Energy 296 (2024) 130855

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Analyzing the energy metabolism of the automotive industry to study the differences found in this sector across EU countries

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ARTICLE INFO

Handling Editor: P Ferreira

Keywords:
Motor vehicles industry
MuSIASEM
Metabolism
GHG emissions
Efficiency
Decoupling

ABSTRACT

The automotive industry plays a key economic and political role in developed countries due to its contribution to exports, employment and revenues. Fragmentation of production and offshoring have distributed manufacturing stages among EU national automotive industries. An energy metabolic perspective allows us to explain differences in performance determined by the expression of different functions and the weight within the national economy. This paper analyses the Motor vehicles industry (MVI) and its sub-sectors in 8 EU countries in 2018 visualizing data in end-use matrixes, a Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) tool. We study the relation over energy carriers (electricity, and thermal energy), GHG emissions, working time, and value added at three different scales: the whole national economy, the MVI sector, and the subsectors within MVI. Through this multi-scale and multi-dimensional characterisation, we cluster the countries according to their functional specialization in (i) manufacturing intermediate parts and modules, (ii) final assembly of vehicles, and (iii) management and engineering design. This representation provides an integrated overview of this industry in relation to its core-periphery dynamics in the spatial division of labour. Additionaly, we provide new insights to labor productivity, efficiency, decoupling and structural changes for sustainability.

1. Introduction

In some European countries, the automotive industry has a great symbolic and political role, triggering public discussion on sustainability transitions. This arises from the substantial GHG emissions and air pollution generated by the use of road vehicles and the need for alternative mobility and transport systems. In political discussions, jobs and value added are often considered the main outcomes of this industry, even more than the production of vehicles itself [1–3]. Variables like employment, trade and value added have already been included in analyses of the European automotive industry in the economics and geography literature [4–8]. However, other fundamental variables for sustainability related to the environmental dimension, such as sectoral direct energy consumption and emissions, have not gotten proper attention yet. To address this research gap, we propose in this paper a more comprehensive characterization of this sector's performance manifesting the material basis of the economy.

Moreover, our analysis spans across levels: the national economy, the sector and its lower-level subsectors. This way, we can examine different relevant aspects of the Motor Vehicles Industry (MVI): its role in the economy, the overall characteristics of the sector, and the differences in performance of the lower-level sub-compartments expressing different functions. This allows the exploration of the influence of the national context and the many possible roles within the same sector in a highly internationalised economy.

In conclusion, this paper describes the metabolic patterns of the European motor vehicles industry in 8 of its most significant countries adopting a multi-dimensional and multi-scale approach: the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM). We simultaneously characterize the size (extensive variables like total labor, and total energy carriers consumption) and intensive qualities (such as labor productivity, and energy carrier consumption per hour of work) of sectors and subsectors. In the analysis, we consider: (i) the fund human activity: the hours of employment in the sector, (ii) the flows: extensive variables of energy carriers (electricity, and thermal), GHG emissions, gross value added and vehicle production; and (iii) flow per hour of human activity: intensive variables linked to the intensity of the metabolic pace. This broader and structured quantification of the economic performance of sectors goes beyond value in monetary terms and towards the quantification of the biophysical flows of the economy. Through this richer characterization, we cluster the countries according

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https://doi.org/10.1016/j.energy.2024.130855
Received 6 June 2023; Received in revised form 11 January 2024; Accepted 27 February 2024
Available online 9 March 2024

Abbreviations

EJP	Economic Job Productivity
EMR	Energy Metabolic Rate
ET	Energy Throughput
HA	Human Activity
GER	Gross Energy Requirement
GHGER	Greenhouse Gas Emission Rate
GVA	Gross Value Added
IOT	Input-Output Tables
LCV	Light Commercial Vehicles
MVI	Motor vehicles industry
MuSIASEM	Multi-Scale Integrated Assessment of Societal and Environmental Metabolism
VPR	Vehicle Production Rate

to their metabolic patterns and unravel the functional specialization, and regional dynamics in the European Union and global production networks. Different levels of value capture, resource use and GHG emissions can be linked to specific processes unevenly allocated in space but dependent on each other. This approach flags the problems associated with the use of simplistic indicators such as economic energy intensity (€/MJ), that can lead to misleading conclusions of decoupling (as discussed in section 4.2).

