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Economic and environmental impacts of the shifts to electromobility in Spain

A multiregional input–output framework

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Abstract

The decarbonization of transport is a key goal facing climate change. The electrification of the powertrain for passenger cars is part of this goal to reduce carbon emissions. This involves a big change in the global supply chain, specifically in countries with a high weight of the traditional automotive sector, such as Spain, where above 10% of the GDP comes from this industry. There is a forecasted shift from the sector of traditional automotive parts to the electric sector, where batteries and electric components will be the major part of the powertrain. This work evaluates socioeconomic and environmental impacts of the changes in the car industry from the ramp-up of the electric vehicles market in Spain, and also in the European Union and the rest of the world. To do it, we use an environmentally extended multiregional and multi-sectoral input–output model. Our simulations include the technological change and demand shifts estimated to achieve the penetration of electric vehicles up to 2030 and 2050. The results show significant impacts on employment and economic indicators by 2050, when the share of electric vehicles is expected to increase up to a relevant level.

KEYWORDS
electromobility, embodied emissions, electric vehicles, global value chains, industrial ecology, multiregional input–output

1 | INTRODUCTION

The European Union (EU) aims to achieve carbon neutrality by 2050; that is at the core of the European Green Deal (COM/2019/640). To achieve this, the EU needs to transform its energy system, a major contributor for greenhouse emissions in the world accounting for 75% of the total. Three main pillars support the strategy for this transformation: energy efficiency, direct electrification of end-use sectors, and use of clean fuels in cases where electrification is not possible (COM/2019/640). Specifically in the transport sector, this calls for the need to generalize the use of electric vehicles (EV). The crisis caused by the pandemic reinforced the objectives of the “EU Green Deal”—a green recovery with an economy more sustainable, digital, and resilient. However, as established in the United Nations' Sustainable Development Goals (UN's SDG), this trend must come with a balance in social terms.

The transition from combustion engines to electric powertrains must consider the implications of related sectors such as electricity, battery production, and overall transport policy. Prior literature shows that future transport policies should consider a wider approach when establishing the replacement of current vehicles and schedule for general fleet electrification (Kagawa et al., 2011, 2013; Nakamoto et al., 2019).

Moreover, this transition must consider the implications throughout the global value chain. Vehicle electrification policies are crucial for specific regions with relevant traditional automotive industries. Europe is experiencing a progressive and accelerated replacement of traditional powertrains in the car industry, with expected global economic, social, and environmental impacts. In this context, Spain is highly affected since the automotive sector accounts for 8.1% of the gross domestic product (GDP) for direct contribution to car and components production. Spain is the ninth vehicle producer in the world and the second in Europe (after Germany). According to ANFAC (2022), the automotive sector accounts for 9% of the employment of the entire population in Spain considering direct and indirect economic activity (production, distribution, trading, repair, etc.). The production of vehicles and components represents 9% of total exports of Spain. The National Integrated Energy and Climate Plan in Spain (PNIEC in its Spanish Acronym, 2021–2030) sets the goal of implementing five million EVs by 2030 (three million passenger cars and two million motorcycles, light commercial vehicles, and buses). This plan is in line with the European Commission's communication to the European Parliament in December 2020 (Sustainable and Smart Mobility Strategy), that aims to reduce 90% of the transport sector's emissions by 2050 with nearly all cars, vans, buses, and heavy-duty vehicles with zero emission. An intermediate evaluation in this strategy sets the quantity of zero-emission vehicles (ZEV)[1] to be at least 30 million by 2030. In this paper, all electric vehicles are categorized as ZEV.

Therefore, the shift in technology involves a change in the supplier chain and transfer between industries. On the one hand, the current automotive sector must be prepared for the development and production of new components. On the other hand, other industries not traditional to the automotive market can enter with specific products for electromobility. The policymakers must consider the provision of support to the companies and all the sectors in the global supply chain involved in this transition.

In this context, we use a multi-sectoral and multiregional input–output (MRIO) approach to evaluate the economic and social impacts of electromobility on the Spanish economy. Specifically, this study aims at evaluating the penetration of the electrification of powertrains in Spain by using an MRIO analysis, and including the penetration of the EV market in other regions due to the high interdependence for the automotive sector in the overall economy. Our scenarios are based on technological changes and demand shifts associated with implementing EVs by 2030 to 2050. Additionally, changes in final demand take into account the share of electricity consumption based on the evolution of the car fleet and alternative options for electricity production alternatives. Facing other methodologies for evaluation, MRIO covers a whole view of the economy and social impacts with a balanced requirement of information and assumptions. There are many studies based on the overall life cycle of the vehicle itself that analyze the direct emissions and emissions due to production (Nordelöf et al., 2014), but this type of analysis based mostly on life cycle assessment (LCA) does not enable the consideration of effects on other industries and the overall effect on economy and other social impacts. The MRIO models include all the global supply chain for analysis of economic and social indicators and have been used to calculate economy-wide emissions directly and indirectly produced by the production of a specific product (Kagawa et al., 2013). This method connects a highly disaggregated input–output table which is extended with an emission intensity vector.

