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Metals for energy & digital transition in Spain: Demand, recycling and sufficiency alternatives

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ABSTRACT

This study employs Material Flow Analysis (MFA) to comprehensively forecast metal demand in alignment with energy and digital transition policies at the country level, focusing on Spain. Our analysis spans eight technologies and ten metal groups, projecting metal demand and end-of-life recycling by 2050. We apply ambitious collection and recycling rate objectives, providing estimates of primary extraction requirements. We define and evaluate six scenarios targeting circular economy and sufficiency alternatives aimed at reducing primary extraction. Our results highlight electric mobility as the predominant driver of future metal demand, accounting for 54–92 % of cumulative demand for aluminum, copper, manganese, cobalt, nickel, lithium, dysprosium, and neodymium. From a global justice perspective, the 'equitable fraction of global reserves' for lithium and cobalt is surpassed. Ambitious recycling efforts could potentially cover 23–68 % of the cumulative metal demand between 2020 and 2050, while implementing circular economy and sufficiency alternatives might reduce primary extraction requirements by 11–61 %.

1. Introduction

The global demand for minerals in the energy transition has experienced a substantial rise. Between 2017 and 2022, lithium demand tripled, cobalt demand rose by 70 %, and nickel demand increased by 40 %, primarily driven by the energy sector (IEA 2023). Many countries, including India (IEA), Japan (IEA), United States (IEA), Canada (IEA), Brazil (IEA), South Africa (IEA) and Australia (IEA), have recently established critical mineral lists and strategies to respond to the evolving market context. To address these challenges, the European Union (EU) has adopted the 'Critical Raw Materials Act' as one of the key elements in its 'Green Deal Industrial Plan' (European Commission (EC) 2023). This policy aims to ensure a reliable supply of raw materials for the domestic production of low-carbon technologies. The drive toward onshoring mineral extraction finds its justification in the 'security–sustainability nexus' (Riofrancos, 2022)

Numerous global studies (Zuser and Rechberger, 2011; Elshkaki and Graedel, 2013; Stamp et al., 2014; Grandell et al., 2016; Tokimatsu et al., 2018; A. Valero et al., 2018; Månberger and Stenqvist, 2018; de Koning et al., 2018; Dominković et al., 2018; A. Valero et al., 2018; Habib et al., 2020; Calvo and Valero, 2022; Zhang et al., 2023; Liang et al., 2023) highlight a significant surge in demand for specific metals during the energy transition, but diverge on which metals will face the highest demand and potential supply issues due to uncertainties in future technologies (Calderon et al., 2024). Despite these variations, all emphasize the crucial role of public policies and recycling in mitigating supply risks. This contrasts with limited research on individual countries and regions (e.g., Germany (Viebahn et al., 2015), USA (Nassar et al., 2016), UK and Turkey (Kucukvar et al., 2018; Kucukvar et al., 2017), China (Wang et al., 2019; Elshkaki, 2019), EU (L. Gregoir and van Acker, 2022; E. Commission et al., 2020)), where decisions on policies and recycling capabilities are within state jurisdiction. Additionally, these studies do not comprehensively address all aspects of energy and digital transition technologies. Some exclusively focus on electricity production technologies (Zuser and Rechberger, 2011; Elshkaki and Graedel, 2013; Stamp et al., 2014; Viebahn et al., 2015; Nassar et al., 2016; Kucukvar et al., 2017; Wang et al., 2019; Elshkaki, 2019), others centre solely on mobility (Dominković et al., 2018; Habib et al., 2020; Zhang et al., 2023), and some consider both aspects (Tokimatsu et al., 2018; A. Valero et al., 2018; Månberger and Stenqvist, 2018; de Koning et al., 2018; A. Valero et al., 2018; Calvo and Valero, 2022; Liang et al., 2023; Calderon et al., 2024). Only one study (Grandell et al., 2016)

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incorporates lighting, a component of Electrical and Electronic Equipment (EEE). However, none of these studies encompass the entirety of EEE, a crucial aspect of the digital transition accompanying the energy transition. Most of these studies use Material Flow Analysis (MFA), a key method in industrial ecology (Zhang et al., 2023). Other studies, employ methods like input-output analysis (de Koning et al., 2018; Kucukvar et al., 2018; Kucukvar et al., 2017), which are also considered MFA studies (Zhang et al., 2023). In a previous study (Valero et al., 2015), an MFA for Spain was conducted as a case study to assess the suitability of exergy-based indicators for mineral resource efficiency, but it lacked sectoral or forecast analysis of future raw material demand. Dynamic MFA, categorized as retrospective or prospective and flow-driven or stock-driven (Augiseau and Barles, 2017), is widely adopted (Zhang et al., 2023; Wang et al., 2019). Regarding future scenarios, most studies use global projections from organizations like IRENA or IEA (Calderon et al., 2024). Notably, only a few articles (Viebahn et al., 2015; Wang et al., 2019) present scenarios based on Germany and China's public policies, respectively.

This paper introduces novel perspectives compared to existing literature. Firstly, by developing a comprehensive analysis of metal demand forecasting specifically linked to country-level energy and digital transition policies in Spain. Despite European-level studies (L. Gregoir and van Acker, 2022; E. Commission et al., 2020) and the Spanish Government's recent approval of the 'Roadmap for the Sustainable Management of Mineral Raw Materials' (E. MITERD 2022) a gap exists in understanding future metal demand forecasting, raising concerns among environmental organizations about a 'mining boom' (Amigos de la Tierra, 2022). Our approach in this paper is better suited for encouraging region-specific policies than global studies due to: (1) country-level energy transition and recycling decisions, (2) analysing state policies' viability and shortcomings, and (3) the state's geopolitical situation influencing metal criticality. Secondly, the study includes Electrical and Electronic Equipment (EEE), crucial for the digital transition accompanying changes in energy and mobility, also referred to as the 4th industrial revolution (Wang et al., 2019).

In order to fulfil the existing information gap, we establish the following three objectives:

1. Estimate the demand for metals related to Spain's energy and digital transition policies up to 2050, determine the proportion of this demand that can be satisfied through metal recycling, and the proportion that should be supplied through primary extraction (Section 3.1.).
2. Explore various sufficiency alternatives to reduce the overall demand for metals and minimize reliance on primary extraction (Section 3.2.).
3. Evaluate the resulting primary extraction from two perspectives: environmental impacts and equitable distribution of global mineral reserves (Section 3.3.).