The organization of the paper is the following. First, we present the MuSIASEM approach. Second, we present the results on production and size at the focal level: the motor vehicles industry (MVI). Third, we provide a multilevel characterization of the quantitative analysis. The size and metabolic characteristics of MVI (at the level n) are compared with the corresponding size and metabolic characteristics of the whole Paid work sector (at the level n+2) within which the MVI is operating. Fourth, we analyze the size and the metabolic characteristics of three subsectors (at the level n-1) of the MVI sector, to study how their differences can be explained by their different functions. Finally, we discuss the implications of the results of the analysis for sustainability and present the conclusions.

2. Methodology

MuSIASEM is an accounting framework developed for analyzing the metabolic pattern of social-ecological systems [9–11]. It allows to characterize both the size and the metabolic characteristics of the elements of a socio-economic systems across levels and dimensions using a multilevel end-use matrix [12,13]. The matrix includes the direct requirements of flows and funds that are used and produced by a sector (extensive variables) and the productivity or the requirement of flows per unit of fund across the different levels and dimensions (metabolic rates) [14]. Therefore, it allows studying the nexus across scales and levels by characterizing economic sectors in a multi-dimensional way. This approach has been applied for the comparison between manufacturing sectors in Bulgaria, Finland and Spain [13], and for the pulp and paper industry in EU countries [15], for the study of countries and regions [16–24], cities [25], islands [26,27], and the residential sector [28–30].

2.1. Indicators and data sources

The variables and their data sources are listed in Table 1. These are classified into flows and funds, according to the Georgescu-Roegen scheme [31]. Funds define the size of the structural components of the system that must be maintained during the period of analysis. In relation to economic analysis, there are three main relevant funds – human activity, power capacity, and land use. In this paper, we consider only the fund Human Activity (Mh/year) that refers to the working time invested in the sector. Working time data comes from National accounts employment data by industry [32] and Annual detailed enterprise statistics – industry and construction [33]; see Supplementary Material for clarifications on the matching at the different levels.

Table 1
Extensive variables of analysis and data sources.

	Variable		Unit	Definition	Data sources
FUND	Human Activity	HA	Mh	Paid work time	[32,33]
FLOWS	Production of vehicles		units	Passenger cars, Light Commercial Vehicles (LCV), Heavy trucks, Buses, and aggregated total.	[34]
	Value Added	GVA	M€	Gross Value Added – Chain linked volumes 2010-million euro	[35]
		VA		Value Added at factor cost.	[33]
	GHG emissions	GHG	ton CO_{2eq}	CO_{2eq} + CO_{2eq} of biomass used as a fuel	[36]
	Energy Throughput (electricity, thermal, and Gross Energy Requirement)	ET_{el}, ET_{th}, ET_{GER}	TJ	Gross Energy Requirements have been calculated using the partial substitution method assuming a conversion efficiency of 38,6% [39] for electricity.	[37]

Flows are either inputs that are metabolized (consumption intensity per unit of fund) or outputs produced (fund productivity). This paper analyzes the following flows: production of vehicles, Gross Value Added, GHG emissions (outputs) and Energy Throughput (inputs). Production of vehicles includes both the four main types of vehicles - passenger cars, Light Commercial Vehicles (LCV), heavy trucks, and buses - and their simple aggregation (i.e., not weighted). This data comes from EAMA [34]. Gross Value Added at the level C29 [35] is in Chain linked volumes 2010-million euro, whereas, for the lowest levels [33], it is in Value Added at factor cost (see Appendix for the matching of the two levels). Direct GHG emissions from Eurostat [36] include only direct emissions of the sector from the categories "Greenhouse gases" and "Carbon dioxide from biomass used as a fuel". Energy Throughput comes from the category "End use" in Energy supply and use by NACE Rev.2 activity [37]. We make a distinction between electricity and thermal energy, considering the fundamental qualitative differences between these kinds of energy carriers [38]. However, figures also use a Gross Energy Requirement (an aggregation of the two in quantities into a number of Joules "thermal equivalent" for clarity) [39].