This input–output (IO) approach has been previously used in the literature regarding evaluating electromobility transition in different regions, such as in China (Kang et al., 2019, 2021), where the potential reallocation effects are discussed. In this work, the input–output approach also enables to evaluate reduction of investment and operation costs in the light-duty passenger transport sector, adding value in relation to bottom-up models. Shibusawa & Miyata (2017) showed that hybrid EVs can produce positive effects from a macroeconomic perspective, whereas pure electric passenger cars could result in negative effects in Japan. Turner et al. (2018) highlighted the significant role of services industries (not only direct related industry) in the United Kingdom, showing the impact of increasing the consumption of electricity for the domestic supply chain. Leurent & Windisch (2015) showed that the location of production of EVs and components is relevant in France, and they conclude that the incentive bonus for EV purchases is justified by energy independence, domestic industry, and environmental quality. Kolpakov & Galinger (2020) recently suggested that an increased share of EVs could lead to the worsening of the macroeconomic indicators due to the critical need for additional imports and the shortfall of natural gas or coal sales in Russia. This methodology was also used to evaluate interdependent economies like China and Japan (Shibusawa & Xu, 2013). Japan depends heavily on the motor vehicle industry, while China is expanding rapidly in the sector of EVs. Other macroeconomic models have been applied in Australia, highlighting the impact of scenarios in the evaluation and suggesting a transformational pace of change to achieve results, requiring urgent policy action (Broadbent et al., 2022).

The paper is organized as follows. Section 2 outlines the method and database. Section 3 describes the scenarios simulated and the results obtained. Section 4 presents our concluding remarks.

2 | METHODS

2.1 | The environmentally extended MRIO model

We developed a multiregional and multi-sectoral input–output model (MRIO) with a specific focus on the Spanish economy and its relationship with the rest of Europe and the world. The fundamental purpose of the input–output framework is the analysis of the interdependence of industries and regions (Miller & Blair, 2009).

Our starting point is the representation of a global economy with n industries and m regions/countries, where $\mathbf{x}$ denotes the total output, and $\boldsymbol{x}^r$ the total output generated by region r, and $\mathbf{Z} = (Z_{ij}^{rs})$ is an $mn \times mn$ matrix of multiregional intermediate flows. Let us denote the vector $mn \times m$ of the total final demand of regions by $\mathbf{y} = (y_i^r) = (\sum_s y_i^{rs})$, where each element $\boldsymbol{y}_i^r$ represents the worldwide final demand for products of the industry in country r, and i is a unitary vector $mn \times 1$.

$$\mathbf{x} = \mathbf{Z} + \mathbf{y} \tag{1}$$

We denote the matrix $mn \times mn$ of technical coefficients in this multiregional framework by $\mathbf{A} = (a_{ij}^{rs})$, where each element represents the volume of intermediate input i produced in region r that is used as input to produce one unit of output j in region s. Substituting $\mathbf{Ax}$ for $\mathbf{Z}$, the equilibrium equation can be expressed in terms of the Leontief inverse matrix $\mathbf{L}$ as follows:

$$\mathbf{x} = \mathbf{Ax} + \mathbf{y} \rightarrow \mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} = \mathbf{Ly} \tag{2}$$

The representative element in $\mathbf{L}$, $\mathbf{L} = (l_{ij}^{rs})$, represents all the production generated in sector i in region r to fulfil the demands of inputs incorporated in all the steps of the production chain and ending in the final demand of sector j in region s. In consequence, the elements in $\mathbf{L}$ capture the production embodied in all the economic flows linking sectors i and j, and regions r and s through the international supply chains.

Thus, the Leontief inverse ($\mathbf{L}$) is the tool to link final demands in any region and sector (private and public consumption, investment, and final exports) with all the production generated in the whole economy (across the global supply chain) to fulfil these final demands. In this sense, production, technology, and final demand are sectorial and geographically connected in the MRIO framework.

Moreover, this MRIO can be extended to account for the inputs, resources, and environmental impacts linked to the production in each region and sector (Wiedmann et al., 2007, 2013, among others).

More specifically, if we consider a vector of resource intensity, $\boldsymbol{w}_i^r = (W_i^r / \boldsymbol{x}_i^r)$ being the use of resources in sector and country r per unit of output), we can write[2]:

$$\boldsymbol{\Omega} = \hat{\mathbf{w}}\,\mathbf{L}\hat{\mathbf{y}} \tag{3}$$

Being $\boldsymbol{\Omega}$ the $nm \times nm$ matrix of resources embodied in the full supply chains associated with the final demand. In this matrix, each element shows the resource used in each country r and sector i that produce those inputs that directly and indirectly are associated with the final demand of sector j in country s. The sum of the elements in the row depicts the total use of resources in that sector and country i, s. The sum of the elements in each column shows all the resources in the global economy in the generation of all the inputs that are used to produce a given final demand. In this way, these columns capture the resources embodied in the full supply chain of the final good, j, in country, s.

The modifications in the MRIO to explore the economic and social impacts include changes in the technological matrix $\mathbf{A}$ and in the final demand $\mathbf{y}$. The change in the technological matrix represents the difference in inputs for a given industry and can also include the creation of a new industry with the corresponding definition of inputs. In the case of the final demand, the changes represent the differences in consumption of the different sectors that may occur when a new technology with different function requirements appears in the society.

