (values included in Appendix A in Supplementary material)

A = vehicle part

m = mass (g)

i = metal assessed

The downcycling degree of each component is calculated as the difference in thermodynamic rarity of each part, using the metal composition of the original pieces and the average scrap metal composition. The average scrap composition is selected considering the type of alloy used to manufacture the vehicle part (steel, aluminum, copper or zinc alloy). Eq. (3) shows the expression used:

$$D\,(A) = \sum_{i=1}^{n} \Delta R\,(i) \tag{3}$$

Where:

D = downcycling

A = vehicle part

i = metal assessed

Δ R = $R_{ave\_metal\_scrap} - R_{ori\_metal\_comp}$

$R_{ave\_metal\_scrap}$ = Thermodynamic rarity of the car part manufactured with average metal scrap.

$R_{ori\_metal\_comp}$ = Thermodynamic rarity of the car part manufactured with the original metal composition.

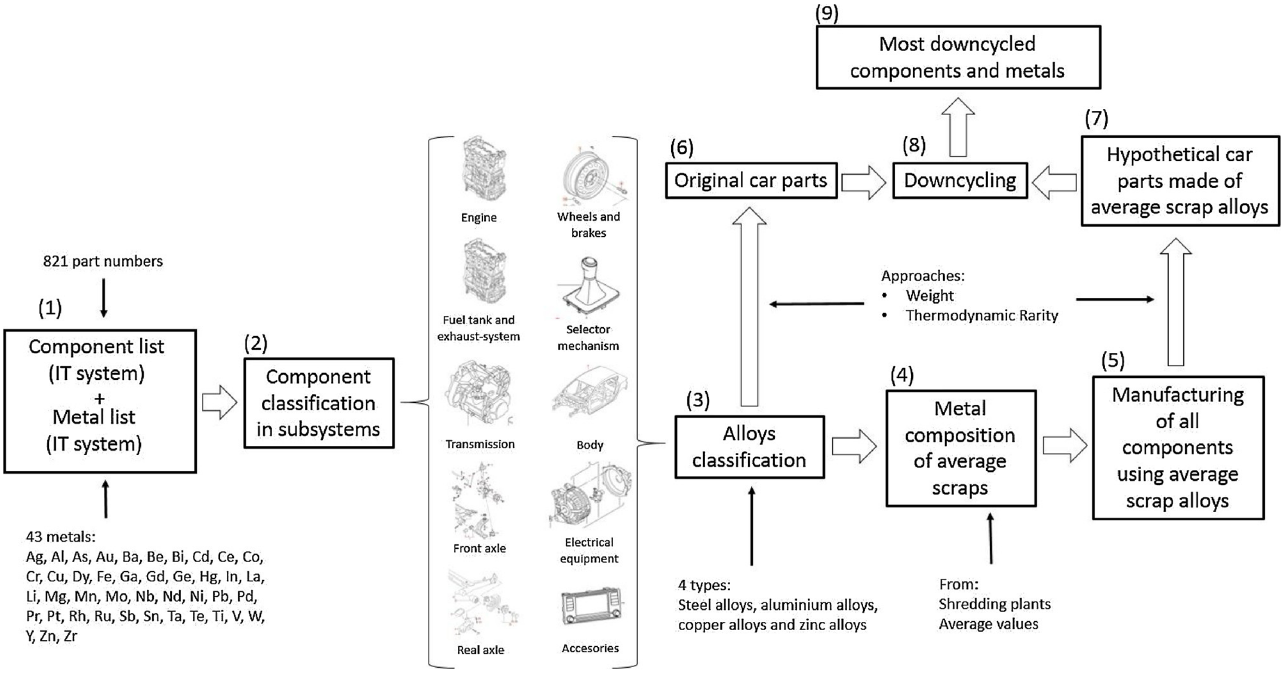

Fig. 2. Data gathering and downcycling assessment methodology.

Downcycling, as defined in Eq. (3), will always be a negative value as it represents a loss incurred from an initial situation to a final situation where quality is lost. A high negative value of downcycling indicates that an important quantity of the metals contained in the given car part are not functionally recycled. On the contrary, a small value of downcycling means that these metals are not only recycled but also to a higher degree functionally recycled. It may occur that a heavy car part denoted as “A” has a lower downcyclability degree than a lighter one denoted as “B”. The reason for this can come from two factors: 1) because A, as opposed to B, is composed of mainly fully recyclable materials (such as steel), and/or 2) because B incorporates non-recyclable materials with a much higher rarity than A. As will be seen in Section 4, that is the case of the turbo distributor, a much lighter component than for instance the cyclinder block, but with a higher downcycling degree mainly due to its chromium and niobium contents.

3.3. Case study description

Herein, the vehicle used as a case study is a SEAT Leon III model, which belongs to the hatchback sector. It is equipped with a 2.0 Diesel engine and manual gearbox. Its total weight is 1270 kg and considering only metals, 780 kg. From the vehicle, the metal content of battery, catalytic converter, tires, and fluids have been removed as they are disassembled before the shredding processes. Consequently, the final metal weight under study is 730 kg. Table B.1 (Supplementary material), included in Appendix B (Supplementary material), lists the metal composition of the studied vehicle. The composition of different vehicle parts from recycling alloys originates from shredding plants and alloy manufacturers. In Table B.2 (Supplementary material) included in Appendix B (Supplementary material), the scrap compositions are listed.

4. Results and discussion

4.1. Downcycling assessment

Table 1 presents the results obtained by applying the methodology described in Section 3. As evident from Table 1, metal downcycling is equal to 32.8 kg, accounting for 4.5% of the total analyzed weight of the car, meaning that 32.8 kg of metals have not been functionally recycled. This indicates that the ELV directive is satisfied, as more than 85% of the vehicle would be recycled. However, a completely different situation occurs when one assigns a quality value to metals using the thermodynamic rarity indicator. In such a case, the loss increases to 21,647 MJ, or equivalently, −26.95 rt% of the total thermodynamic rarity of the analyzed metals in the vehicle. If the ELV directive targets are expressed in terms of rarity, current recycling systems would not be enforcing the law. In order, the most downcycled subsystems are: accessories, electrical and electronic equipment, fuel tank, exhaust system, and engine. The values listed in Table 1 are calculated using the scrap composition described in Appendix B (Supplementary material). Nevertheless, the sensitivity of downcycling values has been assessed using two different scrap compositions. The results vary in the range of 3.9–4.5 wt.% and 23.7–27.0 rt%. Appendix E (Supplementary material) includes the scrap composition used in this sensitivity assessment.

Table 1
Downcycling by vehicle subsystem in mass and thermodynamic rarity.

	Mass (g/veh)		Thermodynamic Rarity (MJ/veh)	
Engine	−6024.39	−5.34%	−10,905.50	−35.64%
Fuel tank and exhaust system	−3480.60	−19.95%	−762.76	−58.79%
Transmission	−696.55	−1.77%	−168.27	−5.27%
Front axle	−1729.59	−3.75%	−678.24	−8.23%
Rear axle	−827.91	−3.03%	−313.54	−25.40%
Wheels and brakes	−2907.38	−5.85%	−1246.27	−13.97%
Selector mechanism	−114.48	−3.22%	−43.23	−26.82%
Body	−11,602.71	−2.85%	−2369.72	−13.11%
Electrical and electronic	−5169.93	−20.85%	−4461.13	−57.36%
Accessories	−285.73	−10.90%	−698.52	−87.30%
Total	**−32,839.28**	**−4.50%**	**−21,647.22**	**−26.95%**

Fig. 3(a) and (b) show the downcycling values per metal. Fig. 3(a) illustrates metals whose downcycling is greater than 1000 MJ and Fig. 3(b) illustrates those whose downcycling is lower than this value. Using the thermodynamic rarity approach, the most downcycled metals are Al, Pd, Pt, Cu, Ta, and Au. Aluminum has the highest loss in

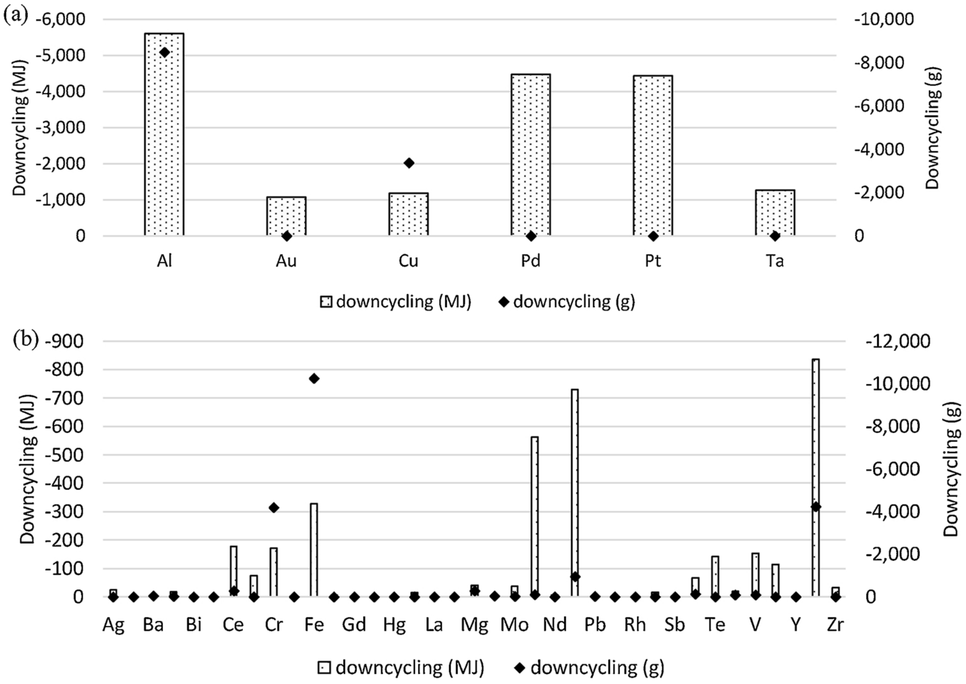

Fig. 3. Downcycling by metal measured by weight and rarity. (a) Metals whose downcycling is greater than 1.000 MJ and (b) metals whose downcycling is lower than 1.000 MJ.

thermodynamic rarity for two main reasons: (1) its greater rarity value (661.64 GJ/ton) with respect to other common metal like iron (31.85 GJ/ton) and (2) because aluminum used as an alloying element in steel is not functionally recycled (not used as aluminum source). In this model the average Al content in the steel is 0.75%, whereas that in the average steel scrap only 0.08%. This means that on average, 0.67% of Al would need to be added to the steel alloy. The difference in Al content is a consequence of the use of ultra-high strength steel alloys (UHSS) in the analyzed vehicle. UHSS requires a larger aluminum content (2%) than conventional steel alloys (such as martensitic high strength steels with an Al content of below 0.02%). The analyzed vehicle uses UHSS in several heavy parts such as the floor or cross member footwell. This is why the average aluminum content in steel is rather high (0.75%).

Notably, even if Cu is the most downcycled metal by weight, in terms of rarity, Pd, Pt, and Ta are more relevant. In the cases of Pt and Pd, although catalytic converters are disassembled and recycled prior to the shredding operation, there are more quantities of these metals in other components such as particle filters or rear windscreen cleaner motor. Regarding metals with downcycling figures less than 1.000 MJ, the most relevant metal is Zn followed by Ni and Nb; all of them are used as steel alloys. Nickel and niobium are relevant because, even if their concentrations in the car are low, their specific rarities are high compared to other studied metals such as Zn. For Zn, notably, although there are specific post-shredding processes to recover it, these are only appropriate for parts made almost exclusively with Zn (i.e., a silent block bracket). Zinc contents in steel alloys are, in turn, downcycled or lost.