2. Materials and methods

We conducted this research by focusing on the domestic requirements of technologies set to be deployed in Spain until 2050 in alignment with the public policies of energy and digital transition, regardless of their place of manufacture. To achieve this, we developed a dynamic, retrospective (1990–2022) and prospective (2023–2050) Material Flow Analysis (MFA) (Brunner and Rechberger, 2003) using MATLAB. The system boundary of our MFA is defined by the installation and end-of-life of Spain's green and digital transition technologies between 1990 and 2050, with ten metal groups described as material flows. First, we will outline the analysed technologies, followed by a description of the selected groups of metals.

Our analysis covered eight technologies closely associated with the energy and digital transition: wind, photovoltaic, electric cars and buses, electrolyzers for green hydrogen production, energy storage batteries, electric vehicle charging stations, power lines and substations, and electric and electronic equipment (EEE). Following the categorization established by Müller et al. (Müller et al., 2014), we analyzed the first six technologies using a stock-driven MFA and the latter two using a flow-driven MFA. In the stock-driven MFA, the key exogenous parameter determining the annual target is the number of technologies in use, while in the flow-driven MFA, the primary exogenous parameter is the annual installations of these technologies. Additionally, we included end-of-life internal combustion engine (ICE) passenger cars as a metal recycling source within our analysis.

Ten metal groups were selected based of three criteria: (1) their significance in the increase of mining license concessions in Spain ('m'), (2) the centrality of their demand in energy and digital transition technologies ('t'), and (3) their classification as critical ('c') or strategic ('s') raw materials by the EU. Guided by these criteria: aluminum (t, c), copper (m, t, c, s), cobalt (m, t, c, s), lithium (m, t, c, s), manganese (m, t, c), nickel (m, t, s), gold (m, t), silver (m, t), Platinum Group Metals (platinum and palladium) (t, c, s), and rare earths (dysprosium and neodymium) (m, t, c, s).

In the following, we describe the calculation model (2.1.), the scenarios (2.2.), the circular economy and sufficiency measures considered (2.3.), and the factors with which we evaluate the impact of the resulting primary extraction (2.4.).

2.1. Calculation model and main parameters

The following set of equations describe the relationship between the main parameters of our calculation model.

$$\textit{Metal demand}\begin{cases} I_j(t) = \left[S_j(t) - S_j(t-1)\right] + EoL_j(t) \\ I_j(t,k) = I_j(t)\cdot D_j(t,k) \\ M_j(t,m) = \sum_{k\in j}\left[I_j(t,k)\cdot N_j(t,k,m)\right] \\ M(t,m) = \sum_j M_j(t,m) \end{cases}$$

$$\textit{End of life and recycling}\begin{cases} EoL_j(t) = L_j(t,t)\times I_j(t) \\ MEoL_j(t,m) = L_j(t,t)\times M_j(t,m) \\ MCol_j(t,m) = RCol_j(t)\cdot MEoL_j(t,m) \\ MRec_j(t,m) = RRec_j(t,m)\cdot MCol_j(t,m) \\ MRec(t,m) = \sum_j MRec_j(t,m) \end{cases}$$

$$\textit{Primary extraction and impacts}\begin{cases} P(t,m) = \dfrac{MRec(t,m)}{M(t,m)}\cdot 100 \\ MExt(t,m) = M(t,m) - MRec(t,m) \\ Imp_o(t) = \sum_m MExt(t,m)\cdot F_o(m) \end{cases}$$

Being t the year of evaluation, j the technology considered, k the sub-technologies studied, m the metals analysed, o the evaluated environmental impacts, I_j the annual installation of technology, S_j the annual stock of technology, EoL_j the annual dismantling of technology, D_j the annual distribution of sub-technology installation, M_j the annual metal demand of a technology, N_j the metal intensity of a sub-technology, L_j the probability of dismantling a technology, $MEoL_j$ the metal contained in end-of-life technology, $MCol_j$ the metal collected from end-of-life technology, $MRec_j$ the metal recycled from end-of-life technology, P the annual percentage of demand met by recycling for each metal, $MExt$ the annual primary extraction requirements for each metal, F_o the environmental impact factor and Imp_o the annual primary extraction impacts. Fig. 1 illustrates a simplified representation of the calculation model developed for this research, distinguishing between exogenous (yellow) and endogenous (green) parameters and showing the main interactions.

Next, we describe the functioning of the model for the predominant

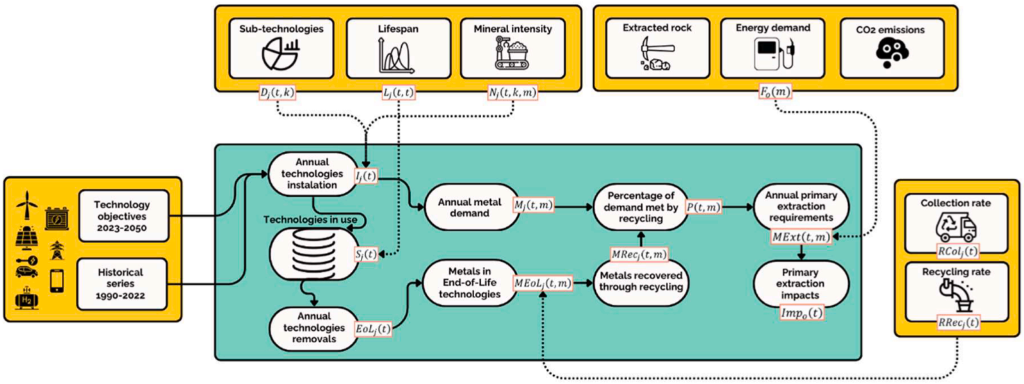

Fig. 1. Simplified diagram of the MFA calculation model.

case, which is the stock-driven MFA. The objectives establish the stock of technologies that should be operational in a given year. By comparing this figure with the previous year and considering the technologies dismantled during the year, we obtain the annual installation of technologies. This annual installation is then broken down based on the annual distribution of sub-technologies. Multiplying the installation of sub-technologies by their corresponding mineral intensity yields the annual metal demand. Simultaneously, we determine the technologies dismantled by multiplying the annual installations by a probability matrix defined by the lifespan distribution. Applying the same probability matrix to the metal demand of a technology allows us to identify the metals contained in end-of-life technologies. These figures are then multiplied by the specific collection and recycling rates for each year, technology and metal, providing quantity of metals recovered from recycling. Lastly, by comparing the annual metal demand with the metals recovered from recycling, we estimate the associated primary extraction requirements. Subsequently, these annual primary extraction requirements are multiplied by environmental impact factors. In the case of flow-driven MFA (power lines and substations, and EEE), the objective sets the annual installations, and the rest operates in the same manner.