2.2 | Database

This paper used data from the EXIOBASE database (Stadler et al., 2018). This EXIOBASE database presents a detailed number of sectors and environmental extensions allowing us to explore appropriate activities under the production chain of interest. For this study, sectors were aggregated according to the most relevant production chains and businesses for mobility, resulting in 57 sectors. The list of sectors is presented in Supporting Information S1. From now on, this sector will be denoted as traditional automotive sector, focusing the analysis on the industrial production of the vehicles and components. Likewise, regions are aggregated up to three regions: Spain, the rest of EU+28 and the United Kingdom, and the rest of the world (ROW) for 2016.

3 | RESULTS

3.1 | Description of scenarios

We evaluate here the technological change in the production of vehicles, and the final demand change of economic agents. The definition of scenarios is a key topic for the analysis of impact. The scenarios include specific technological changes and demand modifications based on the study completed by Faber et al. (2006). We describe the two scenarios proposed:

3.1.1 | Scenario 1

This scenario evaluates the technological change required in producing EVs in relation to the conventional thermal engine models by 2030 and 2050. This is calculated based on the gradual evolution of EV market share for a later timeframe in relation to literature values for 2030. Ulrich and Lehr (2020) state that "*the shift is not linear but is evolving in line with the EV market share changes over time.*" For Spain, the evolution of EV market share is calculated with the model designed by the OVEMS[3] (Frías Marin & Roman Ubeda, 2019). This model calculates the number of passenger cars per powertrain based on the existing fleet (around 25 million in 2019), and the total consumption and emissions for this fleet. The target of 90% for CO_2 direct emissions reduction could be reached by 2050 through strong fleet electrification (Krause et al., 2020). This scenario drives to a 2050 fleet composition for new passenger vehicles as follows: 92.5% for battery EV (BEV) and 7.5% for plug-in hybrid EV (PHEV). This data was calculated using the study completed by Krause et al. (2020), considering 85% of passenger cars are small and medium cars of which 100% are BEVs, and the rest of large and SUV cars with 50% of BEVs and PHEVs. We simulate this technological change through changes in the technical coefficient matrix $\mathbf{A}$ (A_{ij}^{rs}) (Equation 2) by increasing the weight of electrical input components and decreasing the weight of traditional components of the motor vehicle industry in line with Bauer et al. (2018)[4] both for 2030 and 2050.

Based on these estimations, we assume that the change in the technical coefficients from 2016 to 2030 corresponds to a car fleet share change from 0.24% in 2016 (original MRIO technical matrix) to 10.76% in 2030. In 2050, the car fleet share for electrified powertrains is 80.42% (notice the calculations consider the difference between new vehicles share in the previous paragraph and existing car fleet since replacement rate).

3.1.2 | Scenario 2

This scenario combines the evolution adopted in Scenario 1 by 2050, together with the impact of changes in final demand based on the simultaneous increase in electricity and decrease in fossil fuel consumption.[5] That is, it includes the changes in the technical coefficient matrix together with consumption modification.[6] The changes in demand for electricity and fossil fuel consumption were taken from the literature (IEA, 2020). These changes in demand mean that electricity demand will increase by 37.12% in Spain and Europe and 16.74% in the ROW due to EVs. As previously presented, it was assumed that the share of EVs will be 80.42% in 2050 (assumption for the European region). The value for occidental regions aligns with predictions in different references (Mai et al., 2018; McKinsey, 2018).[7] Based on data for 2016 and 2030 for the ROW, and taking the rate of EV introduction in Europe, the share of electrified powertrains in the ROW will reach approximately 35% in 2050.[8] This second scenario includes three different cases for electricity production alternatives for the evaluation of environmental impacts, given the relevance of the electricity-mix sources (Kang et al., 2019; Kito et al., 2022):

- Case 1 (base case): Increase electricity production with the current production distribution.
- Case 2: Electricity increases only in low-intensive renewable sources for Europe (according to sustainability objectives).[9] For the ROW, electricity increases proportionally in all the sources (by coal, gas, nuclear, hydro, wind, and biomass).
- Case 3: Similar sustainability objectives for all regions.

Oil displacement from EV fleet is translated for scenario definition with a modification in the demand in 2050 of different sectors: manufacture of motor spirit, manufacture of gas oil, the aggregated other fuels, and retail sale of automotive fuel. It is considered that the manufacture of motor spirit is exclusive for vehicle consumption, with a reduction of 80% for Europe (including Spain) and 50% for the ROW (IEA, 2020).

3.2 | Results of scenarios

We analyzed now the impacts of these scenarios by studying a set of economic (production), social (jobs and wages), and environmental (CO_2 emissions) results.

Table 1 shows the impact that traditional automotive and electric components sectors have on total production for Scenarios 1 and 2. As expected, the traditional automotive sector will decrease. Conversely, the electric component sector will likely increase due to the production of new components such as batteries, electric motors, and other electric actuators.

Results show that the effect up to 2030 is not significant for the sectors under analysis (traditional automotive and electric component sectors), and the total production could increase. The effect on production is noticeable in the automotive sector, but the impact is still low. The maximum contribution is a decrease in production of the traditional automotive sector in the ROW of 0.96%. Meanwhile, the electronic components sector is increasing by 0.84% in Europe. The data obtained for the overall impact confirms previous works found adverse long-term effects (Ulrich & Lehr, 2016). This can be because Europe uses the most innovative technology, whereas there are more commodities in other regions since automotive is

TABLE 1 Percentage change in production in Scenarios 1 and 2.