Finally, Table 2 presents the top 3 most downcycled vehicle parts for each subsystem given in Table 1, with the three most downcycled metals presented for each case. This type of analysis allows identifying the parts where eco-design efforts should be made in order to recover the most from valuable raw materials. The list has been made by ordering downcycling in percentage with respect to the initial thermodynamic rarity value for each subsystem. In the case of the engine, Pt and Pd used in particle filter, Nb and Cr used in turbo distributor, and W and Nb used also in turbo guide van housing, are notable. In the matter of fuel tank and exhaust subsystems, the most downcycled metals are Ni and Cr used in alloys for exhaust pipe, closing cap, and clamp. In relation to transmission, Ni and Mo used to manufacture shafts are the most downcycled metals. In the front axle, the steering wheel is highlighted, owing to the use of Au, Ta, and Cu in the electricity transmission system located in the steering rod. In the rear axle, Al is the most downcycled metal, which is also present in axle dampers. The breaking system is included in the wheels and brakes category; in this subsystem, the metals Al, Cu, Ga, Ta, and Ni used in sensor, distributor, and pump are the most downcycled. In the selector mechanism category, Ni, Cr, and Zn used as steel alloys in the clear level and ventilator together with Ta, Al, and Pd used in foot adjusting are notable. The inner mirror is the most downcycled part in the body owing to its gold content for the anti-glare system, there are also highlighted the seat belts, that use Al, Zn, and Ni. In electrical and electronic equipment, the metals used in sensors such as Ta, Au, Ni, Pd, or Pt are the most downcycled. Finally, with respect to accessories, which also include any electrical equipment, the most downcycled parts are those that use Au and Ta such as the control unit or aerial amplifier and those that use Au, Pd such as the speed sensor. Appendix D in the Supplementary material incorporates the list of vehicle parts ordered by downcycling rate measured in MJ. This list contains 27 parts representing 80% of the total downcycling of the vehicle (17.317 out of a total of 21.647 MJ).

One can additionally perform an economic analysis to put this loss into perspective. Accordingly, we have used commodity prices as published by the United States Geological Survey (USGS, 2017) and included in Appendix C (Supplementary material) of the supplementary information. This loss would be equivalent to €174.74 per car, which indicates that, over the lifetime of a vehicle model, the total loss would be €183 M (considering an annual production of 150,000 units per year during 7 years). Note that this figure only represents an order of magnitude of the stringent importance of this issue, as price fluctuations can be significant even within a year.

4.2. Downcycling reduction recommendations

This research has allowed to obtain not only the downcycling degree of cars, but also to identify those car parts that contain the most critical and valuable metals. As such, in light of the results obtained,

Table 2
The top 3 most downcycled components in each category.

Description	Vehicle subsystem	Thermodynamic Rarity (MJ/veh)	Downcycling (%)	metal 1	metal 2	metal 3
Particle filter	Engine	8,613.48	−99.72%	Pt	Pd	Cu
Turbo distributor	Engine	260.71	−97.86%	Nb	Cr	–
Turbo guide vane housing	Engine	185.32	−88.77%	W	Nb	Cr
Clamp	Fuel tank and exhaust system	12.35	−75.88%	Ni	Mo	Cr
Front pipe	Fuel tank and exhaust system	379.57	−74.89%	Ni	Al	Cr
Closing cap	Fuel tank and exhaust system	0.91	−73.38%	Ni	Cr	Zn
Shaft	Transmission	11.68	−33.74%	Ni	Mo	Cr
Reverse shaft	Transmission	35.35	−28.92%	Ni	Sn	Mo
5th gear shaft	Transmission	32.74	−28.44%	Ni	Mo	Cu
Input pinion	Front axle	13.11	−27.87%	Ni	Cr	–
Track control arm	Front axle	260.76	−20.07%	Mo	Nb	V
Steering wheel	Front axle	147.94	−19.70%	Ta	Au	Cu
Axle dampers	Rear axle	206.55	−80.74%	Al	Cu	Zn
Feathering	Rear axle	0.30	−17.13%	Zn	–	–
Rear axle	Rear axle	840.17	−16.31%	Al	V	Ni
Break assistance pump	Wheels and brakes	352	−82.10%	Al	Ga	Ta
Brake distributor	Wheels and brakes	9.05	−58.76%	Al	Cu	Ni
Brake sensor	Wheels and brakes	7.02	−57.80%	Al	Cu	Ni
Foot adjusting	Selector mechanism	12.93	−76.22%	Ta	Al	Pd
Clear level	Selector mechanism	0.78	−71.85%	Ni	Cr	Zn
Ventilator	Selector mechanism	0.11	−58.41%	Ni	Cr	Zn
Seat belt	Body	84.02	−83.90%	Al	Zn	Ni
Bracket	Body	9.74	−76.30%	Ni	Cr	–
Inner rear mirror	Body	185.02	−74.90%	Au	Fe	Mg
Airbag circuit	Electrical and electronic	118.51	−98.81%	Ta	Au	Pd
Rain sensor	Electrical and electronic	7.23	−98.51%	Ta	Au	Pd
Temperature sensor	Electrical and electronic	45.01	−98.39%	Pt	Ni	Cu
Speed sensor	Accessories	5.16	−98.46%	Au	Pd	Cu
Control unit	Accessories	600.52	−95.04%	Ta	Au	Al
Aerial amplifier	Accessories	37.41	−83.53%	Au	Ta	Pt

some eco-design recommendations can be already proposed. Note that for a deeper analysis, further studies regarding recyclability and dismantling times of the selected car parts together with the corresponding energy and economic cost assessments should be performed. Below is a list of some of these recommendations.

- Disassembly of electric and electronic components that use valuable metals such as Au, Ag, REEs, platinum group metals (PGMs), Sn, Ta, or Te before shredding. Some of the most identified critical parts are: panel instrument, lighting switchers, LED lamps, power window motors, windscreen cleaner motors, electronic control units, rain sensors, electric mirrors, aerial amplifiers, and infotainment devices. This operation could be done even using automation by means of robots (Li et al., 2017) and would allow that specific recycling processes are implemented at a later stage.
- Application of hybrid recycling processes for the aforementioned parts as in the case of waste electric and electronic equipment (WEEEs) (Arda et al., 2017; Awasthi and Li, 2017; Cui and Zhang, 2008). These recycling processes should be mechanical-hydro-metallurgical-biometallurgical. This is because the sole application of mechanical techniques is not compatible with the recycling of other materials such as indium in the displays or REEs in LEDs (Ardente et al., 2014). Using this approach, valuable metals such as Au, Ag, Cr, Cu, Ga, In, Mg, Mo, Nb, Ni, Pd, Pt, Sn, Ta, V, or W would be recycled. This operation could be even developed in WEEE recycling plants as some of them are already implementing these processes.
- Disassembly of engine and gearbox components made of special steel alloys (high content of Cr, Mo, Nb, Ni, Ti, or W). Some of these components include the exhaust pipe, o-rings, turbos, pinions, and gear shafts. Owing to the excessive time required for removing some of these parts (i.e., removing o-ring from an engine requires the cylinder head cap, cylinder head, connecting rods, and pistons to be disassembled before and this operation requires at least 1 h), an intermediate situation could be implemented. This situation could be that engines and gearbox are disassembled from the rest of the vehicle before shredding. Notably, in a vehicle manufacturing plant, the entire powertrain (including front axle, gearbox, engine, and rear axle) is joined to the body in less than 30 s and hence, this operation could also be implemented via a reverse approach.
- Application of specific shredding processes for different vehicle parts mainly made of steel and aluminum alloys (i.e., engines, gearboxes, and bodies) to produce different scrap qualities with the aim of manufacturing different qualities of alloys using them.
- For the above, it is important for ELV authorized treatment centers to be equipped with information systems showing the location of the components that must be disassembled before and indicating the proper procedure for the same. This recommendation could be implemented using the International Dismantling Information System (IDIS, 2016), which currently shows information related to batteries, fluids, or airbags and in which the most important vehicle manufacturers participate.
- To implement novel post shredder treatments to recycle critical metals from the scrap obtained as output after the application of conventional recycling methods and from the ASR.
- Invest in eco-design to favor end-of-life recycling by enabling easier and faster disassembly of valuable components in ELV authorized treatment centers. This measure should also be implemented with an increase in the use of standard union systems avoiding the use of specific tools to remove these parts. The potential of this measure has been assessed and may reduce dismantling time to a third by simply innovating joining (Santini et al., 2010).

The latest recommendation is the most important, as the previous one depends on the disassembly costs. Consequently, disassembly times must be as short as possible and design should be aligned with this premise.

5. Conclusions

Automobile recycling processes are designed to recycle metals that contribute to the largest part of the vehicle's weight (i.e., steel and aluminum alloys). Yet vehicles have evolved into complex machines that require a myriad of different and valuable metals. As a result of a desynchronization between manufacturers and recyclers companies, many valuable metals end up downcycled or even worse, in landfills.

As was shown in this paper, thermodynamic rarity is a very useful indicator for measuring downcycling, as it accounts not only for the quantity, but also for the quality of the metals that become functionally lost in ELV recycling processes. This same analysis carried out in mass terms would lead to conclude that downcycling does not practically occur (less than 5%), since the car is composed (by weight) almost exclusively of iron, aluminum and copper, elements that are usually functionally recycled. On the contrary, with thermodynamic rarity, minor, but valuable metals have a much higher specific weight, and as such, the downcyclability degree of the analyzed car increases to around 27%. This is because rarity is a physical measure of resources, considering their relative scarcity in the crust and the energy required to obtain the specific commodities with prevailing technologies. This way, even if gold or platinum are imperceptible metals in the overall weight of the car, they are not when converting their tonnages in rarity terms. This simple aspect has a key application in the car industry and in any resource intensive industry. Mainly, it allows very quickly, to identify those parts of the car that are more valuable from a material point of view.

Accordingly, from more than 800 different metal parts that contain a car, the method allows to select those that are the most valuable from a material point of view and whose metals become to an important degree downcycled. With the results obtained in this study, we have been able to point to certain eco-design strategies that would allow to decrease the downcyclability degree of the car. Thanks to this macro assessment in a future research the authors will work on a detailed recyclability analysis where most downcycled components identified will be assessed taking into consideration chemical and physical interactions that take place under different recycling strategies.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.resconrec.2018.04.006.

References

Achzet, Benjamin, Helbig, Christoph, 2013. How to evaluate raw material supply risks—an overview. Resour. Policy 38 (4), 435–447. Retrieved September 5, 2016. http://www.sciencedirect.com/science/article/pii/S0301420713000445.

Alonso, Elisa, Gregory, Jeremy, Field, Frank, Kirchain, Randolph, 2007. Material availability and the supply chain: risks, effects, and responses. Environ. Sci. Technol. 41 (19), 6649–6656.

Amini, Hassan, Remmerswaal, JohanessA., Castro, Maria B., Reuter, Markus A., 2007. Quantifying the quality loss and resource efficiency of recycling by means of exergy analysis. J. Clean. Prod. 15 (10), 907–913.

Andersson, Magnus, Söderman, MariaLjunggren, Sandén, BjörnA., 2016. Are Scarce Metals in Cars Functionally Recycled? Retrieved July 14, 2016. Waste Management, New York, N.Y. http://www.sciencedirect.com/science/article/pii/S0956053X16303361.

Arda, I.şıldar, Rene, Eldon, De Van Hullebusch, Eric, Lens, Piet, 2017. Electronic waste as a secondary source of critical metals: management and recovery technologies. Resour. Conserv. Recycl. http://dx.doi.org/10.1016/j.resconrec.2017.07.031. (December 2016).