In summary, we employed a consumption-based approach to estimate metal demand, irrespective of the geographical location of technology manufacturing. Simultaneously, we compared this demand with the potential domestic metal recycling from these technologies. While this simplification does not precisely mirror real-world supply chains, it provides us with a clearer insight into the mineral dimension of a country's energy and digital transition.

The technology objectives are based on Spain's energy and digital transition policies (see SI 1 for a description). Nonetheless, the information these documents provide is insufficient to model the metal requirements associated with the technologies projected for 2050. so additional assumptions from other references need to be incorporated (see SI 2 for a description).

Table 1
Summary of the most relevant parameters that define the evolution of the considered technologies.

Technology	Technology objectives			Lifetime distribution	Sub-technologies	Main references
	2020	2030	2050			
Wind [GW]	28 (h)	62 (p)	90 (p, e)	Weibull λ = 20 years k = 2,0	Onshore / Offshore 4 wind turbines technologies	(Zimmermann et al., 2013; MITERD, 2020a, 2020b; MITERD, 2023; Commission et al., 2020b)
Photovoltaic [GW]	12 (h)	76 (p)	111 (p, e)	Weibull λ = 20 years k = 2,5	Crystalline silicon / Thin film 3 thin film sub-technologies	(MITERD, 2020a, 2020b; MITERD, 2023; IRENA, 2016)
Electric cars [million]	0,05 (h)	3,3 (p)	17 (e)	Weibull λ = 10 years k = 3,5	7 battery cathode chemistries	(Bongartz et al., 2021; Iglesias-Émbil et al., 2020; MITERD, 2020a; MITERD, 2023; Monitor-Deloitte, 2017; IEA, 2022; BNEF, 2022)
Electric buses [thousands]	0,2 (h)	13 (e)	80 (e)	Weibull λ = 12 years k = 3,5	7 battery cathode chemistries	(Bongartz et al., 2021; Iglesias-Émbil et al., 2020; BNEF, 2022)
Electric vehicle charging stations [units]	7.607 (h)	3.216.224 (e)	0,9 per electric car (e)	Weibull λ = 12 years k = 4,0	3 charging stations levels	(Everis 2021; Mastoi et al., 2022; Zhang et al., 2019; Meticulous research 2021)
Electrolyzers [GW]	0,0 (h)	11 (p)	103 (e)	Weibull λ = 7–31 years k = 5,0	3 types	(MITERD, 2020a, 2020c; MITERD, 2023; Study IndWEDe, 2018; IEA, 2023b)
Energy storage batteries [GWh]	18 (h)	50 (p)	77 (p)	Weibull λ = 15 years k = 3,5	7 battery cathode chemistries	(Bongartz et al., 2021; World Bank, 2020; MITERD, 2020a; MITERD, 2021; MITERD, 2023)
Power lines [km/year]	1.472 (h)	1.791 (e)	2.075 (e)	Normal μ = 40 years σ = 8,0	66, 132, 220 & 400 kV overhead lines, cable, repowering and submarine cables	(IEA 2021; MITERD and REE 2020; Zamora, 2021; Felipe-Andreu et al., 2022)
Electric substations [units/year]	121 (h)	150 (e)	187 (e)	Normal μ = 40 years σ = 8,0	66, 132, 220 & 400 kV	(IEA 2021; MITERD and REE 2020; Zamora, 2021)
Electric and electronic equipment	Placed on the market (h)	2016–2021 trends with maximum ±2 % annual variation (e)		Category specific	43 categories	(J. Torrubia et al., 2023; MINCOTUR 2022)

2.2. Scenarios

We applied the described model to evaluate eight scenarios. We analysed a transition scenario (TS) in which the objectives of public policies related to energy and digital transition are achieved, accompanied by ambitious collection and potential recycling rates by 2050. This scenario does not represent a continuation of business-as-usual observed trends but rather illustrates a significant transformation. In addition to the TS, we also analysed the implications of maintaining current collection and recycling rates (TS-current rates) and explore six circular economy and sufficiency measures (Alternative 1–6).

Table 1 summarizes the main parameters for each technology in the transition scenario (TS), indicating whether the technology targets are derived directly from historical series (designated as 'h'), public policies (designated as 'p') or estimated by us (designated as 'e'). Tables 45 and 48 of Supplementary Information contain the collection and recycling rates considered for each technology.

Additionally, we determined collection and recycling rates by considering relevant legislation on Waste Electrical and Electronic Equipment (WEEE) (BOE 2021a), vehicles (BOE 2021b), and batteries (BOE 2021a), as well as assumptions from international reports, including those by the World Bank (World Bank 2020), KU Leuven University (Gregoir and van Acker, 2022), and the Institute for Sustainable Futures at the University of Sydney (Dominish et al., 2019). Using this data, we establish current and potential collection and recycling rates, which evolve linearly to represent year-to-year improvements (see SI 3 for a description). In 2050, potential rates are applied to all technologies, except for electric batteries, which are subject to ambitious recycling targets mandated by the EU battery recycling regulation (European Parliament and European Council, 2023) by 2030.

Detailed explanations of the references and assumptions used to establish the exogenous parameters of the model can be found in the Supplementary information. A full summary of the exogenous parameters used to define the transition scenario (TS) can be found in SI 4.1.

2.3. Circular economy and sufficiency measures

We consider six alternative scenarios in which we implement various circular economy and sufficiency measures aimed at softening the growth in metal demand and reducing primary extraction requirements. Building upon consulted literature (Baars et al., 2017; Dominish et al., 2021; Simas et al., 2022; T. Riofrancos et al., 2023), we define the following characteristics of our alternative scenarios:

1. Extending the useful life of wind, photovoltaic, and electric car technologies: Up to 30 years in the first two cases and up to 16 years in the third.
2. Apply potential collection and recycling rates in 2030 instead of 2050: This affects all technologies except batteries, where the potential recycling rate was already set in 2030 in the TS due to existing legislation.
3. Limiting the size of electric car batteries: Keeping their size at the current 55 kWh, as opposed to the increase to 70 kWh considered in the TS as an extension of the trends observed in the past.
4. Applying a second life in energy storage to 25 % of the batteries of electric vehicles that reach the end of their useful life: Considering a 20 % loss of capacity at end-of-life in electric mobility.
5. Alternative mobility scenario with a substantial reduction in the number of passenger cars in circulation and a drastic increase in the number of buses: With a fleet of passenger cars and electric buses in 2050 of 9 million and 250 thousand, respectively, compared to 17 million and 80 thousand in the transition scenario.
6. All alternatives combined

2.4. Impacts of primary extraction and equitable fraction

To evaluate the outcomes of primary metal extraction, we analyze both the associated impacts and the comparison with the 'equitable fraction of global reserves' parameter. Our focus is centered on three primary impacts: extracted rock, energy consumption, and CO2 emissions. We assess the first impact using the rock-to-metal parameter, which quantifies the amount of rock that must be mined per ton of metal (Nassar et al., 2022). To analyze energy consumption related to the extraction, concentration, and refining processes, we conduct a detailed breakdown considering various energy sources, such as natural gas, diesel, coal, and electricity. Our methodology is based on our previous research (J. Torrubia et al., 2023). Concerning CO2 emissions, we rely on data from Nuss and Eckelman's research (Nuss and Eckelman, 2014).