		Scenario 1		*Scenario 2*
		2030	*2050*	*2050*
Total production	Spain	0.26	−0.12	−0.60
	Europe	0.37	−0.01	−0.47
	ROW	0.15	−0.19	−1.16
	Global economy	0.21	−0.14	−0.98
Production of traditional automotive components	Spain	−0.38	−6.08	−6.21
	Europe	−0.50	−6.82	−6.91
	ROW	−0.96	−8.92	−9.02
	Global economy	−0.81	−8.23	−8.33
Production of electric components	Spain	0.76	1.47	1.59
	Europe	0.84	1.47	1.66
	ROW	0.61	0.86	0.82
	Global economy	0.67	1.01	1.02

a mature sector with high-scale economies. More interestingly, a higher impact can be noticed for the simulation in 2050. The effect on total production is significant in Scenario 2, with a total reduction of 0.98% and a balance unfavorable for the ROW. The impact in the two sectors considered in the electromobility transition is not dependent on demand, so there are similar values for Scenarios 1 and 2 by 2050. The total decrease in the traditional automotive sector reaches a reduction value of 9.02% for the ROW, and 8.33% for total value. As for the electric components sectors, the increase reaches the highest value for Europe with 1.66%, whereas the increase for ROW is 1.02%. As explained before, there is an imbalance between Europe and the ROW that is increased with a higher deployment of EVs. This could be explained by the weight of exports and delocalized production of commodities in low-cost countries that represent a high percentage in the ROW. In the more industrialized countries, such as those in Europe, the most innovative sector, such as the electric components, could grow more than in other regions.

The effects in Spain are relevant. Specifically, the "manufacture of motor vehicles" sector represents a weight of 4.05% in the total production. The weight in Spain contrasts with 3.08% in the rest of Europe, and 2.35% in the ROW. The electric components industry represents 1.02% of Spain's total production, 1.31% in the rest of Europe, and 1.42% in the ROW. Thus, the overall economic impact will be lower than that of the traditional automotive sector.

Apart from the mentioned sectors and the overall impact in the whole economy, the impact in other sectors are also relevant mainly for Scenario 2, depending on the economic structure of the regions. In particular for sectors related to fuel, such as extraction, manufacture and retail sale, as for the production and distribution of electricity (Table S1 in Supporting Information S2).

These results show agreement with the overall trends obtained in previous works done with MRIO methodology for other regions. In particular these results match with those with similar conditions in relation to the dependence with the traditional automotive sector and the need of importing alternative components for EVs (Leurent & Windisch et al., 2015; Shibusawa & Miyata, 2017; Shibusawa & Xu, 2013).

As explained, we aim at understanding how the penetration of EV could affect reallocation of job, attending different skills, and wages. The automotive sector has a significant role in the Spanish workforce percentage, representing 4.11% of employment (number of hours) and up to 6.21% for medium-skilled workers. For the number of people, it is translated into 4.53% of employment—considered within the "manufacture of motor vehicles" category. In Europe, the total number of hours for this industry accounts for 3.91%, whereas for the ROW, this percentage drops to 2.75%. A structural difference with Europe is that in Spain, the relative amount of low-skilled workers in the traditional automotive sector is higher, being quite equilibrated with medium-skilled workers. In Europe, medium-skilled workers are the highest number of workers in the automotive sector.

Tables 2 and 3 present changes in employment in the traditional automotive sector and the whole economy by 2050.[10] This study evaluated the impact of Scenario 1 to analyze the influence of technological change by 2050. In 2050, the gaps between the regions are high, with a difference for the ROW higher than points of percentage for low- and high-skilled workers in hours (e.g., −8.04% vs. −5.57% in Spain and −4.47% in Europe for high-skilled workers). An exception is the medium-skilled workers, as the percentage impact in Spain (8.31%) is similar to the ROW (because these workers represented 6.21% of total medium-skilled workers in Spain).

We observe that Spain is significantly more affected than the rest of Europe, both in the number of people employed in the automotive sector as in hours and wages (more direct than indirect jobs). Quantitatively, this reduction of 6.93% means a decrease of 50,000 people in the sector by 2050. When considering the employment changes in the traditional sectors, the supply chain changes, and new demands of employment, the total number of people employed in all industries would be approximately 140,000. This means that 90,000 people from other sectors are impacted.

TABLE 2 Percentage changes in employment in the traditional automotive sector by 2050.

		Scenario 1		
		2050		
		Low skilled	*Medium skilled*	*High skilled*
Employment (h)	*Spain*	−3.69	−8.31	−5.57
	Europe	−4.66	−4.25	−4.47
	ROW	−8.80	−8.53	−8.04
	Total	**−6.23**	**−6.49**	**−6.89**
Wages (M€)	*Spain*	−4.30	−9.13	−6.98
	Europe	−4.72	−4.34	−4.54
	ROW	−8.15	−8.29	−8.00
	Total	−6.79	−6.79	v7.12

TABLE 3 Percentage changes in employment (people) in the traditional automotive sector and in the whole economy by 2050.