Ardente, Fulvio, Mathieux, Fabrice, Recchioni, Marco, 2014. Recycling of electronic displays: analysis of pre-processing and potential ecodesign improvements. Resour. Conserv. Recycl. 92, 158–171. http://dx.doi.org/10.1016/j.resconrec.2014.09.005. Retrieved.

Awasthi, Abhishek Kumar, Li, Jinhui, 2017. An overview of the potential of eco-friendly hybrid strategy for metal recyc ling from WEEE. Resour. Conserv. Recycl. 126 (July), 228–239. http://dx.doi.org/10.1016/j.resconrec.2017.07.014. Retrieved.

Castro, Maria B., Remmerswaal, Johannes A., Brezet, Han, Reuter, Markus A., 2007. Exergy losses during recycling and the resource efficiency of product systems. Resour. Conserv. Recycl. 52 (2), 219–233.

Castro, Maria B., Remmerswaaland, Johannes A., Reuter, Markus A., Boin, U.J.M., 2004. A thermodynamic approach to the compatibility of materials combinations for recycling. Resour. Conserv. Recycl. 43 (1), 1–19.

Cox, Dennis, Singer, Donald A., 1992. Grade and Tonnage Model of Distal Disseminated Ag-Au.

Cui, Jirang, Zhang, Liangjun, 2008. Metallurgical recovery of metals from electronic waste: a review. J. Hazard. Mater. 158 (2–3), 228–256. Retrieved October 20, 2017. http://www.sciencedirect.com/science/article/pii/S0304389408002161?via%3Dihub.

Du, Xiaoyue, Restrepo, Eliette, Widmer, Rolf, Wäger, Patrick, 2015. Quantifying the distribution of critical metals in conventional passenger vehicles using input-driven and output-driven approaches: a comparative study. J. Mater. Cycles Waste Manage. 218–228.

Ehrenberger, Simone, Friedrich, Horst E., 2013. Life-cycle assessment of the recycling of magnesium vehicle components. JOM 65 (10), 1303–1309.

European Commission, 2014. Report on critical raw materials for the EU. Report of the Ad Hoc Working Group on Defining Critical Raw Materials.

European Commission, 2017a. Environment. Retrieved October 20, 2017. http://ec.europa.eu/environment/waste/elv/index.htm.

European Commission, 2017b. Study on the Review of the List of Critical Raw Materials. Retrieved. https://publications.europa.eu/en/publication-detail/-/publication/08fdab5f-9766-11e7-b92d-01aa75ed71a1/language-en.

Eurostat, 2015. Passenger Cars in the EU - Statistics Explained. Retrieved. http://ec.europa.eu/eurostat/web/waste/key-waste-streams/elvs.

Grosjean, Camille, Herrera Miranda, Pamela, Perrin, Marion, Poggi, Philippe, 2012. Assessment of world lithium resources and consequences of their geographic distribution on the expected development of the electric vehicle industry. Renew. Sustain. Energy Rev. 16, 1735–1744.

Gutowski, Timothy G., 2008. Thermodynamics and recycling: a review. Pp. 321–332. IEEE International Symposium on Electronics and the Environment. In Absolute Versus Relative Environmental Sustainability: What can the Cradle-to-Cradle and Ecoefficiency Concepts Learn from Each Other.

Gutowski, Timothy G., Dahmus, Jeffrey B., 2005. Mixing entropy and product recycling. Pp. 72–76. Electronics and the Environment, 2005. Proceedings of the 2005 IEEE International Symposium on. IEEE.

Hatayama, Hiroki, Daigo, Ichiro, Matsuno, Yasunari, Adachi, Yoshihiro, 2012. Evolution of aluminum recycling initiated by the introduction of next-Generation vehicles and scrap sorting technology. Resour. Conserv. Recycl. 66, 8–14.

Hernandez, Maria, Messagie, Maarten, Gennaro, Michele De, Van Mierlo, Joeri, 2017. Resource depletion in an electric vehicle powertrain using different LCA impact methods. Resour. Conserv. Recycl. 120, 119–130. http://dx.doi.org/10.1016/j.resconrec.2016.11.005. Retrieved.

IDIS, 2016. International Dismantling Information System. Retrieved October 25, 2017. http://www.idis2.com/.

Ignatenko, Olga, Van Schaik, Antoinette, Reuter, Markus A., 2007. Exergy as a tool for evaluation of the resource efficiency of recycling systems. Miner. Eng. 20 (9 SPEC. ISS), 862–874.

Ignatenko, Olga, Van Schaik, Antoinette, Reuter, Markus A., 2008. Recycling system flexibility: the fundamental solution to achieve high energy and material recovery quotas. J. Clean. Prod. 16 (4), 432–449.

Juska, Claudette, 2007. Moving Toward Sustainable Plastics. The Ecology Center, Michigan, USA.

Kushnir, Duncan, Sandén, BjörnA., 2012. The time dimension and lithium resource constraints for electric vehicles. Resour. Policy 37 (1), 93–103. Retrieved September 5, 2016. http://www.sciencedirect.com/science/article/pii/S0301420711000754.

Li, Jie, Barwood, Michael, Rahimifard, Shahin, 2017. Robotic disassembly for increased recovery of strategically important materials from electrical vehicles. Robot. Comput. Integr. Manuf. 0 (March 2016), 1–10.

Løvik, Amund N., Modaresi, Roja, Müller, Daniel B., 2014. Long-term strategies for increased recycling of automotive aluminum and its alloying elements. Environ. Sci. Technol. 48 (8), 4257–4265.

Maurice, Philippe, Niero, Monia, Bey, Niki, Paraskevas, Dimos, 2017. Environmental screening of novel technologies to increase material circularity: a case study on aluminium cans. Resour. Conserv. Recycl. 127 (June), 96–106. http://dx.doi.org/10.1016/j.resconrec.2017.07.013. Retrieved.

Merriam-Webster, 1995. Dictionary. Retrieved October 26, 2017. https://www.merriam-webster.com/dictionary/downcycle.

Meskers, Christina, Reuter, Markus A., Boin, U., Kvithyld, A., 2008. A fundamental metric for metal recycling applied to coated magnesium. Metall. Mater. Trans. B 39 (3), 500–517.

Millet, Dominique, Yvars, Pierre-Alain, Tonnelier, Pierre, 2012. A method for identifying the worst recycling case: application on a range of vehicles in the automotive sector. Resour. Conserv. Recycl. 68, 1–13.

Modaresi, Roja, Müller, Daniel B., 2012. The role of automobiles for the future of aluminum recycling. Environ. Sci. Technol. 46 (16), 8587–8594.

Nickel Institute, 2016. Recycling of Nickel-Containing Materials in Automobiles.

Ohno, Hajime, Matsubae, Kazuyo, Nakajima, Kenichi, Kondo, Yasushi, Nakamura, Shinichiro, Nagasaka, Tetsuya, 2015. Toward the efficient recycling of alloying elements from end of life vehicle steel scrap. Resour. Conserv. Recycl. 100, 11–20.

Ohno, Hajime, Matsubae, Kazuyo, Nakajima, Kenichi, Nakamura, Shinichiro, Nagasaka, Tetsuya, 2014. Unintentional flow of alloying elements in steel during recycling of end-of-life vehicles. J. Ind. Ecol. 18 (2), 242–253.

Ortego, Abel, Valero, Alicia, Valero, Antonio, Restrepo, Eliette, 2017. Vehicles and critical raw materials. A sustainability assessment using thermodynamic rarity. Ind. Ecol. http://dx.doi.org/10.1111/jiec.12737. First published: 10 March 2018.

Outotec, 2017. HSC Sim 9. Retrieved January 8, 2018. https://www.outotec.com/products/digital-solutions/hsc-chemistry/hsc-sim-process-simulation-module/.

Restrepo, Eliette, Løvik, AmundN., Wäger, Patrick, Widmer, Rolf, Lonka, Radek, Müller, Daniel B., 2016. Stocks, flows and distribution of critical metals in embedded electronics in passenger vehicles. Environ. Sci. Technol.

Reuter, Markus A., 2016. Digitalizing the circular economy: circular economy engineering defined by the metallurgical internet of things. Metall. Mater. Trans. B 47 (6), 3194–3220.

Reuter, Markus A., Van Schaik, Antoinette, Ignatenko, Olga, Haan, Geert-Jan De, 2006. Fundamental limits for the recycling of end-of-life vehicles. Miner. Eng. 19 (5), 433–449.

Riba, Jordi-Roger, López-Torres, Carlos, Romeral, Luís, Garcia, Antoni, 2016. Rare-earth-free propulsion motors for electric vehicles: a technology review. Renew. Sustain. Energy Rev. 57, 367–379.

Santini, Alessandro, et al., 2010. Assessment of ecodesign potential in reaching new recycling targets. Resour. Conserv. Recycl. 54 (12), 1128–1134.

Van Schaik, Antoinette, Reuter, Markus A., 2007. The use of fuzzy rule models to link automotive design to recycling rate calculation. Miner. Eng. 20 (9), 875–890. Retrieved April 3, 2017. http://www.sciencedirect.com/science/article/pii/S0892687507000891.

Van Schaik, Antoinette, Reuter, Markus A., Boin, U.M.J., Dalmijn, W.L., 2002. Dynamic modelling and optimisation of the resource cycle of passenger vehicles. Miner. Eng. 15 (11), 1001–1016. Retrieved April 3, 2017. http://www.sciencedirect.com/science/article/pii/S0892687502000808.

Van Schaik, Antoinette, Reuter, Markus A., Castro, Bernardete, Remmerswaal, Han, 2003. The Role of Product Design and Liberation in the Optimisation of Recycling Passenger Vehicles (October). pp. 1768–1777.

Schmidt, Tobias, Buchert, Matthias, Schebek, Liselotte, 2016. Investigation of the primary production routes of nickel and cobalt products used for li-ion batteries. Resour. Conserv. Recycl. 112, 107–122. Retrieved September 6, 2016. http://www.sciencedirect.com/science/article/pii/S092134491630101X.

Scrosati, Bruno, Garche, J.ürgen, 2010. Lithium batteries: status, prospects and future. J. Power Sources 195 (9), 2419–2430. Retrieved August 25, 2016. http://www.sciencedirect.com/science/article/pii/S0378775309020564.

Simic, Vladimir, Dimitrijevic, Branka, 2012. Production planning for vehicle recycling factories in the EU legislative and global business environments. Resour. Conserv. Recycl. 60, 78–88.

Simic, Vladimir, Dimitrijevic, Branka, 2013. Risk explicit interval linear programming model for long-term planning of vehicle recycling in the EU legislative context under uncertainty. Resour. Conserv. Recycl. 73, 197–210.

Simon, B.álint, Ziemann, Saskia, Weil, Marcel, 2015. Potential metal requirement of active materials in lithium-ion battery cells of electric vehicles and its impact on reserves: focus on Europe. Resour. Conserv. Recycl. 104, 300–310.

USGS, 2017. Publications and Data Products. Retrieved October 19, 2017. https://minerals.usgs.gov/minerals/pubs/.

Valero, Alicia, Valero, Antonio, Gómez, Javier B., 2011. The crepuscular planet. A model for the exhausted continental crust. Energy 36 (1), 694–707. Retrieved October 3, 2016. http://www.sciencedirect.com/science/article/pii/S036054421000513X.

Valero, Antonio, Valero, Alicia, 2015. Thanatia: The Destiny of the Earth's Mineral Resources: A Cradle-to-Cradle Thermodynamic Assessment. World Scientific, New Jersey.