Additionally, we estimate the 'equitable fraction of global reserves' by comparing Spain's population of 47 million to the global population, representing approximately 0.6 % of the world's population. From a global justice perspective, this translates into Spain's share of mineral reserves being equivalent to 0.6 % of the world's reserves. We derive this parameter using data from the global reserves in 2022, sourced from the United States Geological Survey (USGS) (USGS 2023).

3. Results

Eight scenarios are evaluated: transition scenario (TS), transition scenario maintaining current collection and recycling rates (TS-current rates), and six circular economy and sufficiency alternatives (Alternative 1–6). In the following sections the main results obtained from the calculation model are summarized.

3.1. Demand and recycling of metals in Spain's energy and digital transition by 2050

The analyzed period exceeds the lifespan of many technologies, requiring equipment renewal. To reach the target of 90 GW of wind and 111 GW of photovoltaic capacity by 2050, 133 GW and 188 GW, respectively, would need to be installed. The challenge is more significant for electric cars, where achieving a fleet of 17 million by 2050 requires manufacturing 34 million between 2020 and 2050. This results in annual battery requirements dominated by electric cars: 53 GWh in 2030, 108 GWh in 2040, and 163 GWh in 2050. Policies banning the sale (2035) and circulation (2050) of ICE vehicles force 32 million and 88 thousand ICE passenger cars and buses to reach end-of-life between 2020 and 2050.

The resulting cumulative metal demand between 2020 and 2050 is 2.6 kt of Ag, 7176 kt of Al, 0.1 kt of Au, 4251 kt of Cu, 166 kt of Co, 226 kt of Li, 710 kt of Mn, 823 kt of Ni, 45 kt of Dy+Nd and 0.1 kt of Pd+Pt. Fig. 2 graphically represents the cumulative full-results between 2020 and 2050 in a Sankey diagram, from the sourcing of metal demand to the end-of-life processes. Here, we can differentiate the origin and destination of the flows, their magnitude and their life cycle stages. A dynamic representation of annual full-results can be explored in the Supplementary Information.

Thus, we clearly see how demand for all metals is dominated mainly by electric mobility technologies. Electric mobility is responsible for 54–58 % of the 2020–2050 cumulative demand for aluminum and copper, 73–92 % for manganese, cobalt, nickel, and lithium, and 79 % for dysprosium and neodymium. Meanwhile, wind technologies are responsible for only 16 % of the demand for dysprosium and neodymium, and substations and power lines account for only 10–11 % of the demand for copper and aluminum. EEE placed on the market demand approximately 5–12 % of most metals and up to 35 % of the total demand for gold. We also see how the manufacture of electrolyzers for the production of green hydrogen is the main driver (77 %) of palladium and platinum demand.

Regarding the recycling of considered technologies, the cumulative

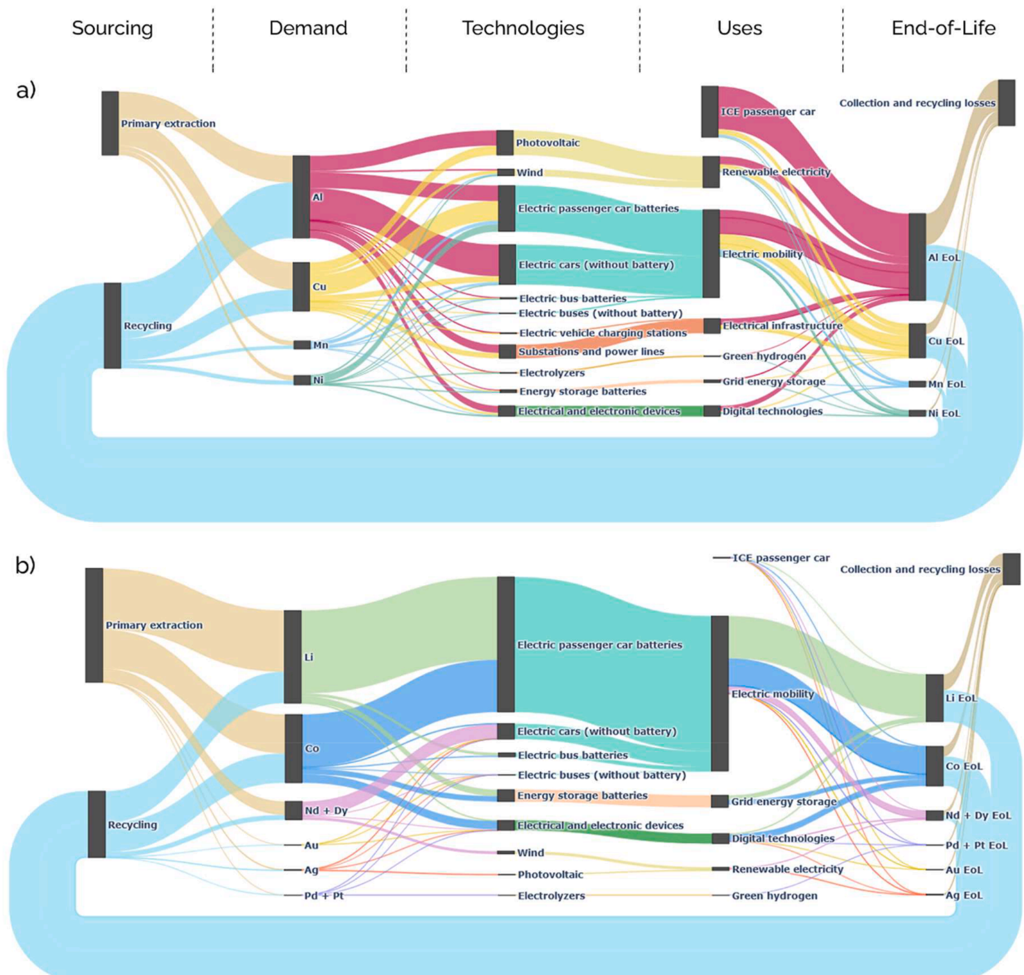

Fig. 2. Sankey diagram for aluminum, copper, manganese and nickel (a) and for lithium, cobalt, rare earths (Nd + Dy), gold, silver and PGM (Pd + Pt) (b) cumulative results for the energy and digital transition in Spain between 2020 and 2050. Five lifecycle stages are differentiated: sourcing, demand, technologies, uses and end-of-life. The difference between the inflows and outflows magnitude at the "Uses" nodes reflects the amount of the 2020–2050 cumulative demand that remains as metal stock at the end of the considered period.