To compare the metabolic characteristics of countries, we use flow/fund rates, keeping the fund Human Activity as a reference. These are:

- Vehicle Production Rate (VPR): vehicles produced per 1000 h of work.
- Economic Job Productivity (EJP): Value Added produced per hour of work.
- GHG Emission Rate (GHGER): direct greenhouse gases emitted per hour of work.
- Energy Metabolic Rates (EMR_{el}, EMR_{th}, EMR_{GER}): energy carriers consumed per hour of work. This is a proxy of the capitalization/automatization of the industry.

2.2. Levels of analysis

The levels of analysis correspond to the NACE Rev.2 statistical classification (Fig. 1). The focal sector (level n) is the division *D29-Manufacture of motor vehicles, trailers and semi-trailers*[1] (MVI). Then this sector is contextualised within the Manufacturing sector (level n+1) inside the overall national Paid Work sector (n+2). To identify possible patterns of functional specialization, we analyze the subsectors of MVI at the level n-1. For these subsectors (C291, C292, and C293 groups), we have data for value added at factor cost and human activity [33]. The matching of subsector data (level n-1) with National Accounts data (level n) is explained in more detail in the Supplementary Material. There are significant discrepancies between databases in some cases due to the different methodologies and approaches used by national statistical offices. These are related to the allocation of companies to sectors, since companies usually have more than one activity: principal, secondary, and ancillary [40]. Because of this discrepancy, we have not included France in the analysis of subsectors (level n-1).

2.3. Selection of countries and year

The selection of countries was defined firstly by employment. We included those countries with more than 100Mh of work per year in the motor vehicles industry. For some of the countries fulfilling this condition, there was a lack of data for Energy Throughput: Slovakia, the UK, and Romania. This limited the selection of countries to eight: Czechia, Germany, Spain, France, Hungary, Italy, Poland, and Sweden. This sample is quite significant in relation to the EU auto industry. In 2018, the selected sample of countries represented: 77% of working hours, 89% of wages, 95% of GHG emissions, 82% of car production, and 83% of vehicle production in the total MVI sector of the whole EU 27 (EU member states composition after 2020).

The analysis shows a picture of the state of the industry in 2018, a relatively recent year before the COVID-19 pandemic. The exceptional measures taken for the pandemic strongly affected the industry after 2020, but they are not addressed in this study.

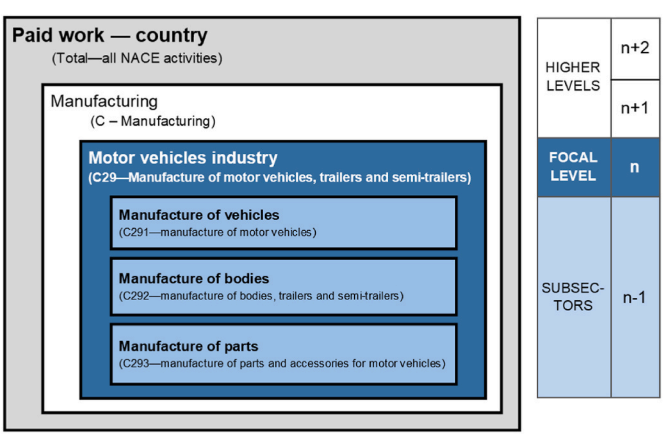

Fig. 1. Levels of analysis of the paper.

[1] Motor vehicles include passenger cars, commercial vehicles (vans, lorries and over-the-road tractors for semi-trailers), coaches, buses, trolley-buses, snowmobiles, golf carts, amphibious vehicles, fire engines, street sweepers, travelling libraries, armoured cars, concrete-mixer lorries, ATVs, go-carts and race cars. Also included are motor vehicle engines (other than electric ones) and chassis.

3. Results

3.1. Motor vehicles industry (level n)

The various flows and funds referring to the MVI of the 8 selected countries for the year 2018 are shown in the End-use matrix in Table 2. In this table, the values of flows and funds are given in terms of extensive variables (quantities over year).

The various benchmarks calculated by dividing the flows by the fund Human activity of the MVI of the 8 selected countries for the year 2018 are shown in the End-use matrix in Table 3. In this table, the values are given in terms of intensive variables generated by flow/fund ratios (quantities per unit of human activity).