		Scenario 1 (2050)
Automotive sector	*Spain*	−6.93
	Europe	−4.53
	ROW	−7.77
	Total	−7.13
Total economy	*Spain*	−0.64
	Europe	−0.24
	ROW	−0.29
	Total	−0.29

TABLE 4 Percentage changes in CO_2 emissions in direct and embodied emissions in Scenario 2 by 2050.

	Direct emissions			*Embodied emissions*		
	Case 1 (base case)	*Case 2*	*Case 3*	*Case 1 (base case)*	*Case 2*	*Case 3*
Spain	−1.08	−2.93	−2.23	0.16	−1.61	−1.08
Europe	0.16	−1.74	−0.97	0.66	−1.14	−0.48
ROW	0.13	0.15	−1.86	0.01	−0.29	−1.94
Total	0.12	−0.43	−1.71	0.12	−0.43	−1.71

The fact that medium-skilled workers are more affected in the automotive sector in Spain indicates that developing higher-value capabilities could lower the impact. In fact, the overall effect on employment in Spain is the lowest for high-skilled workers. This is similar in Europe, but the difference in employment is not as related to the workers' skills. The study also calculated the impact on wages. Similar to the evolution of employment, there was a slightly higher decrease in Spain's salaries compared to other regions. This is most noticeable in the case of medium-skilled workers in the traditional automotive sector.

Finally, we analyze environmental impacts in Table 4. We focus here on the impacts in Scenario 2 (technological change and demand shifts included), due to the modifications in fuel and electricity consumption. The analysis is focused in a first stage on CO_2 emissions, since they are the largest contributor to global warming. We observe the different impacts when alternative sources for electricity generation are considered. Results show significant differences in the European region, where reductions in embodied emissions are lower than direct ones. It is due to the imports from other regions add emissions that are not accounted for in the regional production. The difference is even higher for Spain, given the impact in the sector. On the contrary, the difference between embodied and direct emissions is not that high for the ROW, since the dependence on imports is considerably lower (much higher volume of production in the region).

The changes are close or under 1% except for production-based emissions in Spain (−2.2%) and consumption-based emissions in ROW (−1.94%). For direct emissions, the main effects are manufacture of motor spirit and manufacturing of motor vehicles sector (traditional automotive), given by

TABLE 5 Changes in flows of total embodied emissions for the three regions from 2016 to 2050 (values of CO_2 emissions in Gt and percentage—all sectors).

	From								
	Spain			*Europe*			*ROW*		
To	*2016*	*2050*	*Change*	*2016*	*2050*	*Change*	*2016*	*2050*	*Change*
Spain	*1927*	*1908*	−1.01	*301*	*298*	−1.21	*206*	*203*	−1.49
Europe	*420*	*412*	−1.92	*29,043*	*28,937*	−0.37	*4005*	*3971*	−0.86
ROW	*540*	*503*	−6.85	*5645*	*5453*	−3.41	*181,038*	*177,626*	−1.88

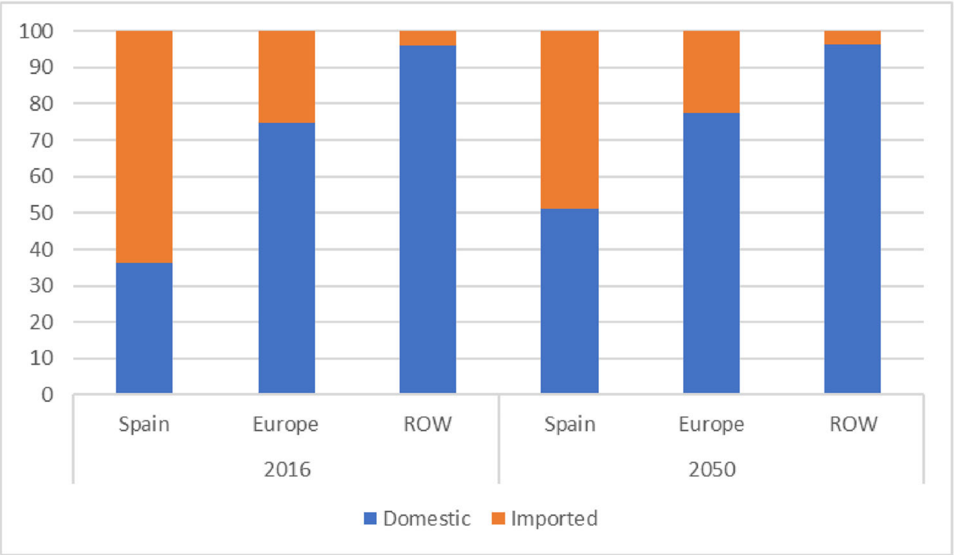

FIGURE 1 Share of embodied emissions for the production of vehicles (percentage domestic and imported emissions). Underlying data for this figure are available in Table S2 of Supporting Information S3.

the components (technological change), more CO_2 intensive than the sector of partial replacement ("manufacture of electrical machinery"). In the case of embodied emissions, the main effect is associated with the decrease of fossil fuel consumption (high weight in embodied emissions in the starting year of analysis).

If we disaggregate the embodied emissions in the regions, we could observe the effects of electromobility transition of vehicle production for the interregional flows, expressed as share of domestic and imported emissions (Figure S1 in Supporting Information S2). The fact that the three considered regions are so different in size (Spain, Europe, and ROW) makes the changes more visible in the figures' evaluation (Table 5) than in graphical representation.