metal recovery between 2020 and 2050 in the transition scenario amounts to 1 kt Ag, 4494 kt Al, <1 kt Au, 1616 kt Cu, 71 kt Co, 77 kt Li, 312 kt Mn, 385 kt Ni, 12 kt Dy+Nd and 0.0 kt Pd+Pt. Electric mobility holds a central position in metal recovery as a result of its importance in demand, especially significant for cobalt (76 %), lithium (91 %), nickel (71 %), and dysprosium and neodymium (77 %). End-of-life ICE

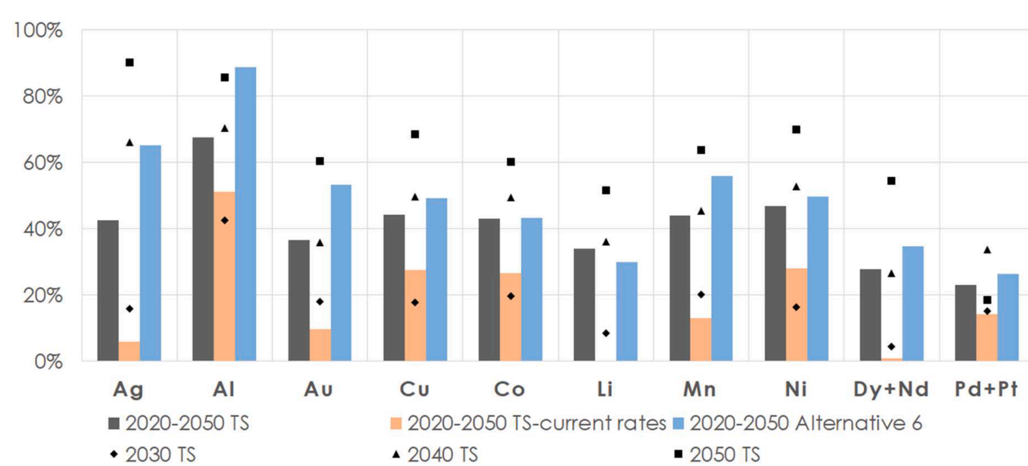

Fig. 3. Percentage of the demand for the Spanish energy and digital transition met from the recycling of the technologies considered. Bar representation for cumulative results between 2020 and 2050 for Transition Scenario (TS), Transition Scenario maintaining current collection and recycling rates (TS-current rates) and Alternative 6 (All circular economy and sufficiency alternatives combined). Spot representation for annual results in 2030, 2040, 2050 in the Transition Scenario (TS).

passenger cars account for 47 % of aluminum recycling and 53 % of palladium and platinum recycling. WEEE recycling would be responsible for 35 % of gold recovery. Fig. 3 shows the percentage of the demand from Spain's energy and digital transition that could be met by recycling the technologies considered. We show both the annual results for 2030, 2040, 2050 in the TS and the cumulative results between 2020 and 2050 for three scenarios: TS, TS-current rates and Alternative 6.

Under the ambitious collection and recycling rates considered in the TS, metal recycling could meet 23–68 % of the 2020–2050 cumulative metal demand, reducing primary extraction requirements. When combined with circular economy and sufficiency measures (Alternative 6), this figure rises to 26–89 %. However, maintaining current collection and recycling rates (TS-current rates) reduces this to 1–51 %. Including recycling sources from other sectors could yield higher percentages. Discrepancies between recycled metals and collection/recycling rates are influenced by annual technology demand and technology lifespan. For example, the recycling rate for Pd+Pt in 2050 is lower than in 2040 due to increased hydrogen technology adoption in that decade. Additionally, under Alternative 6, recycled Li decreases due to reduced availability caused by declining demand for batteries in this scenario.

Combining demand and recycling results allows us to estimate primary extraction requirements. Cumulative primary extraction requirements between 2020 and 2050 amount to 1.5 kt Ag, 2682 kt Al, 0.1 kt Au, 2635 kt Cu, 95 kt Co, 149 kt Li, 398 kt Mn, 438 kt Ni, 32 kt Dy+Nd and 0.1 kt Pd+Pt. The evolution of the annual primary extraction requirements experiences two clearly differentiated periods: a strong growth between 2020 and 2030, reaching a compound annual growth rate (CAGR) of 20–32 % for metals such as manganese (20 %), nickel (28 %), lithium (32 %) or dysprosium and neodymium (23 %), followed by a softening in the subsequent decades of 2030–2040 and 2040–2050, where the CAGR is below 5 % and 2 %, respectively. The maximum primary extraction requirement is reached around 2030 for metals such as aluminum (118,420 t), copper (103,658 t) and nickel (19,385 t), while it is delayed until 2040–2050 for metals such as gold (3.4 t), cobalt (3886 t), lithium (6973 t), manganese (16,413 t), dysprosium and neodymium (1396 t), and palladium and platinum (9.2 t). In the case of silver, the maximum primary extraction requirements (120 t) would occur in 2023, with a subsequent decrease due to a drastic reduction in the mineral intensity of silver in photovoltaic technologies, together with an increase in their recycling rates.