Väyrynen, Antti, Salminen, Justin, 2012. Lithium ion battery production. J. Chem. Thermodyn. 46, 80–85. Retrieved September 5, 2016. http://www.sciencedirect.com/science/article/pii/S0021961411003090.

Vidovic, Milorad, Dimitrijevic, Branka, Ratkovic, Branislava, Simic, Vladimir, 2011. A novel covering approach to positioning ELV collection points. Resour. Conserv. Recycl. 57, 1–9. http://dx.doi.org/10.1016/j.resconrec.2011.09.013. Retrieved.

Widmer, Rolf, Du, Xiaoyue, Haag, Olaf, Restrepo, Eliette, Wäger, Patrick A., 2015. Scarce metals in conventional passenger vehicles and end-of-life vehicle shredder output. Environ. Sci. Technol. 2, 4591–4599.

Zorpas, Antonis, Inglezakis, Vassilis, 2012. Automotive industry challenges in meeting EU 2015 environmental standard. Technol. Soc. 34 (1), 55–83 Retrieved October 20, 2017.

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A.5 Paper V

Ortego, A. Valero, Al. Valero, A. Iglesias, M. Towards material efficiency vehicles. Eco-design recommendations based on metal sustainability assessments. *SAE International Journal of Materials and Manufacturing.* Vol 11, Issue 3. **September 2018.**

Impact Factor: 0.41. (SJR) Scimago Journal and Country Rank. The scientific impact is not very high, but it is one of the most relevant journals in the automobile industry.

Scope: The Journal is assembled to present and promote wide-ranging research of the following areas: materials (materials development, analysis, modeling, and testing); design (design analysis, modeling, simulations, and optimization) and manufacturing (manufacturing practices, process, simulations, and methodologies).

Contribution to the work:

- To make a revision of scientific publications about the state of the art concerning eco-design of vehicles.
- To develop the method for identifying the most critical components based on the second law of Thermodynamics.
- To apply the method in a case study.
- To analyze the different types of eco-design strategies that could be applied.
- To collect information about the disassembly time of those components identified as critical.
- To define eco-design measures for identified critical components.

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Toward Material Efficient Vehicles: Ecodesign Recommendations Based on Metal Sustainability Assessments

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Abstract

Current End-of-Life Vehicle (ELV) recycling processes are mainly based on mechanical separation techniques. These methods are designed to recycle those metals with the highest contribution in the vehicle weight such as steel, aluminum, and copper. However, a conventional vehicle uses around 50 different types of metals, some of them considered critical by the European Commission. The lack of specific recycling processes makes that these metals become downcycled in steel or aluminum or, in the worst case, end in landfills. With the aim to define several ecodesign recommendations from a raw material point of view, it is proposed to apply a thermodynamic methodology based on exergy analysis. This methodology uses an indicator called thermodynamic rarity to assess metal sustainability. It takes into account the quality of mineral commodities used in a vehicle as a function of their relative abundance in Nature and the energy intensity required to extract and process them. This method is proposed as a tool to identify the most critical components in a vehicle so as to define specific ecodesign recommendations for them.

The methodology is applied to a SEAT Leon 2.0 Diesel III model (segment C). Main recommendations are focused on reducing the use of metals with high thermodynamic rarity values such as Ag, Au, Cu, Ga, In, Pd, Pt, Sn, Ta, and Te. These metals are mainly used in electrical and electronic equipment. It is also recommended to reduce the disassembly time of a number of critical components such as airbag unit, electronic control unit, lighting switcher, antenna amplifiers, panel instrument, sensors, infotainment unit, light-emitting diodes (LEDs), and motors. A fast and easy disassembly would allow in subsequent phases to apply specific recycling processes based on mechanical and hydrometallurgical hybrid approaches instead of only mechanical separation techniques.

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Introduction

The vehicle manufacturing sector is one of the largest raw material consumer [1] and the tendency is that this demand will grow in the future. Global vehicle sales have doubled in the last 30 years [2]. For instance, only in the European Union (EU), the passenger car fleet has grown by 5% in the last 5 years [3] and will keep growing in the coming years [4]. This evolution in vehicle sales will at the same time bring an increase in raw material demand to manufacture them [5].

This issue made the EU to react by enforcing the End-of-Life Vehicle (ELV) Directive (2000/53/EC), aimed at reducing the waste generated by ELVs and at protecting the environment by promoting the reusing and recycling of ELV components [6]. Current ELV recycling processes are typically focused on isolating hazardous content; selling spare parts; recovering and recycling some regulated parts such as batteries, tires, or catalytic converters; and recycling major metals such as iron and aluminum [7]. Yet a vehicle incorporates many more metals than those that are being presently recycled [8]. In the last years not only the quantity but also the type of raw materials required to manufacture vehicles have changed [8]. For example, some steel parts such as engine head, suspension arms, or wheels are being substituted for aluminum alloys for lightweighting purposes [9, 10, 11]: Permanent magnets made of neodymium and dysprosium are being incorporated to manufacture hybrid of fully electric powertrains [12, 13]; other metals such as lithium, cobalt, or rare earths are being used to manufacture batteries [14]; and others like silver, indium, tantalum, or lanthanum to make electronic components [7]. Some of these unrecycled metals such as light rare earth elements (REE), Co, Ga, In, Mg, Nb, Ta, or V, are considered critical due to potential supply risk problems or increasing importance for economic development [15, 16, 17]. Supply risks of certain materials are a serious threat in the automotive sector. This is true especially, with the mass introduction of fully electric and autonomous vehicles, very dependent on some of these critical metals. In this respect, Valero et al. [18] calculated that the recycling rate of some metals demanded by automobile manufacturers such as Ag, Co, Cr, In, or Ta must grow up to 37%, 59%, 47%, 45%, and 19%, respectively, to avoid metal shortages before 2050. Under this scenario, it is clear that more efforts in ensuring raw material efficiency in vehicles should be placed.

In recent decades the sustainability concept has acquired a growing importance, and a large number of methodologies, tools, standards, and regulations have been developed to promote the implementation of its principles inside industrial companies [19]. The developing of products with improved environmental performance is regarded as a crucial component of companies' commitment toward sustainable development [20]. In the case of vehicle manufacturing companies, it has been demonstrated that they are continually working to minimize their environmental impacts and meet legal and customer requirements [21]. It is well known that acting in the design phase is the most important moment inside a product lifetime [22]. During this phase not only the specifications are set but also the quality of recycling, which is conditioned by the liberation of materials during shredding which in turn strongly depends on the design [23]. Therefore, for achieving resource efficiency throughout a vehicle's life cycle, it becomes crucial to apply ecodesign approaches.

In the industrial field, ecodesign can be defined as an approach to consider and integrate environmental aspects in the product development process through the application of strategies aimed at reducing the negative environmental impact along the product lifetime [24]. Ecodesign provides product designers with a range of guiding principles, strategies, and methods [25] and encourages better environmental product performance by means of closing resource loops, minimizing resource consumption, promoting repair and upgrading, product long life, and recycling [22].

In Europe, ecodesign requirements are defined by the European Directive 2009/125/EC, but this legislation applies to all products related to energy with the exception of vehicles [26]. For vehicles, ecodesign approaches are focused on ensuring that the requirements established by the ELV EU Directive [6] and polluted emissions EU regulations [27] are met. In addition to comply with these requirements, vehicle manufacturers can also implement in their products ecodesign approaches according to ISO 14006, as has been the case of some vehicle companies [28]. ISO 14006 has as main aim to reduce the environmental impact of companies throughout the following phases: product design, manufacturing, transport, operation, maintenance, and End-of-Life (EoL) [29].

Common methods used to ecodesign vehicle components are based on Life Cycle Assessment (LCA), assessing products' impacts from a cradle-to-grave perspective, considering material production, product production, product use, and product EoL [5, 30, 31, 32, 33, 34]. In the case of the material production phase, the methodology usually consists of assessing the impacts related to the acquisition of natural resources and their later processing [35] by means of using specific LCA software tools such as GaBi or SimaPro [36]. However, there is an open debate whether these methods reflect well the depletion of natural resources [37].

An example of this discussion is, for instance, the issue of impact allocation when different commodities are obtained in the same process, such as when a valuable and scarce metal like cobalt is produced as a by-product of nickel mining. Cobalt can be seen as a free bonus from nickel extraction, and hence, all impacts can be allocated to nickel. A different approach would be to allocate costs in terms of their respective mass contents or alternatively their monetary costs. However, in such cases, one would omit the scarcity of the metal and also the physical value that it contains.

With the aim to present a method that allows the identification of those components with the highest potential to be ecodesigned from a raw material point of view, an own methodology is presented and applied. This method is based on the second law of thermodynamics and the concept of thermodynamic rarity. This methodology focuses on the physical properties that make raw materials valuable, such as composition and concentration in the crust and the energy intensity to extract and refine them.

It must be noted that the method is presented as a macro assessment and the feasibility to implement each measure should be deeply analyzed in a subsequent research phase. Nevertheless, the method allows us for a quick identification of which components are subject to be ecodesigned.

Methodology

Thermodynamic Assessment

As demonstrated by Ortego et al. [8], a mass-based assessment of metal content in a vehicle does not incentivize the recycling of minor ones such as REE or refractory metals (Mo, Nb, Ta, Re, and W), which are very valuable and scarce elements. In order to propose a new and more equitable approach, an alternative indicator based on the second law of thermodynamics and particularly the exergy concept was proposed. The aim of this indicator, called thermodynamic rarity (or simply rarity), is to allocate a physical value to minerals according to the following parameters: (1) their scarcity in Nature and (2) the net energy required to extract and refine them to obtain the commodity. Scarce and difficult to obtain commodities such as cobalt are several orders of magnitude greater than common ones such as iron. Thermodynamic rarity combines the advantage of mass- and economic-based approaches. It is an indicator strictly based on physical aspects of the commodity and hence is universal, objective, and more stable than monetary approaches. Moreover, although alien to the volatility of the commodity markets, it is also closer to societal perception of value [38].

In order to define ecodesign recommendations for improving metal use efficiency in vehicles, the first step is to analyze the metal content in the car and quantify them through a weighting factor considering the rarity value of each identified metal.

For that endeavor, we first need to take into consideration that primary production of metals comes from mineral deposits scattered throughout the crust and that the physical value of mined minerals comes mainly from their inherent chemical properties as well as the relative concentration of the mineral ore with respect to the earth's crust, that is, its scarcity degree. Such aspects can be physically assessed through a thermodynamic property called exergy, which in layman term represents useful energy and is a measure of the quality of any natural or man-made system with respect to its surrounding environment, also referred to as dead state. The greater the exergy of a system the more it stands out from the environment, and hence the greater its quality. A very concentrated mineral ore has a lot of exergy, which results in a lower exergy expenditure in extraction costs. On the contrary, the scarcer a resource the greater the extraction costs, and these in turn increase exponentially as ore grades become depleted [39].