If the analysis is focused on the sector of production of vehicles (Figure 1), we can observe that the impact is higher, mainly for the region of Spain for the embodied emissions, showing an increase in domestic source emissions in this sector. It could be related to the use of more technological content in the vehicle, meaning that the transitions supposes a decrease in the use of commodities that usually come from low-cost countries.

The contribution of the different sectors can be analyzed in order to understand the interregional flows between the regions. In Figure 2, the contribution of the higher 10 sectors for embodied emissions in Spain are represented (including Spain contribution).

A further analysis can be made in order to understand the balance of imported emissions in Spain. It can be observed that the repartition between Europe and ROW are quite balanced for the higher contributor sectors (figure S1 in Supporting Information S2). A further disaggregation of the regions in relevant countries, such as China and United States would be useful to evaluate further the interregional flows (planned as continuation of the work).

Additionally, apart from global warming effect, the road transport is a major contributor for pollutants that are specifically harmful for human health (apart from contributing to different global effects in the earth such as biodiversity loss or acidification). NO_x, CO, and particle matter are pollutants that are directly limited by EU regulation (Limes & Gomes, 2023). SO_x is not directly included in emissions standards but it is also a pollutant related to combustion of fuels and whose production comes mainly from anthropogenic origin. So, Table 6 shows the impact in direct emissions for these pollutants for Case 3 of Scenario 2, with the greatest falls in CO, NO_x, PM2.5, and SO_x direct emissions, being lower than the reductions in CO_2 direct emissions.[11]

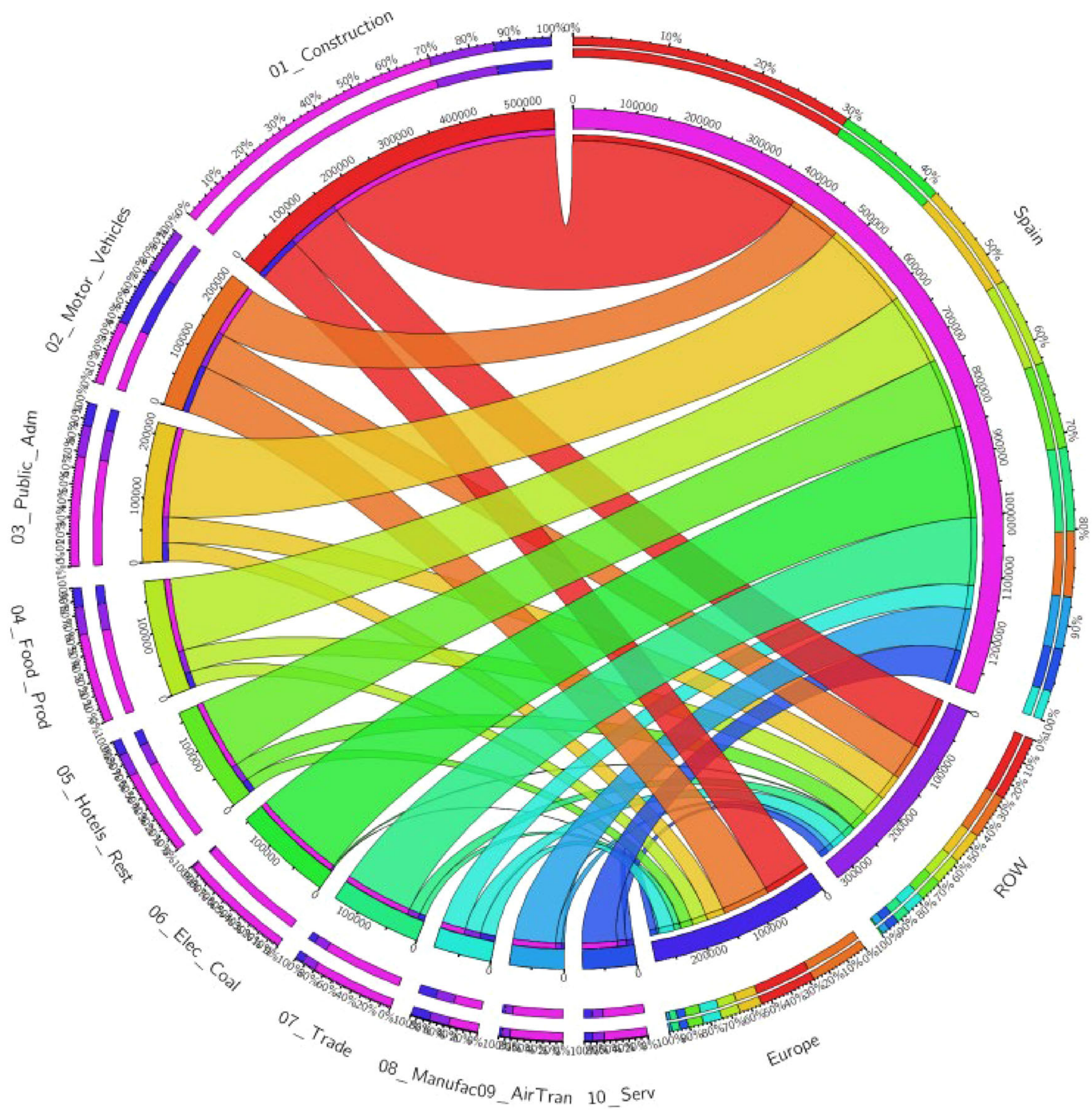

FIGURE 2 Embodied emissions for Spain for the 10 first sectors in quantity (proportional values). Underlying data for this figure are available in Table S3 of Supporting Information S3.