3.1.1. Size in employment and number of vehicles

The main variables defining size and output in the Motor vehicles industry at the national level are Human Activity and vehicle production (Fig. 2). By far, the most prominent actor is Germany, with around 1277 Mh of employment and 5.4 M vehicles. Germany, with only 25% of the population in the set of 8 countries represented 38% of the vehicle production, 39% of the working time, 64% of the Gross Value Added and 67% of the wages in the total MVI of the set of countries in 2018 (Table 2). This shows the centrality of Germany in the MVI of our sample of countries (and also EU-27).

The next-largest country in terms of Human Activity is Poland, with 650 Mh (20% of the set of 8 countries). However, the large employment does not translate in a large vehicle production (654 thousand, 5%), which is lower than in other countries with half its employment. In fact, Poland was only the 6th largest vehicle producer in the set of countries, with a very low Vehicle Production Rate (1.0 veh/1000 h).

In this graph, the country with the second highest vehicle production is Spain (2.2 M–18%), and third, France (1.6 M–14%). These are also the countries with the highest Vehicle Production Rates - above 10 veh/1000 h. These countries can do this while operating at a lower level of employment (ES – 8% and FR – 5%) than Czechia (10%) and Italy (9%). The smallest country is Sweden, both in terms of production and work (0.3 M vehicles – 2% and 123 Mh – 4%), which also has the lowest population (10.1 M inhabitants – 3%).

3.1.2. Metabolic pattern within the national economy (levels n+2 and n)

In the supplementary material, we compare the metabolic rates and size of the MVI of each country to those of the national context of Paid Work (n+2) and Manufacturing (n+1): Energy Metabolic Rates (electricity and thermal), Economic Job Productivity. There, we see how MVI has generally higher EJP and lower GHG Emission Rate (GHGER) and EMR-thermal than the average Paid work and Manufacturing. Here we present only the differences in metabolic characteristics of the individual countries by comparing the emissions (GHG Emission Rate) of the whole Paid Work sector (level n+2) with the emission of the MVI sector (level n) over the sample of 8 countries (Fig. 3). In all countries, the emissions of Paid work are larger than the ones of MVI. In some cases, such as Czechia, Poland and Hungary, the difference is wider. For example, Poland in 2018 the general emission of PW (GHGER) is about 6.8 $kgCO_{2e}$/h while MVI's is only 0.5 $kgCO_{2e}$/h. This shows the beneficial role of MVI in the national economy, with a rather low GHG emission rate and high Economic Job Productivity (EJP). We can see this lower GHGER compared to the average in each national economy even when we include indirect emissions in electricity production (Fig. 4).

3.1.3. Metabolic patterns

In this section, we explore the relations between flow/fund ratios in the Motor vehicles industry in each country. Fig. 5 shows the Energy Metabolic Rate (EMR, in gross energy requirement per hour of paid work) against Economic Job Productivity (EJP, €/h) in 2018. The size of the circles reflects the size of total Human Activity and the dotted lines show reference to economic energy efficiency (€/MJ in Gross Energy

Table 2
Extensive End-Use matrix describing the Motor Vehicles Industry in selected countries (top rows) and the overall values for the MVI considered on the whole sample (bottom) - 2018. Percentages refer to the share of the total of selected countries.

	Population		Motor Vehicles Industry																	
			Human Activity		Workers		Gross Value Added		Wages		GHG emissions		Energy Throughput electricity		Energy Throughput thermal		Car Production		Vehicle production	
	million	%	Mh	%	thousand	%	€ 10^9	%	€ 10^9	%	kton CO_{2e}	%	TJ	%	TJ	%	thousand	%	thousand	%
Germany	82.8	25%	1277	39%	906	44%	128.7	64%	57.2	67%	5241	57%	53.8	43%	67.5	54%	4894	41%	5449	38%
Czechia	10.6	3%	338	10%	209	10%	9.2	5%	3.6	4%	297	3%	10.8	9%	9.5	8%	1409	12%	1414	10%
France	67.0	21%	165	5%	106	5%	12.1	6%	5.4	6%	974	11%	16.6	13%	17.7	14%	1685	14%	2344	16%
Hungary	9.8	3%	215	6%	119	6%	5.5	3%	1.8	2%	265	3%	6.1	5%	3.8	3%	464	4%	464	3%
Italy	60.5	19%	289	9%	177	9%	17.5	9%	5.8	7%	419	5%	10.3	8%	8.7	7%	683	6%	1023	7%
Poland	38.0	12%	650	20%	318	15%	6.0	3%	3.3	4%	333	4%	9.0	7%	5.7	5%	366	3%	654	5%
Spain	46.7	14%	258	8%	160	8%	12.9	6%	5.2	6%	1499	16%	13.1	10%	8.8	7%	2169	18%	2833	20%
Sweden	10.1	3%	123	4%	78	4%	10.5	5%	3.7	4%	201	2%	5.9	5%	3.4	3%	292	2%	345	2%
Total	**325.4**		**3315**		**2074**		**202.4**		**85.8**		**9229**		**125.6**		**125.0**		**11960**		**14527**	