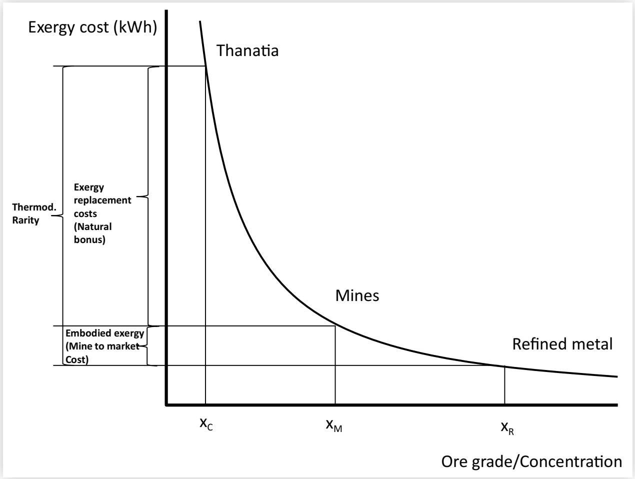
Scarcity in the crust is captured through the so-called *exergy replacement costs*, which is a hypothetical exergy cost that would be required if a given mineral would need to be restored to its initial conditions of composition and concentration as it was found in the original mines (cradle), from a complete dispersed state (grave) [40]. It can be seen as the hypothetical bonus granted by Nature for having minerals concentrated in mines and not dispersed throughout the crust. In turn, the net energy required to extract and refine the mineral to obtain a commodity is calculated through conventional *embodied exergy costs*.

Thermodynamic rarity is calculated as the sum of the exergy replacement cost with the embodied exergy costs (see Figure 1). As long as the ore grades in mines are high, embodied exergy costs will be low compared to exergy replacement costs. Yet with extraction, ore grades decline and more energy is required to extract the same amount of ore. Accordingly, embodied exergies increase, whereas exergy replacement costs decrease. If technology does not change, rarity can be assumed to be constant. This assumption is supported by the study of Calvo et al. [39] who, for the case of copper, observed that ore grades have generally declined throughout history, and albeit the implementation of certain improvements, energy costs had increased.

Thermodynamic rarity can be thus defined as the amount of exergy resources needed to obtain a mineral commodity from ordinary rock using prevailing technologies.

As stated by Ortego et al. [8], thermodynamic rarity does not take into account how materials are found in a specific vehicle component. Indeed materials can be homogenously spread throughout the whole vehicle or found almost pure in certain components. This fact would obviously very much affect the recyclability of the vehicle [42] but the rarity would remain the same. Thus, rarity only measures in energy terms, the impact of using those raw materials in a vehicle or any other application, considering the state of mineral ores in the earth and mining and beneficiation energies. Thermodynamic

FIGURE 1 Thermodynamic rarity and ore grades. Adapted from [41].



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rarity values for the 46 metals analyzed in this study are included in Appendix A. Such values are the weighting factors for each metal used in a car to identify the most critical components in the vehicle. From there, ecodesign recommendations can be easily derived.

Critical Vehicle Components Identification

To apply this thermodynamic approach into a vehicle, the quantity of iron and aluminum contained in the vehicle was initially removed. This was done for two main reasons: (1) because current ELV recycling processes are already recovering these metals in shredding plants, so from a metal sustainability point of view, these are not critical; and (2) because the weight contribution of these metals are much larger than the rest. In the case study analyzed in this article, iron and aluminum contribute to 84.3% and 8.1% of the total metal weight, respectively. This significant mass contribution does not allow to see clearly the criticality of other used metals because their weights are several orders of magnitude lower. Moreover, these are usually not functionally recycled but become downcycled with iron and aluminum (i.e., incorporated in minor quantities in the matrix of iron or aluminum blocks with no functional use).

The identification of critical components is done by using two thermodynamic indicators: thermodynamic rarity [kJ] and rarity intensity [kJ/g]. The first one has been previously explained in detail, and the second one is a ratio between the thermodynamic rarity and the weight of the given component. This second parameter allows to identify those components that, despite having little weight, have a high concentration of valuable metals with respect to their total weight.

Firstly, a table needs to be built in which the quantity of each studied metal for each vehicle component is represented (see Table 1).

Once this table is built, the thermodynamic rarity assessment is made by multiplying the weight of each metal by the thermodynamic rarity value of each metal (Equation 1).

$$Rarity(A)=\sum_{i=1}^{n} m(i)\cdot Rarity(i) \qquad \text{Eq. (1)}$$

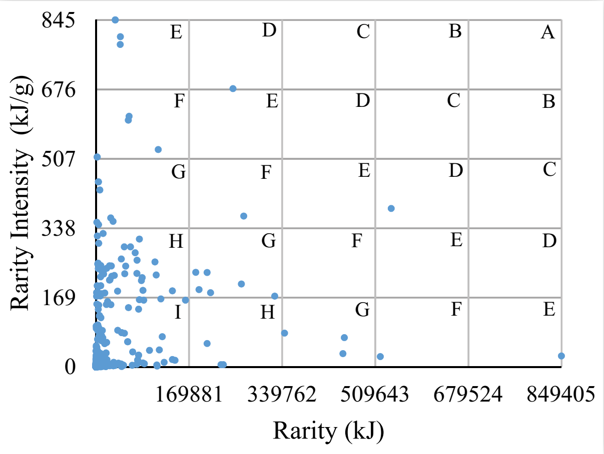
where A is a vehicle component, i is the studied metal, m is the mass in gr of metal i, and *Rarity* is the thermodynamic rarity values, expressed in kJ/gr, of the 46 metals included in Appendix A.

After this first thermodynamic assessment, all vehicle components are classified into 10 groups considering both indicators. The classification is as follows: one category for those component whose rarity is higher than 1 GJ, and nine additional categories (from A to I) according to thermodynamic rarity and rarity intensity values. The value ranges of each category (from A to I) is calculated by dividing the total range of rarity and rarity intensity into five equal parts, obtaining a matrix of 5 rows with 5 columns, as shown in Figure 2.

TABLE 1 Example of table to make the thermodynamic assessment.

	Metal 1	...	Metal *n*
Component 1			
...			
Component *n*			

FIGURE 2 Components classification. On the left the categories' zones and on the right the position for each of the 794 components assessed.



The reason to make one category called rarity higher than 1 GJ and to exclude it from the rest of the categories (from A to I) is because there are three vehicle components (the engine, gearbox, and front axle) which are included without a disaggregation level in smallest components (i.e., crankshaft, engine head, clutch, servo steering, or fuel pump). As a result, these parts have a very high rarity value compared with the rest, and must be studied individually. After this classification, ecodesign measures are recommended to be focused on parts with thermodynamic rarity values higher than 1 GJ and those which belong to A to G groups, that is, medium to high rarity and rarity intensity.

Results

Case Study Description

The vehicle used in the present study is a SEAT Leon III model, which belongs to the hatchback sector. It is equipped with a 2.0 Diesel engine and manual gearbox. Its total weight is 1,270 kg and 780 kg if only its metal content is considered. This vehicle has 1,051 parts but only 794 use any kind of metal. This happens because there are a good number of components which are fully made using plastics, rubbers, glass, or textiles.

Identified Critical Components

After the thermodynamic assessment, from an initial list of 794 components, 31 were identified as critical. Table 2 summarizes the number of vehicle parts for each criticality category.

TABLE 2 Number of vehicle parts, parts classification, and selected critical components.

Total components	794
Critical components	31
Components in category (>1 GJ)	2
Components in category (A)	0
Components in category (B)	0
Components in category (C)	0
Components in category (D)	2
Components in category (E)	4
Components in category (F)	7
Components in category (G)	16
Components in category (H)	49
Components in category (I)	714

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The classification procedure is shown in Figure 2, representing the value ranges for rarity and rarity intensity as well as the different classification groups (from A to I). It is worth noting that the largest number of parts have both medium rarity and rarity intensity values. Nevertheless there are certain components that have at least high values in one of the two indicators.

The identified critical components have a total rarity of 39.6 GJ. This figure is 85% above the total vehicle rarity (46.2 GJ). This classification procedure is in line with the Pareto principle, because less than 20% of vehicle components (31 components over 794) have more than 80% of the vehicle's rarity (39.6 GJ over 46.2 GJ). Table 3 shows the selected components.

From the previous list, the battery is excluded in the ecodesign assessment. This is so because batteries are already disassembled from ELV in the authorized treatment centers to be subsequently sent to specific recycling plants according to the requirements of EU Directive 2006/66/EC [43].

Once critical components are identified, ecodesign recommendations are proposed. The template used to list ecodesign proposals is included in Appendix B.

Ecodesign Proposals

The recommendations are classified into the following four categories: (type 1) facilitating disassembly, (type 2) critical metal substitutability, (type 3) retrofitting, (type 4) new approaches. In addition to the thermodynamic approach used, the recommendations are also based on the feedback received by the car manufacturer and several ELV recycling center visits and interviews. A more detail explanation about each category is described below.

Types of Recommendations

Type 1: Facilitating Disassembly. The aim of this category is to define recommendations oriented to facilitating disassembly. In order to do that, we first need to know the disassembly times of the identified parts. This information is retrieved from an internal SEAT IT system.

TABLE 3 List of critical components identified.

Description	Rarity (kJ)	Rarity intensity (kJ/g)	Group
Engine	32,099,655.39	191.52	>1 GJ
Gearbox	1,734,110.12	33.14	>1 GJ
Infotainment unit	538,664.92	386.19	D
Onboard supply control unit	250,164.31	677.90	D
Front axle	849,407.35	26.81	E
Exhaust gases temperature sensor	44,318.77	785.39	E
Aerial amplifier (left side)	35,217.40	845.45	E
Aerial amplifier (right side)	35,217.40	845.45	E
Battery	518,856.02	25.19	F
Combi instrument	269,509.99	367.46	F
Airbag control unit	113,556.86	529.44	F
Door control unit (driver)	60,603.42	610.61	F
Door control unit (passenger)	59,165.19	600.97	F
Lamp for ambience lighting (driver)	2,147.97	511.30	F
Lamp for ambience lighting (passenger)	2,147.97	511.30	F
Generator	453,144.52	71.54	G
Intermediate exhaust pipe with rear silencer	450,583.58	32.45	G
Starter	344,093.86	82.64	G
Wiring	326,124.54	172.64	G
Wiring for rear lighting	265,318.42	202.30	G
Exterior rear mirror (left side)	209,219.21	180.97	G
Exterior rear mirror (right side)	202,880.78	230.21	G
Wiring for front lighting motor	188,196.00	188.48	G
Rear screen cleaner motor	182,001.13	230.49	G
Additional brake light	31,345.25	354.58	G
Lighting switcher	26,870.75	362.84	G
Rain sensor	7,124.03	431.08	G
Air quality sensor	4,922.18	346.80	G
Speed sensor (left front tire)	4,548.35	450.91	G
Speed sensor (right front tire)	4,548.35	450.91	G
Cable shoe used for anti-twist device	1,726.88	352.43	G

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This measure is proposed because the difficulty and cost of separating parts from products limits the development of circular economy strategies [44]. In the case of automobiles, pretreatment based on dismantling can significantly reduce Automotive Shredder Residue (ASR) disposed in landfills [45]. A clear example is the case of Ta. Tantalum is very difficult to recover through metallurgical processes unless the parts containing them are removed and processed separately from the others [46]. These measures would allow that these parts could be easily disassembled in ELV authorized treatment centers. Subsequently, these components could be sent to two types of industries: (i) specific recycling centers, where the most valuable metals are recovered applying mechanical and chemical processes, and (ii) retrofitting companies, where a component could be refurbished and updated for its eventual use in new or used vehicles.

Type 2: Critical Metal Substitutability. As explained previously, vehicle parts are considered critical because they use valuable and scarce metals. One ecodesign approach is to substitute those metals by less critical ones. Substitutability must be carefully analyzed, because substitution usually also affects the performance of the components, due to changes in some properties like density, electrical conductivity, thermal conductivity, or dilatation coefficient. At this stage, substitutability recommendations are based on information included in the United States Geological Survey (USGS) [47] reports.