So far, the analysis developed has evaluated the impact on the economic, social, and environmental variables of technological changes and demand concluding the contribution of changes in electromobility to the reduction of global emissions.

Finally, we offer some indications of the magnitude that this operation part would have for the case of Spain[12] for CO_2 emissions. For that analysis, the well-to-wheel greenhouse emissions for different type of vehicles: gCO_2/km (Nordelöf et al., 2014) is considered. According to data calculated for emissions in an overall approach of LCA for vehicles (Nordelöf et al., 2014), the emissions for the different powertrains would be:

- EV: Mean 60 gCO_2/km (for electricity production with energy mix 190 gCO_2/kWh), considered as conservative scenario/minimum value approximately 2 gCO_2/km (if most sustainable energy mix is considered for electricity generation: 11 gCO_2/kWh), considered as sustainable scenario.
- Diesel vehicle: 145 gCO_2/km.

If these emissions in operation are added to the embodied emissions of production, we obtain that total emission from 2016 to 2050 could be reduced by 8.39% in Case 1, 14.22% in Case 2, and 18.17% in Case 3 (values in table S2- Supporting Information S2). Even if the energy mix for production itself is not corresponding to a sustainable scenario, the fact of introducing EVs plays an important role for overall CO_2 reduction when considering the operation (Kang et al., 2021).

TABLE 6 Percentage changes in pollutant emissions in direct in Case 3 of Scenario 2 by 2050.

	Direct emissions				
	Case 3				
	SO_X	*NO_X*	*CO*	*PM10*	*PM2.5*
Spain	−1.09	−1.27	−1.51	−0.95	−1.18
Europe	0.16	−0.24	−0.50	−0.20	−0.32
ROW	−0.88	−0.99	−0.58	−0.70	−0.77
Total	−0.73	−0.87	−0.57	−0.63	−0.71

Furthermore, the significant reduction in Case 3 suggests the need to speed up the transition to electromobility to generate noticeable beneficial environmental effects.

4 | CONCLUSION

This work evaluates the potential impacts of electrification for automotive sector by means of the use of an environmentally extended MRIO model. The main objective is to assess the impact for the Spanish industry, and compare with the position of this industry in relation to Europe and the ROW. The policies announced so far establish limitations in the use and banning of internal combustion engines vehicles, but most of these policies are referred to 2030 horizon. However, we assume the relevance of studying more future impacts, given the fact that industries need to be prepared and, what is more, the general scenario should be predicted in order to define the proper policies in the coming years.

For that, the main contribution of this work has been to estimate the impacts not only for 2030 (for which extensive predictions can be found) but for a longer horizon up to the year 2050. The evolution of vehicle fleet has been estimated with a specific tool, determining how the production chain in the automotive sector changes up to 2050. The changes in the industry have been extrapolated from a literature value that shifts the inputs of the traditional automotive sector introducing a higher share for electric components. The changes in demand had been also inferred from changes in 2050. The study has been done with the aim of understanding the isolated effects of linked to substitution, so the principle of "ceteris paribus" has been followed, not including other potential relevant factors such as changes in productivity or economic growth rates.

When only production shift is included (technological change), the impact on general macroeconomic indicators is limited. In fact, for 2030 the total production increases, and the maximum effect is a decrease in the traditional automotive sector of 0.81%. However, in 2050, when the production shift includes the higher number of electric cars produced, the overall effect presents a fall in the global economy by almost 1%. For the sectors where the technological change has been implemented, the effect goes up to a fall by 8.23% for the traditional automotive sector and an increase in the electric component sector of 1.01%.

In the case of Spain, with a significant unemployment rate, it is important to analyze the impact of the electrification transition. Results by 2050 show a significant effect of the transition that leads to the maximum decrease in employment for medium-skilled workers of 8.31%. Policy implications would refer to government policies that would require actions in the employment market to ensure a fair transition, considering re-capability, relocation of activities, or definition of the appropriate supply chain. The impact in Spain can be more relevant because most of Spain's production centers do not have research and development and central services. Thus, upgrading the function level of production centers in Spain can decrease the impact of the transition.

The environmental extension of the MRIO database with CO_2 emissions enables us to calculate the changes in emissions for the transition. The reduction in emissions is only really noticeable when there is a strategy for the use of electricity coming from renewable sources. Otherwise, the impact of electrification by itself stands for a small reduction. In Spain, the reduction reaches levels of 1.08% and 2.23% for embodied and direct emissions, respectively, without considering the emissions from the operation of the vehicle. If this is considered, the impact in Spain could lead to a reduction from 8.39% to 18.17% of total emissions, depending on the source of electricity. This value compares well with previous analysis in other regions where also the emission intensity of electricity has been evaluated, such as in China where this range is established in a range 13% to 18% (Kang et al., 2021).