3.2. Circular economy and sufficiency alternatives

Below, we describe the key results obtained by analyzing the six circular economy and sufficiency alternatives:

1. Extending the lifespan: The installations and removals between 2020 and 2050 decrease compared to the TS for wind technologies (-14 % and -26 %), photovoltaic (-14 % and -30 %), and electric cars (-25 % and -49 %).
2. Applying potential collection and recycling rates in 2030: Losses in the collection and recycling processes for silver are reduced by 37 %, those for gold by 31 %, and those for dysprosium and neodymium by 41 %.
3. Limiting the size of electric car batteries: Annual requirements for new batteries are reduced to 50 GWh in 2030 (-6 %), 93 GWh in 2040 (-14 %) and 131 GWh in 2050 (-20 %).
4. Second life in energy storage for EoL electric mobility batteries: We observe a saturation phenomenon in which, from 2037, the batteries available for second lives in energy storage exceed the requirements of this sector. This means that only 80.4 % of the batteries earmarked for this purpose will be used in 2020–2050.
5. Alternative mobility scenario: Cumulative registrations of electric cars between 2020 and 2050 are reduced to 23 million (-32 %), while those of electric buses are increased to 346 thousand (+157 %). Annual requirements for new batteries are reduced to 53 GWh in 2030 (0 %), 85 GWh in 2040 (-21 %), and 131 GWh in 2050 (-48 %).
6. All alternatives combined: A steady state in demand is reached for almost all metals analyzed, except for palladium and platinum. After rapid growth up to 2030, subsequent demand up to 2050 remains stable or even decreases. The percentage of demand that can be met through recycling reaches 100 % for metals such as silver (by 2036), aluminum (by 2040), or nickel (by 2049), while for all other metals, this percentage is considerably higher than in the TS. The annual requirement for new batteries is reduced to 48 GWh in 2030 (-9 %), 51 GWh in 2040 (-53 %), and 51 GWh in 2050 (-69 %).

Fig. 4 shows the variation in cumulative primary extraction requirements between 2020 and 2050 for each alternative compared to the transition scenario.

The alternatives that yield the most substantial reduction in primary extraction are those that limit the size of the batteries of electric cars (Alternative 3) and those that propose an alternative mobility scenario (Alternative 5) emphasizing a significant reduction in the car fleet and promoting a modal shift towards public transportation. In the former case, a 6–16 % reduction in primary extraction requirements is attained, while in the latter case, it amounts to 5–35 %. When all the proposed circular economy and sufficiency alternatives are combined (Alternative 6), a reduction in primary extraction requirements ranging from 11 % to 61 % is achieved.

3.3. Impacts of primary extraction and equitable fraction of reserves

When assessing primary extraction impacts, aluminum emerges as the primary contributor, responsible for over 50 % of CO_2 emissions, electricity consumption, and coal usage. This is due to both its substantial primary extraction requirements (cumulative 2682 kt between 2020 and 2050) and its energy-intensive refining process. Additionally, we have uncovered overlooked factors, such as significant rock extraction during primary gold extraction (247 kt), considering its geological scarcity. Copper stands out for rock extraction due to its relative scarcity (ore grades below 0.6 %) and high primary extraction, totaling 2372 kt. Dysprosium and neodymium are notable for their energy consumption, despite representing only 0.5 % of total extraction requirements; they consume 5 % of electricity, 7 % of diesel, and 9 % of natural gas due to energy-intensive refining.

The impact parameters stabilize after a rapid growth phase until 2030: rock extraction at around 73 Mt/year, energy consumption at around 14 PJ/year, and CO_2 emissions at around 1.2 Mt/year. To contextualize, Spain's 2019 primary energy consumption was 5279 PJ, and 2022 CO_2 emissions were 305 Mt. Cumulative energy consumption and CO_2 emissions between 2020 and 2050 from metal primary extraction represent 8 % of Spain's current annual energy consumption and 12 % of its annual emissions. Visualizing the rock results, in 2050, it would take two Cape bulk carriers (each with a capacity of 110 kt) to transport the 166 kt of metals obtained from primary extraction. However, considering the rock extraction, additional 636 Cape bulk carriers would be needed to transport the 70 Mt of extracted rock.

When considering all circular economy and sufficiency alternatives (Alternative 6), impact parameters decrease by 31–52 %. Conversely, in the least favorable scenario with no improvements in collection and recycling processes (TS-current rates), rock extraction, energy consumption, and CO_2 emissions would increase by 34–44 % compared to TS.

Lastly, Fig. 5 compares the cumulative primary extraction requirements between 2020 and 2050 relative to the 'equitable fraction of global reserves' (0.6 %). The results are displayed for three scenarios: TS, TS-current rates, and Alternative 6.

These results indicate that the demand for metals required for Spain's energy and digital transition technologies between 2020 and 2050 would exceed the 'equitable fraction' of global cobalt reserves

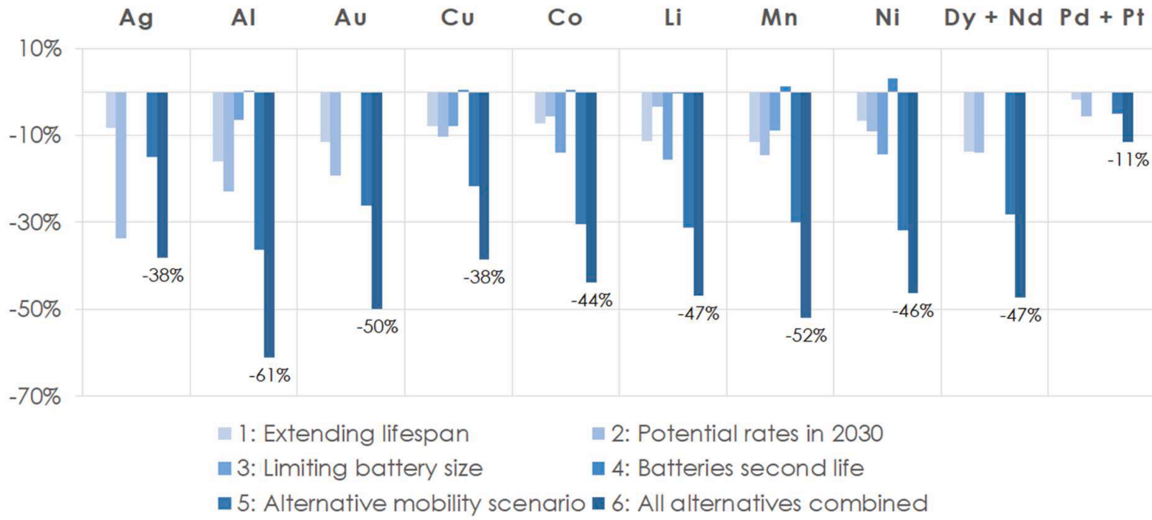

Fig. 4. Variation of 2020–2050 cumulative primary extraction for the different circular economy and sufficiency alternatives compared to the transition scenario.