Type 3: Retrofitting. The fact that a vehicle arrives to its end of life does not necessary mean that all parts constituting the vehicle have lost their functionality. Indeed, the lifetime of many car components is greater than that of the vehicle as a whole. This is something very well known by ELV authorized treatment centers whose main business is based on the selling of EoL car parts. Another option is retrofitting. If the lifetime of certain components is high enough, these could eventually be retrofitted and updated to be subsequently used in new or used vehicles. It is well known that retrofitting is an effective way to maintain products in a closed loop, reducing both environmental impacts and manufacturing costs [48]. By means of this measure, it would be possible to reduce the demand of critical metals to manufacture new vehicles and to increase the time that a component stays in the technosphere. Note that retrofitting should be done with care, because this might be a barrier for potential vehicle buyers. Yet retrofitting can take place with long-lasting parts that are not necessarily visible to the end user. This is in fact already being done in some industrial vehicles, which use retrofitted engines from previously used models [49].

Type 4: New Approaches. Sometimes a component can be improved by means of applying innovative measures that change the component approach or requirements. As an example, some years ago certain vehicles were equipped with phones, but nowadays it is commonly extended that radio devices allow the use of personal phones through Bluetooth technology. Another example is the substitution of the CD reader through USB bus readers.

Recommendations

The type of ecodesign measures applied and the most valuable metals used for each component are summarized in Appendix C. From the initial list of 46 metals (excluding Fe and Al), 23 metals have been selected as the most valuable ones among the critical components. From all ecodesign measures (type 1 to type 4), facilitating disassembly and critical metal substitutability have been proposed in all cases. Retrofitting and new approaches measures have been proposed in 16 components. Information concerning metal content and ecodesign assessment for each component are not published due to confidential issues. Below is a description of the most relevant results of the study which are classified for each ecodesign category.

Type 1 Recommendations: Facilitating Disassembly. The generator, which is currently placed at the bottom part of the engine, should be better placed in the upper part, as this would facilitate disassembly and the recovery of its valuable metals. The generator is moved by a multifunction belt, meaning that this measure could be easily implemented. The combi instrument could be also designed to be removed from the upper part of the dashboard. This would avoid the airbag and steering wheel to be removed first (see Figure 3). As for the wires that connect the battery, they have a high thickness (and copper content) due to the maximum power demand required to move the starter. With a redesign they could be also disassembled when the batteries are removed in ELV authorized treatment centers. Finally, a common disassembling of engine, gearbox, and front axle would allow that specific recycling processes are applied to recover valuable metals of specific components such as suspension arms (Nb, Mo, V), turbo (Nb, Cr, W),

FIGURE 3 Combi-instrument location.

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exhaust pipe (Pd, Ni, Zr), exhaust temperature gases sensor (Pt, Ni, Cu), or servo steering (Cu). This operation could be easily implemented because these components are designed to be quickly assembled in vehicle manufacturing factories.

Type 2 Recommendations: Critical Metal Substitutability. Copper is the metal that appears most frequently in all selected components (30 times). Copper is followed by three metals with high rarity values such as gold (Au), tantalum, and palladium that appear 20, 19, and 17 times, respectively. This is why substitutability recommendations are mostly focused on such metals. Below we list some of the possible alternatives:

Aluminum instead of copper in certain wirings: As is well known, aluminum is an alternative to copper for wiring. It should be taken into account though that aluminum has 61% of the copper conductivity, but it has only 30% of the weight. An aluminum cable with the same conductivity than copper will weight up to 50%, less but it will be also thicker. Moreover, the use of aluminum as a conductive material implies the addition of other elements such as Fe, Cu, Mg, or Cr. On the other hand, the linear expansion coefficient is around 36% higher than for copper, what might constitute a problem in several applications with high temperatures.

Silver plating instead of gold plating in electronic contacts: Gold, as a native element, has very useful properties such as high conductivity, corrosion resistance, high melting point, or reflectivity. These properties make that the electronic sector has become the most important gold consumer. Nevertheless, electronic parts are rarely made entirely of gold because of the material's cost. This is why manufacturers use electroplating to apply a thin layer of gold over the main material that comprises the component. As an alternative, silver plating can be also used. Silver has as main benefit its lower cost.

Moreover, it has other key properties such us the highest electrical and thermal conductivity of any metal. That said, its main weakness with respect to gold plating comes from its corrosion resistance [50]. For a better corrosion resistance, a nickel undercoat with silver plating can be used. This alternative should be carefully analyzed mainly for those components responsible for safety systems.

Ceramic capacitors instead of tantalum capacitors: Ceramic capacitors have the highest market share, but tantalum capacitors provide a feasible alternative if higher breakdown strengths are required. The reduced costs, smaller size (suitable for space-constrained electronic circuits), high-frequency characteristics, higher reliability, ripple control, and longevity are driving the market to replace tantalum capacitors with ceramic capacitors wherever possible. Nevertheless, from an environmental point of view, the highest electrical energy consumption during fabrication alongside the use of nickel paste is the major environmental hotspot for ceramic capacitors [51]. So the environmental benefits associated to substitution must be carefully assessed.

At this point it must be also highlighted that the substitution of precious metals such as Pt or Au can have counterproductive effects because they play a key role in driving the economics of recycling [52]. Nevertheless, since they are not being recycled in vehicles, it will always be better if they are substituted by less critical materials.

Type 3 Recommendations: Retrofitting. From a retrofitting point of view (ecodesign measure 3), it is key - the availability of reusable parts. Such parts can only come from models with high production values such as those in segment C. The destiny of such parts would be in turn vehicles with smaller sales figures and where the focus is not placed on newest designs. This is why a clear destiny of retrofitted parts would be in industrial vehicles. Particularly, retrofitting would be a plausible option for the combi instrument, lighting switcher, rain sensor, rear screen cleaner motor, additional braking light, air quality sensor, or exhausts gases temperature sensor (see Figure 4 with different examples about components that use scarce metals and could be retrofitted).

Retrofitting of engine and gearbox parts could be also considered. Particularly for the engine, this could be done by using disassembled cylinder bores such as in some industrial engine cases. This measure would not hinder the engine for being updated to new performance requirements, because these changes mainly affect auxiliary systems like the head engine, the exhaust pipe, or the fuel pump.

The gearbox is manufactured with some valuable metals like magnesium, nickel, chromium, and molybdenum. In the studied vehicle, the gearbox contains 80% of the total magnesium used by the vehicle. Moreover the gearbox is a very unfailing and robust component and is therefore a perfect candidate to be retrofitted. Manual gearbox design has not substantially changed throughout the years, and this operation is a common technique applied in specialist gearbox repair garages.

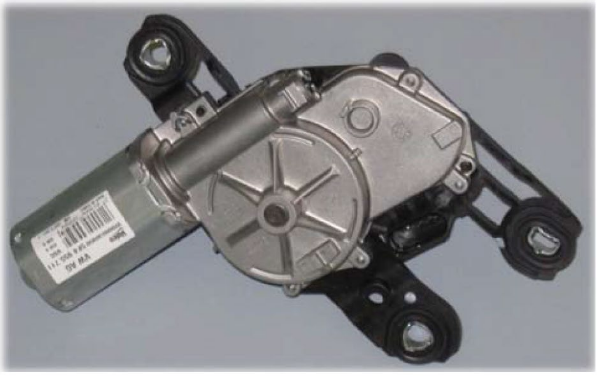
Type 4 Recommendations: New Approaches. In the field of new approaches (ecodesign measure 4), it is recommended to assess the possibility to centralize all electric units (i.e., onboard supply control unit, door unit, airbag unit, electronic control unit, combi-instrument electronic, or electronic from infotainment) in a common unit (see Figure 5 with different examples about current electronic units that use scarce metals).

Through this way, this unit could be easily disassembled and sent from ELV authorized treatment centers to specific recycling plants as it happens with batteries or tires. It is also recommended to assess the impact of changing the vehicle voltage from 12 V to 24 V or 48 V. This measure is being proposed to improve the engine efficiency and the performance of hybrid systems. Note that this measure could also reduce the section of wiring. In this line, the use of Integrated Starter and Generator Technology [53] may well reduce the demand of copper and permanent magnets containing rare earths. Finally, it is proposed to assess the impact that would have the inclusion of combi-instrument information and switchers in

FIGURE 4 Different components that could be retrofitted.

4.a lighting switcher

4.b rain sensor



4.c rear screen cleaner motor

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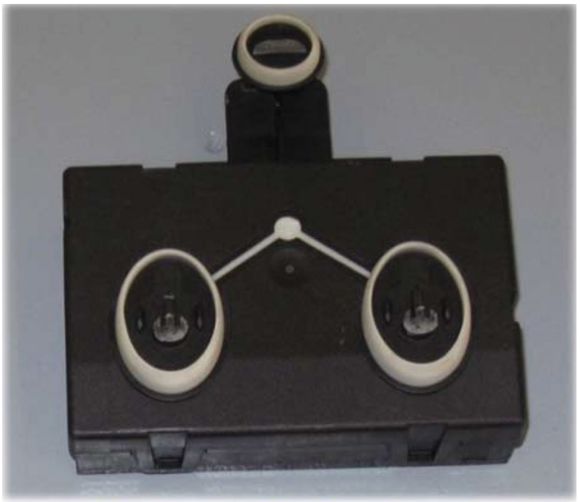
FIGURE 5 Different electronic units.

5.a onboard supply control unit (located under the dashboard)

5.b airbag unit (located under the dashboard)



5.c door control unit (located in doors)

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the screen of infotainment unit. This measure would not only avoid the use of such devices but also the associated wiring.

Ecodesign Measures Implementation. The impact of these measures goes beyond the studied vehicle because many models from the VW group share the identified critical components. In fact, only those parts with an exterior design such as exterior mirrors, additional brake lights, or combi instruments are included in just two models, the analyzed one and the SUV version based on the same platform. This fact also happens with tailor-made components such as wirings.

However, a good number of components are shared by several models: door control unit (29 models), starter (30 models), generator (40 models), rain sensor (45 models), or speed sensor (88 models). So the impact of applying ecodesign techniques goes usually beyond the specific model.

That being said, the application of the proposed ecodesign measures needs a deeper feasibility analysis. From a previous research carried out by the authors in the same vehicle, it was quantified that around 175 € of valuable metals are lost per vehicle when current ELV processes are applied. Taking into consideration a vehicle model lifetime, the total loss would be as high as 183 M€ (considering an annual production of 150,000 units per year in 7 years) [54]. Knowing this figure, the next question is if this loss justifies an investment in new ecodesign alternatives.

We see that the identified measures can be divided into two main groups according to the number of actors that take part. In the first group, only automobile manufacturers are involved. In the second, more stakeholders such as recyclers or dismantler centers are involved. For instance, one measure related to metals substitution affects in principle only to manufacturers. However, a measure where components should be disassembled and subsequently sent to specific recycling or component retrofitting plants would involve several actors: dismantlers, recyclers, and component manufacturers. In any case the economic benefits should be enough to generate a profit for each actor in the logistic chain.

For manufacturers, the economic feasibility could come from the savings achieved through the substitution of critical but also expensive metals by more common and less-expensive ones. Measures related to facilitating disassembly of certain components could be initially and more easily done for vehicles that belong to manufacturers. It is a fact that more and more customers are acquiring services instead of products (renting or leasing instead of purchasing), and hence more vehicles will belong to manufacturers at the end of life. A potential new income source for manufacturers could thus come from the dismantling of valuable components from these ELV or from the application of simple pretreatment operations (i.e., disassembly of capacitors or printed circuit boards from electronic units) which are subsequently sent to specific recycling plants.