In spite of the fact that several assumptions have been made, the numbers justify the continuation of the work for further analysis and proper policy actuations. The model is being extended for the use of a general equilibrium model to introduce more flexible considerations and fiscal and environmental policies. In particular, the explicit consideration of the investment associated with this transformation, the nature of this investment (public, private, domestic, and international), the financing mechanisms, the role of taxation, etc., can outline different medium- and long-term scenarios with additional effects on economic performance, generating incentives or barriers to the development and penetration of these technologies. Also for regional analysis, it is planned to disaggregate regions of Europe and ROW to investigate further the interregional flows.

Finally, as a long period for evaluation has been considered (2030 and 2050 horizon), this work has included in the model only full electric vehicles, considering that the current policy drivers do not include hybrid vehicles with a combustion engine given the fact that they are still CO_2 emitters. However, it may happen that given the resistance of vehicle producers, current economic scenario, and relationships between regions, EU could vary this policy (e.g., CO_2-neutral vehicles fed with synthetic fuels could be permitted due to vehicle manufacturers pressure). In this case, a new sector for hybrid vehicles could be included in the model with the corresponding input repartition depending on the hybridization level of the vehicle. Similarly, as for the possibility of hydrogen-powered vehicles, we have not included them since this solution is not now the trend for passenger cars, but this study could be implemented in the model to compare these technologies. Hydrogen vehicles substitute the combustion engine by a fuel cell and also replace fuel or electricity consumption by hydrogen generation, so in the case it could became a generalized use another set of modifications could be inserted in the model.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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ENDNOTES

[1] ZEV is defined as a vehicle that use a propulsion technology that does not produce internal combustion engine exhaust or other carbon emissions when it operates. So it is referred to operation even if production emissions are emitted. All electric vehicles are categorized as ZEVs.

[2] The final demand is diagonalized with a single main diagonal.

[3] The OVEMS is the Observatory of Electric Vehicle and Sustainable Mobility of the Comillas Pontifical University. This model takes into account the quantity of annual mileage in the country, the percentage share of powertrains for 2050 that should be based on political drivers and the structure of new registrations and unsubscriptions of vehicles, the market acceptance of electric vehicles, an index for renewal of the fleet, and the effect of the length of service. Note that the quantity of annual mileage can be considered constant for the whole car fleet or can increase or decrease depending on social evolutions (big cities concentration, homeworking, etc.).

[4] Specifically, the input coefficient for electrical machinery is increased by 2.6% and the motor vehicle industry is declined by 2.6% by 2030 (Ulrich & Lehr, 2020), and assuming an analogy of the current car fleet with production (new and spare parts car products), the shift in technical coefficients by 2050 would change from 2.6% (increase and decrease in the corresponding categories) to 19.8%. This percentage is directly reflected in the sectors of the MRIO table used for this work ("*Manufacture of motor vehicles*" and "*Manufacture of electrical machinery*"). The change is considered for all the regions (Spain, the rest of the EU, and the ROW) since the production and sale of vehicles are highly globalized. Note that we isolate the effects in industry of the assumptions for technological change and demand. No hybridization of vehicles has been considered, but replacement by pure BEV, since hybrid vehicles have been used for transition, but the industry focused on 100% electric-powered cars.

[5] Changes in final demand simultaneously require changes in production. However, changes in final demand are not evaluated by 2030 since the existing information on the change associated with introducing electric vehicles for 2030 is not significant and could be compensated with energy efficiency improvements (IEA, 2020). Therefore, we evaluate impacts by 2050, where a significant change is expected due to the ramp-up of electromobility.

[6] Changes are imposed in final demand including household consumption, government, and investment expenditures. In this work a separate analysis on investment for charging infrastructure has not been evaluated. This will be done as continuation of the present work with a new computational general equilibrium model.

[7] We assume a mean value between the values for stated policies and a sustainable development scenario based on the share of electricity consumption attributable to EVs by region (IEA, 2020). Specifically, we extrapolated the share of electricity consumption in 2050 based on the evolution of the car fleet for Spain (and assuming the same evolution for Europe).

[8] Note that this value seems consistent if the rest of the world is taken as a whole, although there will be vast differences between countries (as introduced, China could achieve a level equal to or even higher than Europe, whereas other big countries such as India, Brazil, and Russia would reach significant lower values). For that point, it is critical to consider the energy mix (mainly the weight of renewable vs. non-renewable sources for environmental effects).

[9] Based on our database, it corresponds to wind and hydro production sources for electricity production. Oil displacement from EV fleet is implemented by 2050 in different sectors: manufacture of motor spirit, manufacture of gas oil, aggregated other fuels, and retail sale of automotive fuel. We assume that the manufacture of motor spirits is exclusive for vehicle consumption, with a reduction of 80% for Europe (including Spain) and 50% for the rest of the world (IEA, 2020).

[10] As has been observed previously, results in 2030 are quite small.

[11] Other additional issues are undoubtedly highly relevant, but their analysis is beyond the scope of this paper.

[12] The number of vehicles are considered constant as the mileage in Spain: 2.86×10^{11}km/year (*"Observatorio del Vehículo Eléctrico y Movilidad Sostenible,"* Observatory of EV and Sustainable Mobility).

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SUPPORTING INFORMATION

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