Table 3
Intensive End-Use matrix describing the Motor Vehicles Industry in selected countries (top rows) and the overall values for the MVI considered on the whole sample (on the bottom) - 2018.

	Hours per worker	Wages per worker	Economic Job Productivity	Hourly wage	GHG Emission Rate	Energy Metabolic Rate - Electricity	Energy Metabolic Rate - Thermal	Car Production Rate	Vehicle Production Rate
	h/worker	€/worker	€/h	€/h	$kgCO_{2e}/h$	MJ/h	MJ/h	cars/1000h	vehicles/1000h
Germany	1410	63151	101	45	4.1	42	53	3.8	4.3
Czechia	1617	17082	27	11	0.9	32	28	4.2	4.2
France	1556	50689	74	33	5.9	101	107	10.2	14.2
Hungary	1803	14977	26	8	1.2	28	18	2.2	2.2
Italy	1629	32576	61	20	1.5	36	30	2.4	3.5
Poland	2044	10245	9	5	0.5	14	9	0.6	1.0
Spain	1614	32311	50	20	5.8	51	34	8.4	11.0
Sweden	1574	47053	85	30	1.6	48	28	2.4	2.8
Total	**1599**	**41387**	**61**	**26**	**2.8**	**38**	**38**	**3.6**	**4.4**

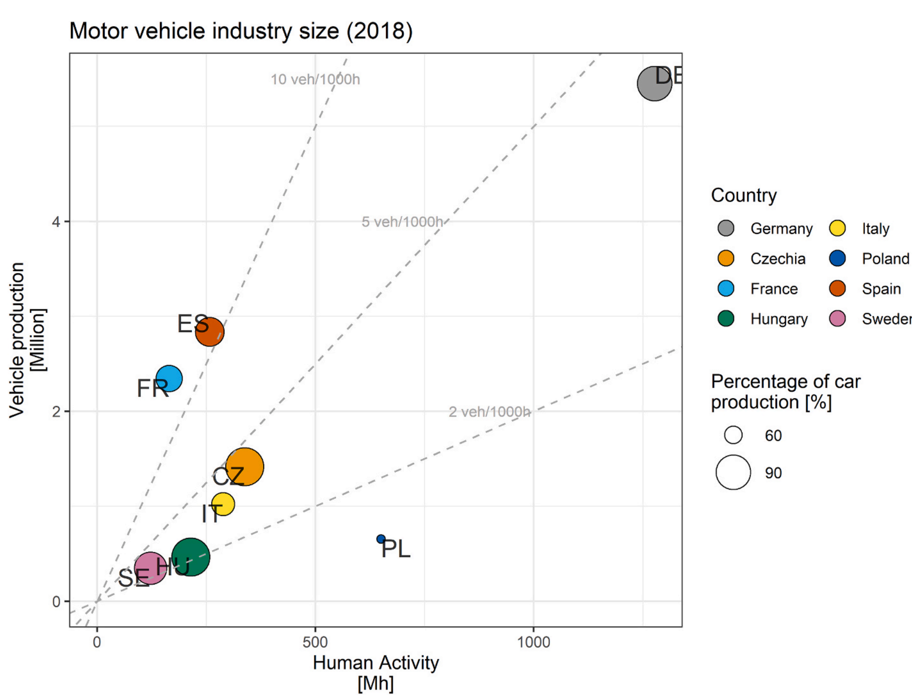

Fig. 2. Human activity (horizontal axis) and vehicle production (vertical axis) in the sample of EU countries (2018). The size of the circles is proportional to the share of car production in total vehicle production. Dotted lines define different levels of Vehicle Production Rate.