In such cases where dismantling centers need to be involved for disassembly, the business model could be centered on the revenues obtained from those components sent to retrofitting companies or alternatively to recyclers. Recyclers in turn would receive components with high concentrations of valuable metals that would be separated by means of mechanical and metallurgical processes and sent again to car or other types of manufacturers.

Conclusions

In the past, automobile manufacturers have been working on improving the environmental performance of their products mainly through fuel efficiency and low emission techniques. Particularly for Europe, efforts on ELV recyclability were focused on ensuring that an 85% recycling quote (measured in mass terms) is achieved. However, vehicle manufacturers must take into consideration that meeting European ELV recycling policies does not guarantee a sustainable use of minor metals, which usually end downcycled in electric arc furnaces with steel and aluminum scrap or in the worst case in landfills. On the contrary, it incentivizes to focus on the bulky and easy to obtain ones: steel and aluminum. Yet are these the most critical ones in terms of future supply risks for the car industry? A new environmental challenge which is resource efficiency especially for minor raw materials is coming up. These additional efforts must be aligned with the adoption of ecodesign strategies to guarantee that resources are really used in a sustainable manner.

Valuable and scarce metals such as Au, Ta, Cu, Pd, Nb, or Sn, among others, are needed to manufacture certain components like engines, gearboxes, starters, alternators, electronic control units, motors, LEDs, switchers, or sensors. It is a fact that current vehicles are equipped with an increasing amount of electrical components that use such metals, for which no specific recycling processes exist. Moreover, since they are spread around the vehicle, disassembly is an extremely difficult task. For this reason, such components must be ecodesigned to be easily disassembled, repaired, updated, and retrofitted. They must be designed to be operational as much time as possible. Only when they cannot be used again, such components must be sent to specific recycling centers to obtain the valuable metals by means of using hybrid recycling approaches (physical and chemical) instead of being sent to common shredder plants where only bulk materials are recovered.

If catalytic converters, batteries, or tires are sent to specific recycling centers once the vehicle ends in an ELV authorized treatment center, why not use this same approach for more components such as screens, electronic units, switchers, or sensors. Why are the screens used in the infotainment unit or in the combi instrument of a vehicle dashboard shredded? These components are equivalent to domestic tablets and contain the same scarce metals (Ag, In, Pd, Sn, Ta …). Yet contrary to tablets, such vehicle units are not considered as waste electrical and electronic equipment (WEEE) and do not enter the specific WEEE recycling center. If they were considered WEEEs, they would be probably redesigned to be easily and quickly disassembled. As shown in this article, the application of the Thermodynamic Rarity approach offers a new dimension to help in the identification of critical components in a car. This new dimension is the consideration of the current and future scarcity of each commodity in the crust and the loss of mineral capital associated to mineral extraction. This loss is irreversible and must be taken into account to know the physical value associated to each raw material because it puts the focus on commodities with possible future shortages from a geological point of view. This method is presented as an easy tool to calculate the metal sustainability of components and to complement the traditional LCA assessment by means of a better understanding of the irreversibility associated to raw material extraction.

Through this method, we have shown that a common hatchback vehicle has more than 30 components considered critical from a raw material point of view. Hence, such parts are a priority to be ecodesigned so as to increase the metal sustainability in the car. For such identified car parts, different ecodesign measures have been proposed.

It should be stated that this methodology does not assess the feasibility of implementing ecodesign alternatives. It only prioritizes those components which are susceptible to be ecodesigned.

In future research, the authors will work on the technical, environmental, and economic feasibility of implementing a business model around the recovering of scarce metals from the identified vehicle components. This will be accomplished by analyzing different metallurgical routes.

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Abbreviations

A - Vehicle component

ASR - Automotive shredder residue

ELV - End life of vehicle

ERC - Exergy replacement cost, GJ/ton

i - Metal

LCA - Life Cycle Assessment

m - Mass

PGM - Platinum group metals

REE - Rare earth element

Rarity - Thermodynamic rarity, kJ/gr

xc - Concentration of a given mineral in the Earth crust

xi - Ore grade of a given mine

xm - Concentration of a given mineral in a mine

xr - Concentration of a given metal in a commercial grade

References

1. Wells, P., “Sustainable Business Models and the Automotive Industry: A Commentary,” *IIMB Manag Rev* 25:228-239, 2013, doi:10.1016/j.iimb.2013.07.001.
2. OICA, “Sales Statistics 2016,” http://www.oica.net/category/sales-statistics/, accessed July 15, 2016.
3. ACEA, “Vehicle Statistics,” 2014.
4. Simic, V. and Dimitrijevic, B., “Risk Explicit Interval Linear Programming Model for Long-Term Planning of Vehicle Recycling in the EU Legislative Context under Uncertainty,” *Resour Conserv Recycl* 73:197-210, 2013.
5. Hernandez, M., Messagie, M., De Gennaro, M., and Van Mierlo, J., “Resource Depletion in an Electric Vehicle Powertrain Using Different LCA Impact Methods,” *Resour Conserv Recycl* 120:119-130, 2017, doi:10.1016/j.resconrec.2016.11.005.
6. “Directive 2000/53/EC of the European Parliament and of the Council on End of Life Vehicles,” vol. 2000L0053, 2000.
7. Andersson, M., Ljunggren Söderman, M., and Sandén, B.A., “Are Scarce Metals in Cars Functionally Recycled?” *Waste Manag*, 2016, doi:10.1016/j.wasman.2016.06.031.
8. Ortego, A., Valero, A., Valero, A., and Restrepo, E., “Vehicles and Critical Raw Materials. A Sustainability Assessment Using Thermodynamic Rarity,” *Ind Ecol*, 2017.
9. Hatayama, H., Daigo, I., Matsuno, Y., and Adachi, Y., “Evolution of Aluminum Recycling Initiated by the Introduction of Next-generation Vehicles and Scrap Sorting Technology,” *Resour Conserv Recycl* 66:8-14, 2012, doi:10.1016/j.resconrec.2012.06.006.
10. Løvik, A.N., Modaresi, R., and Müller, D.B., “Long-Term Strategies for Increased Recycling of Automotive Aluminum and Its Alloying Elements,” *Environ Sci Technol* 48:4257-4265, 2014, doi:10.1021/es405604g.
11. Van Schaik, A. and Reuter, M.A., “Dynamic Modelling and Optimisation of the Resource Cycle of Passenger Vehicles,” *Miner Eng* 15:1001-1016, 2002.
12. Eurostat, “Passenger Cars in the EU-Statistics Explained,” 2015, http://ec.europa.eu/eurostat/web/waste/key-wastestreams/elvs.
13. Riba, J.-R., López-Torres, C., Romeral, L., and Garcia, A., “Rare-Earth-Free Propulsion Motors for Electric Vehicles: A Technology Review,” *Renew Sustain Energy Rev* 57:367-379, 2016, doi:10.1016/j.rser.2015.12.121.
14. Simon, B., Ziemann, S., and Weil, M., “Potential Metal Requirement of Active Materials in Lithium-Ion Battery Cells of Electric Vehicles and Its Impact on Reserves: Focus on Europe,” *Resour Conserv Recycl* 104:300-310, 2015, doi:10.1016/j.resconrec.2015.07.011.
15. Alonso, E., Gregory, J., Field, F., and Kirchain, R., “Material Availability and the Supply Chain: Risks, Effects, and Responses,” *Environ Sci Technol* 41:6649-6656, 2007, doi:10.1021/es070159c.
16. Achzet, B. and Helbig, C., “How to Evaluate Raw Material Supply Risks - An Overview,” *Resour Policy* 38:435-447, 2013, doi:10.1016/j.resourpol.2013.06.003.

17. European Commission, "Report on Critical Raw Materials for the EU. Report of the Ad Hoc Working Group on Defining Critical Raw Materials" 2014.
18. Valero, A., Valero, A., Calvo, G., and Ortego, A., "Material Bottlenecks in the Future Development of Green Technologies," *Renew Sustain Energy Rev* 93:178-200, 2018, doi:10.1016/J.RSER.2018.05.041.
19. Plouffe, S., Lanoie, P., Berneman, C., and Vernier, M.-F., "Economic Benefits Tied to Ecodesign," *J Clean Prod* 19:573-579, 2011, doi:10.1016/J.JCLEPRO.2010.12.003.
20. Rodrigues, V.P., Pigosso, D.C.A., and McAloone, T.C., "Process-Related Key Performance Indicators for Measuring Sustainability Performance of Ecodesign Implementation into Product Development," *J Clean Prod* 139:416-428, 2016, doi:10.1016/J.JCLEPRO.2016.08.046.
21. Poulikidou, S., Björklund, A., and Tyskeng, S., "Empirical Study on Integration of Environmental Aspects into Product Development: Processes, Requirements and the use of Tools in Vehicle Manufacturing Companies in Sweden," *J Clean Prod* 81:34-45, 2014, doi:10.1016/J.JCLEPRO.2014.06.001.
22. Luttropp, C. and Lagerstedt, J., "EcoDesign and The Ten Golden Rules: Generic Advice for Merging Environmental Aspects into Product Development," *J Clean Prod* 14:1396-1408, 2006, doi:10.1016/J.JCLEPRO.2005.11.022.
23. Van Schaik, A. and Reuter, M.A., "The Use of Fuzzy Rule Models to Link Automotive Design to Recycling Rate Calculation," *Miner Eng* 20:875-890, 2007, doi:10.1016/j.mineng.2007.03.016.
24. Rossi, M., Germani, M., and Zamagni, A., "Review of Ecodesign Methods and Tools. Barriers and Strategies for an Effective Implementation in Industrial Companies," *J Clean Prod* 129:361-373, 2016, doi:10.1016/J.JCLEPRO.2016.04.051.
25. den Hollander, M.C., Bakker, C.A., and Hultink, E.J., "Product Design in a Circular Economy: Development of a Typology of Key Concepts and Terms," *J Ind Ecol* 21:517-525, 2017, doi:10.1111/jiec.12610.
26. Parlamento Europeo, Directiva 2009/125/CE del Parlamento Europeo y del Consejo, de 21 de octubre de 2009, por la que se instaura un marco para el establecimiento de requisitos de diseño ecológico aplicables a los productos relacionados con la energía. DOUE Núm 285 2009:26.
27. European Commission, "Emissions in the Automotive Sector," 2017, https://ec.europa.eu/growth/sectors/automotive/environmentprotection/emissions_es, accessed Dec. 26, 2017.
28. SEAT, SEAT has become the first company in the automotive sector in Spain to be certified with the ISO 14006 standard in Ecodesign, 2016, http://www.seat.com/corporate/news/corporate/seatecodesign-certification.html.
29. Arana-Landin, G. and Heras-Saizarbitoria, I., "Paving the Way for the ISO 14006 Ecodesign Standard: An Exploratory Study in Spanish Companies," *J Clean Prod* 19:1007-1015, 2011, doi:10.1016/J.JCLEPRO.2011.01.013.
30. Lee, C.-K., Lee, J.-Y., Choi, Y.-H., and Lee, K.-M., "Application of the Integrated Ecodesign Method Using the GHG Emission as a Single Indicator and Its GHG Recyclability," *J Clean Prod* 112:1692-1699, 2016, doi:10.1016/J.JCLEPRO.2014.10.081.
31. Mayyas, A.T., Mayyas, A.R., and Omar, M., "Sustainable Lightweight Vehicle Design: A Case Study in Eco-Material Selection for Body-in-White," *Lightweight Composite Structures in Transport: Design, Manufacturing, Analysis and Performance* (Elsevier, 2016), 267-302, doi:10.1016/B978-1-78242-325-6.00011-6.
32. Delogu, M., Zanchi, L., Dattilo, C.A., and Pierini, M., "Innovative Composites and Hybrid Materials for Electric Vehicles Lightweight Design in a Sustainability Perspective," *Mater Today Commun* 13:192-209, 2017, doi:10.1016/J.MTCOMM.2017.09.012.
33. Ozbilen, A., Dincer, I., and Hosseini, M., "Comparative Life Cycle Environmental Impact Assessment of Natural Gas and Conventional Vehicles," *Exergetic, Energetic and Environmental Dimensions* (Elsevier, 2018), 913-934, doi:10.1016/B978-0-12-813734-5.00052-4.
34. Viñoles-Cebolla, R., Bastante-Ceca, M.J., and Capuz-Rizo, S.F., "An Integrated Method to Calculate an Automobile's Emissions Throughout Its Life Cycle," *Energy* 83:125-136, 2015, doi:10.1016/j.energy.2015.02.006.
35. Song, J.-S. and Lee, K.-M., "Development of a Low-Carbon Product Design System Based on Embedded GHG Emissions," *Resour Conserv Recycl* 54:547-556, 2010, doi:10.1016/j.resconrec.2009.10.012.
36. Herrmann, I.T. and Moltesen, A., "Does It Matter Which Life Cycle Assessment (LCA) Tool You Choose? - A Comparative Assessment of SimaPro and GaBi," *J Clean Prod* 86:163-169, 2015, doi:10.1016/J.JCLEPRO.2014.08.004.
37. Amini, H., Remmerswaal, J.A., Castro, M.B., and Reuter, M.A., "Quantifying the Quality Loss and Resource Efficiency of Recycling by Means of Exergy Analysis," *J Clean Prod* 15:907-913, 2007, doi:10.1016/j.jclepro.2006.01.010.
38. Ortego, A., Valero, A., Valero, A., and Iglesias, M., "Downcycling in Automobile Recycling Process: A Thermodynamic Assessment," *Resour Conserv Recycl* 136, 2018, doi:10.1016/j.resconrec.2018.04.006.
39. Calvo, G., Mudd, G., Valero, A., and Valero, A., "Decreasing Ore Grades in Global Metallic Mining: A Theoretical Issue or a Global Reality?" *Resources* 5:36, 2016, doi:10.3390/resources5040036.
40. Valero, A. and Valero, A., *Thanatia: The Destiny of the Earth's Mineral Resources: A Cradle-to-Cradle Thermodynamic Assessment* (New Jersey: World Scientific, 2015).
41. Valero, A. and Valero, A., "From Grave to Cradle A Thermodynamic Approach for Accounting for Abiotic Resource Depletion," *Ind Ecol* 17:43-52, 2013.
42. Meskers, C., Reuter, M.A., Boin, U., and Kvithyld, A., "A Fundamental Metric for Metal Recycling Applied to Coated Magnesium," *Metall Mater Trans B Process Metall Mater Process Sci* 39:500-517, 2008, doi:10.1007/s11663-008-9144-8.