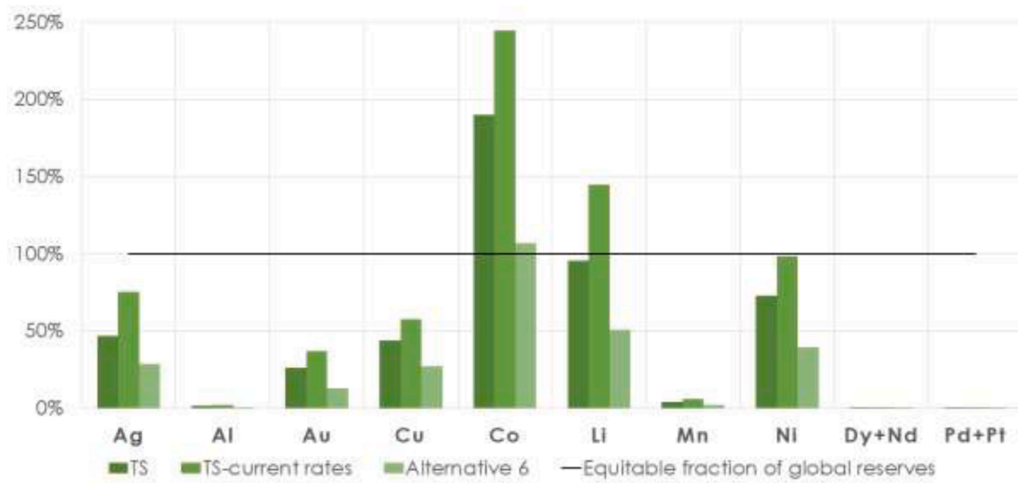

Fig. 5. Comparison of 2020–2050 cumulative primary extraction requirements with respect to the 'equitable fraction of global reserves' of the analyzed metals.

(244 %), nearly reach that of lithium (96 %), and exceed 73 % for nickel. If current collection and recycling rates are maintained, the cumulative primary extraction requirements for lithium would exceed the 'equitable fraction' (145 %), those for nickel would remain near (98 %), and those for cobalt would reach 244 % of the 'equitable fraction'. When combining all circular economy and sufficiency alternatives, 51 % and 39 % of the 'equitable fraction' of lithium and nickel would be consumed, while this parameter would still be above 100 % for cobalt.

4. Discussion

We draw the discussion by focusing on four aspects of the research: limitations, comparisons, the role of recycling and the role of mobility.

4.1. Research limitations

Our research has encountered various limitations that have influenced the results. We can categorize these limitations into four general areas. Firstly, we lack detailed public policies for the development of certain technologies in the energy and digital transition beyond 2030. This limitation has had a significant impact on areas such as electrolyzers for green hydrogen and electric cars, where we had to project our estimates as far as 2050. This uncertainty is particularly relevant in the case of the electric car fleet, as it represents the primary driver of metal demand. Secondly, there is the challenge of implementing ambitious recycling scenarios, hindered by the absence of metal-specific recycling rates in public policies. Achieving this would require overcoming significant obstacles related to metallurgical processes, waste management channels, and the design of technological devices. These achievements are not assured but demand substantial efforts and transformations. Therefore, the results obtained should be interpreted keeping this in mind. Thirdly, we must acknowledge the absence of consideration for metal demand from other sectors of the Spanish economy. Incorporating an analysis of the evolution of other economic sectors during the analyzed period would provide a more comprehensive picture, especially when it comes to widely used metals like copper and aluminum. Fourthly, we do not incorporate the environmental impact of metal recycling into our analysis, a factor that is not negligible and will be analyzed in future studies.

In addition to these limitations, we should also recognize the uncertainty surrounding technological innovation in the future. Such uncertainty could potentially impact the distribution of sub-technologies considered and mineral intensity.

4.2. Comparisons with previous research

It is essential to benchmark our results against international reports for validation. However, as (Calderon et al., 2024) points out, comparing studies is challenging due to the ambiguity of future technologies and the difficulties in predicting technological advancements. Nevertheless, the report 'Metals for Clean Energy: Pathways to solving Europe's raw materials challenge' by KU Leuven University (2022) (L. Gregoir and van Acker, 2022) estimates the demand for metals related to the EU's domestic production of energy transition technologies, offering a good reference for comparison. This report serves as a reference for Spain's mineral resource policies. Notably, it excludes 30 % of electric vehicle batteries, electrolyzers, and 75 % of wind turbine permanent magnets and electric vehicle components, as it doesn't account for technologies imported from abroad the EU.

When comparing our results for Spain to the KU Leuven report, we find that they represent 2–16 % of the metal demand projected in the KU Leuven report for the entire EU's energy transition. In particular, the comparison yields the following results: 8 % for Al, 15 % for Cu, 16 % for Co, 2 % for Li, 13 % for Ni and 62 % for Dy+Nd. This last figure is explained by the domestic production approach adopted by the report. For context, Spain constitutes 6 % of the EU's GDP, 8 % of its energy consumption, and 11 % of its population. This comparison validates our findings, as they align with the expected magnitude, despite differences in assumptions and analytical frameworks.

In the initial years of the study, recycling capacity is not substantial. In 2030, the percentage of recycled metals ranges from 4 to 42 %, reaching 19–90 % by 2050, depending on the metals. This finding aligns with other research, suggesting that the quantity of recycled metals becomes noteworthy only around 2035–2040 (Zuser and Rechberger, 2011; Elshkaki and Graedel, 2013; Månberger and Stenqvist, 2018; Liang et al., 2023; Viebahn et al., 2015; Wang et al., 2019; L. Gregoir and van Acker, 2022). The limited use of most metals in other technologies explains this phenomenon, as they are not commonly held in stock.4.3. The role of the recycling in the energy and digital transition

Recycling plays a central role in reducing primary demand, with metal recycling potentially satisfying 23–68 % of the cumulative metal demand between 2020 and 2050. In the best-case scenario (Alternative 6), this percentage could escalate to 26–89 %. These recycling figures are based on considerations of European and Spanish policies. However, it is important to note that these policies primarily address waste collection (BOE 2021c; BOE 2021d) and only touch upon recycling, particularly in the case of batteries (European Parliament and European Council 2023). Therefore, we had to rely on assumptions from other sources due to the complexity of recycling and the lack of information, especially for critical elements scarcely utilized in the industry over the past three decades (Valero et al., 2018; Wang et al., 2019).

Setting these ambitious policy targets does not guarantee fulfillment, as they surpass the 70 % rate in collection and recycling. Even maintaining the current recycling rate (TS-current rates) would require expanding collection and recycling capacity to accommodate the anticipated rise in end-of-life technologies and metals. New facilities must be ready when the first generation of technologies reaches the end of its lifespan (Zuser and Rechberger, 2011; Habib et al., 2020). Despite these ambitions, current achievements fall short of proposed standards. For instance, lithium recovery in batteries is at 3 % (Calvo and Valero, 2022), far below the European battery regulation's ambitious target of 80 % (European Parliament and European Council 2023).