43. Elwert, T., Goldmann, D., Römer, F., Buchert, M. et al., "Current Developments and Challenges in the Recycling of Key Components of (Hybrid) Electric Vehicles," *Recycling* 1:25-60, 2015, doi:10.3390/recycling1010025.
44. Talens Peiró, L., Ardente, F., and Mathieux, F., "Design for Disassembly Criteria in EU Product Policies for a More Circular Economy: A Method for Analyzing Battery Packs in PC-Tablets and Subnotebooks," *J Ind Ecol* 21:731-741, 2017, doi:10.1111/jiec.12608.
45. Santini, A., Herrmann, C., Passarini, F., Vassura, I. et al., "Assessment of Ecodesign Potential in Reaching New Recycling Targets," *Resour Conserv Recycl* 54:1128-1134, 2010, doi:10.1016/J.RESCONREC.2010.03.006.
46. Fairphone, Ballester, M.Van Schaik, A., and ,Reuter, M.A., "Fairphone's Report on Recyclability. Does Modularity Contribute to a Better Recyclability?" 2017.
47. USGS, "Mineral Commodity Summaries 2017," 2017, doi:10.3133/70180197.
48. Pigosso, D.C.A., Zanette, E.T., Filho, A.G., Ometto, A.R. et al., "Ecodesign Methods Focused on Remanufacturing," *J Clean Prod* 18:21-31, 2010, doi:10.1016/J.JCLEPRO.2009.09.005.
49. VOLVO, Volvo CE's China Remanufacturing Center in Shanghai draws on more than 70 years of remanufacturing experience, 29/09 2017, https://www.volvoce.com/global/en/spiritmagazine/introducing-remanufacturing/, accessed Dec. 20, 2017.
50. Song, J., Wang, L., Zibart, A., Koch, C., "Corrosion Protection of Electrically Conductive Surface," *Metals* (Basel) 2012. doi:10.3390/met2040450.
51. Smith, L., Ibn-Mohammed, T., Lenny Koh, S., and Ian, M.R., "Life Cycle Assessment and Environmental Profile Evaluations of High Volumetric Efficiency Capacitors," *Appl Energy* 220:496-513, 2018, doi:10.1016/j.apenergy.2018.03.067.
52. Reuter, M.A. and Van Schaik, A., "Chapter 53: Gold-A Key Enabler of a Circular Economy: Recycling of Waste Electric and Electronic Equipment," *Gold Ore Process* (2016), 937-958, doi:10.1016/B978-0-444-63658-4.00053-0.
53. VOLVO, "Integrated Starter Generator 2001," https://www.media.volvocars.com/global/engb/media/pressreleases/5278, accessed Dec. 20, 2017.
54. Ortego, A., Valero, A., and Iglesias, M., "Downcycling in Automobile Recycling Process: A Thermodynamic Assessment," *Resour Conserv Recycl*, 2018.
55. Valero, A. and Valero, A., "Thanatia, the Destiny of the Earth's Mineral Resources," 2014.
56. Koltun, P. and Tharumarajah, A., "LCA Study of Rare Earth Metals for Magnesium Alloy Applications," *Mater Sci* 962:803-806, 2010.
57. Valero, A., Valero, A., and Dominguez, A., "Exergy Replacement Cost of Mineral Resources," *Environ Account Manag* 1:147-158, 2013.

Appendix A

Thermodynamic Rarity Values

Table A.1 contains the thermodynamic values of 46 metals analyzed in this article. It must be taken into consideration that the studied vehicle uses 48, but in this assessment both iron and aluminum were excluded. Column B was obtained from an extensive bibliographic revision published in Valero and Valero (2014). It should be noted that in the cases of Dy, Sm, and Tb rarity values are approximated to an average REE. This value was calculated from Koltun and Tharumarajah (2010) data [56]. In the cases of Pd, Pt, Ir, and Ru, values are calculated to an averages platinum group metal element. The details about the calculation procedures are explained by Valero et al. [57] and Valero and Valero [55].

TABLE A.1 Exergy replacement cost, mining-concentration-smelting-refining, and rarity (GJ/ton).

Metal	A, embodied exergy	B, exergy replacement cost	A + B thermodynamic rarity
Ag	1,566	7,371	8,937
As	28	399.84	427.84
Au	108,626	546,057	654,683
Ba	1	38.34	39.34
Be	457.20	252.73	709.93
Bi	56.40	489.22	545.62
Cd	542.40	5,898	6,440.40
Ce	523	97	620
Co	138	10,872	11,010
Cr	36.40	4.50	40.90
Cu	56.70	291.70	348.40
Dy, Eu, Sm, Tb	384	348	732
Ga	610,000	144,828	754,828
Gd	3,607	478	4,085
Ge	498	23,749	24,247
Hf		32,364.36	32,364.36
Hg	409	28,298	28,707
In	3,320	360,598	363,918
Pt, Pd, Ir, Ru		2,870,013.09	2,870,013.09
La	297	39	336
Li	432	546	978
Mg	0	145.73	145.73
Mn	57	16	73
Mo	148	908	1,056
Nb	360	4,422	4,782
Nd	592	78	670
Ni	234	524	758
Pb	4	37	41
Pr	296	577	873
Rh	156	102,931	103,087
Sb	13.40	474.49	487.89
Sn	26.60	426.35	452.95
Ta	3,083	482,828	485,911
Te	589,405.30	2,235,699	2,825,104.30
Ti	196.45	6.67	203.12
V	517	1,055	1,572
W	594	7,429	8,023
Y	1,198	159	1,357
Zn	41.90	155.03	196.93
Zr	1,371.50	654.43	2,025.93

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Appendix B

Template with the Information Collected to Make the Ecodesign Assessment

TABLE B.1 Template to make the ecodesign assessment.

General information						
Code nº:			Designation:			
Provider:						
Model that use it:						
Rarity (kJ):			Density of rarity (kJ/g)			
Metal:						
Rarity over the total (%):						
Mass (g):						
Disassembly time						
Variation with respect to previous model						
Model/code nº	Model I		Model II		Δ Model II - Model I (%)	
Rarity (kJ)						
Ecodesign recommendations						
Facilitating disassembly			Critical metal substitutability			
Retrofitting			New approaches			

Appendix C

Studied Metals and Ecodesign Type of Measure by Component

TABLE C.1 Studied metal and type of ecodesign measure applied in each component: (1) easier disassembly, (2) metal substitutability, (3) retrofitting, (4) new approaches.

	Metal																						Type of measure			
Component	**Ag**	**Au**	**Bi**	**Co**	**Cr**	**Cu**	**Ga**	**In**	**Mg**	**Mn**	**Mo**	**Nb**	**Ni**	**Pb**	**Pd**	**Pt**	**Rh**	**Ru**	**Sn**	**Ta**	**Te**	**Ti**	**Zn**	**(1)**	**(2)**	**(3)**	**(4)**
Engine		X				X							X		X	X				X				X	X	X	
Gearbox						X			X	X	X		X										X	X	X	X	
Infotainment unit		X				X		X							X					X			X	X	X		X
Onboard supply control unit						X			X						X			X		X				X	X		X
Front axle						X					X	X			X	X				X				X	X		
Exhaust gases temperature sensor					X	X				X			X			X	X							X	X	X	
Aerial amplifier (left and right)	X	X				X										X				X			X	X	X	X	
Combi instrument	X	X				X									X				X	X				X	X	X	X
Airbag control unit		X				X									X			X		X			X	X	X	X	X
Door control unit (left and right)		X				X									X			X	X	X				X	X		X
Ambient lighting (left and right)	X	X				X									X			X		X				X	X		
Generator				X		X				X			X						X				X	X	X	X	X
Intermediate exhaust pipe					X	X				X		X	X									X		X	X		
Starter	X					X					X		X								X		X	X	X	X	X
Main wiring	X					X							X						X		X		X	X	X		X
Wiring for rear lighting	X			X		X							X								X		X	X	X		X
Exterior mirrors (right and left)		X				X	X	X	X											X				X	X		X
Wiring for front lighting		X				X							X						X		X		X	X	X		X
Rear screen cleaner motor		X		X		X									X			X		X				X	X	X	
Additional brake light	X	X				X									X				X	X				X	X	X	X
Lighting switcher	X	X			X										X			X		X				X	X	X	X
Rain sensor		X				X							X		X			X		X				X	X	X	
Air quality sensor		X				X									X			X	X	X				X	X	X	
Speed sensor (right and left)	X	X			X										X				X				X	X	X	X	
Battery wiring	X		X			X								X					X					X	X		X
Total	**13**	**20**	**1**	**3**	**2**	**30**	**2**	**3**	**4**	**4**	**3**	**2**	**10**	**1**	**17**	**5**	**1**	**10**	**11**	**19**	**4**	**1**	**12**	**30**	**30**	**16**	**16**