To enhance the plausibility of scenarios, addressing challenges involves prioritizing traceability and collection, particularly for WEEE (J. Torrubia et al., 2023), as only 40 % of the EU's annually generated e-waste is formally treated (Zhang et al., 2017). Improving metal recycling is crucial, necessitating close collaboration between governments and companies: enforcing design and manufacturing standards for critical mineral recycling, eliminating administrative and legal barriers to waste transformation into raw materials, and designing metallurgical plants for critical element recovery are essential steps (Calvo and Valero, 2022; Liang et al., 2023; Viebahn et al., 2015). Currently, only a few industries in Europe can recycle the metals required for the energy and digital transition. However, many can only be economically recoverable when co-recycled with more valuable ones. Some argue that recycling may not always be economically desirable (Wang et al., 2019). Therefore, reinforcing recycling policies in Spain and the EU, such as establishing recycling rates by elements, for all sectors analyzed in this study, is essential.

4.3. The role of the mobility model in future metals demand

The results underscore electric mobility as the primary driver of metal demand during the energy and digital transition. Specifically, lithium and cobalt, linked to electric mobility, exceed the 'equitable fraction of global reserves' as a result of Spain and EU policies aimed at achieving full adoption of electric vehicles by 2035–2050. This ambition also presents a risk to the achievement of the proposed scenarios. Conversely, the other sectors exhibit considerably more modest demands, which implies that the achievement of the targets are much more plausible. This suggests that the future of mobility and metal demand will evolve in tandem. This presents a dual-scale challenge that, if effectively addressed in the coming years, could make the most desirable scenarios in this study achievable.

This dual-scale challenge poses a risk to the automotive sector in Spain, the second-largest European vehicle manufacturer, responsible of 149 thousand direct jobs and 10 % of the country's GDP (CCOO Industria 2023). To enhance circularity, strategies like using abundant materials and maximizing recycled content are crucial (Ortego et al., 2018), and the proposed European Commission end-of-life vehicle regulation addresses some of these aspects (European Commission (EC) 2023). Besides technological advancements, achieving sustainable mobility requires a shift from 'car dependence' (Mattioli et al., 2020). Spain's extensive highway network and high private vehicle usage (Sanz et al., 2016; DGT and IDAE 2019) underscore the need for alternative mobility scenarios, emphasizing reduced car travel distances and a decreased fleet size (Brand-Correa et al., 2020; Brand et al., 2019; Dillman et al., 2021; Kuss and Nicholas, 2022). This approach has inspired the alternative mobility scenario (Alternatives 5), which achieve the greatest reduction in demand. To turn these scenarios into reality, it is imperative to connect the discussion surrounding the demand for metals with the broader discourse on strategies to reduce the number of private vehicles in circulation (T. Riofrancos et al., 2023).

5. Conclusions

The findings of this research yield five key conclusions:

1. Industrial ecology methodologies, such as MFA, serve as valuable and robust tools for conducting country-level research with a tailored approach to public policies. They enable the exploration of scenarios that incorporate sufficiency-based transformations and facilitate the evaluation of accelerated large-scale metal recovery development. This conclusion is shared by other studies (Zhang et al., 2023; Wang et al., 2019).
2. Electric mobility will be the primary driver of future metal demand during Spain's energy and digital transition. Accounting for 54–58 % of the 2020–2050 cumulative demand for aluminum and copper, 73–92 % for manganese, cobalt, nickel, and lithium, and 79 % for dysprosium and neodymium. This is primarily attributed to the projected production of 34 million electric cars within the analyzed period, with the aim of maintaining a fleet of 17 million by 2050.
3. Achieving ambitious collection and recycling systems could meet 23–68 % of the cumulative metal demand between 2020 and 2050 under the Transition Scenario (TS). Between 2020 and 2050, this figure sees significant improvement, increasing from 9 % to 52 % for

lithium and from 4 % to 54 % for dysprosium and neodymium. This requires a substantial increase in current collection and recycling rates, industrial policy planning, establishing effective collection channels, the development of an urban mining industry, and the adoption of recycling-oriented design measures by manufacturers.
4. Implementation of circular economy and sufficiency measures has the potential to reduce primary extraction requirements 11–61 %. The most impactful alternatives for reducing primary extraction include limiting the size of electric car batteries and proposing alternative mobility scenarios that significantly reduce the car fleet while promoting a modal shift towards public transportation.
5. When regarded from a global justice perspective, Spain's primary extraction requirements for the energy and digital transition exceed the 'equitable fraction of global reserves' for lithium and cobalt. However, by combining all circular economy and sufficiency alternatives, it is possible to reduce these requirements to only 51–107 % of the 'equitable fraction' for these metals.

In light of these conclusions, our recommendations focus on three specific areas. First, there is a need to continue expanding the study of future raw material demand in Spain, considering factors such as economic growth and the structural transformations associated with the energy and digital transition. To enhance Spanish public policies on mineral resources, it is essential to supplement them with a comprehensive study that integrates detailed future demand scenarios. Second, the results underscore the importance of incorporating various sufficiency measures into the analysis to reduce demand, particularly in the field of mobility. Enhancing circularity of vehicles and reducing 'car dependence' should be a priority. This highlights the need for research that simultaneously examines the impact of specific transformations on mobility and their associated metallic requirements. Third, we emphasize the importance of conducting studies, engaging in public discussions, and planning for primary extraction requirements while considering the impact on local communities affected by mining, both within and beyond the country's borders. This is crucial to ensure that the energy and digital transition does not inadvertently perpetuate existing territorial and international inequalities.

In summary, the agenda arising from this study includes research conducted at the country-level with a public policies tailored approach, exploration of scenarios integrating sufficiency-based transformations, and evaluation of the advantages of accelerated large-scale metal recovery development.

6. Spotlights

"Metals for energy & digital transition in Spain: demand, recycling and sufficiency alternatives" - Martín Lallana, Jorge Torrubia, Alicia Valero

- Energy and digital transition public policies are driving substantial global demand growth for various metals
- Future metal demand in Spain will be mainly driven by electric mobility, and metal recycling could meet 23–68 % of demand
- When circular economy and sufficiency measures are combined primary extraction requirements could be reduced by 11–61 %
- Large-scale metal recovery industry and sufficiency transformations should be developed alongside transition policies
- Mineral resource policies should encompass comprehensive forecasting, incorporating demand reduction strategies

CRediT authorship contribution statement

Martín Lallana: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jorge Torrubia:** Writing – review & editing, Resources, Investigation, Conceptualization. **Alicia Valero:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Supplementary materials

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