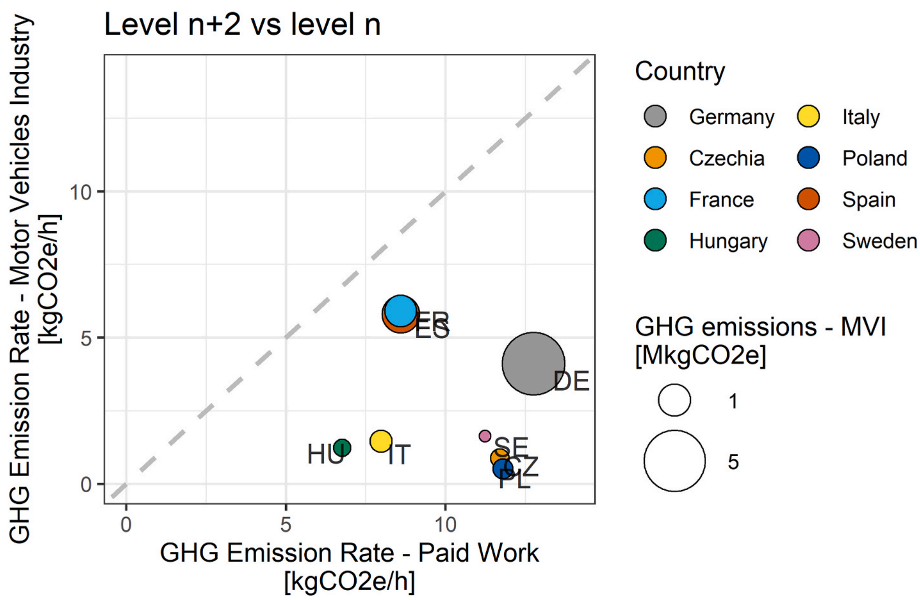

Fig. 3. Emission intensity of paid work and motor vehicles industry for each country (2018). The grey dotted line indicates y = x.

	Motor Vehicles Industry			Electricity production		MVI direct+indirect		Paid Work
	Direct GHG emissions	GHG Emission Rate	Electricity cons.	Emission intensity electricity	Indirect GHG emissions	Total GHG emissions	GHG Emission Rate	GHG Emission Rate
	$ktonCO_{2e}$	$kgCO_{2e}/h$	GWh	$kgCO_{2e}/kWh$	$ktonCO_{2e}$	$ktonCO_{2e}$	$kgCO_{2e}/h$	$kgCO_{2e}/h$
Germany	5241	4.1	14.9	404	6035	11276	8.8	11.7
Czechia	297	0.9	3.0	465	1392	1689	5.0	12.8
France	974	5.9	4.6	58	268	1242	7.5	8.6
Hungary	265	1.2	1.7	251	426	691	3.2	8.6
Italy	419	1.5	2.9	249	713	1132	3.9	8.0
Poland	333	0.5	2.5	784	1951	2284	3.5	6.8
Spain	1499	5.8	3.6	276	1005	2504	9.7	11.8
Sweden	201	1.6	1.7	11	18	219	1.8	11.2
Total	**9229**	**2.8**	**34.9**	**94**	**11808**	**21037**	**6.3**	**10.1**

Fig. 4. GHG emission rate of Motor Vehicles Industry (direct, and direct + indirect) and Paid Work. Emission intensity of electricity comes from EEA [41]. Indirect GHG emissions are calculated by multiplying electricity consumption in the sector by the average emission intensity of electricity in the country.

Requirement).

The Energy Metabolic Rate is higher when the function is mostly manufacturing (instead of design and other ancillary services), and when the facilities are automatized, requiring fewer workers for the production no matter the final product. However, automatization has not necessarily entailed a direct substitution of human labor by robots but more precise control of geometry and quality [42]. Also, automated machinery has not necessarily made work disappear but transformed blue-collar physical work into white-collar management and control. EMRs can also differ in function of the specific processes. For example, the fabrication of engines in foundries is more energy-intensive than the assembly of cars. To put into context, Velasco-Fernández et al [13] shows how the EMRs in Iron and steel in Spain in 2012 (electricity: 689 MJ/h and thermal: 1076 MJ/h) are 21 and 34 times larger than in Transport equipment (electricity: 33 MJ/h and thermal: 32 MJ/h), which includes Motor Vehicles Industry.

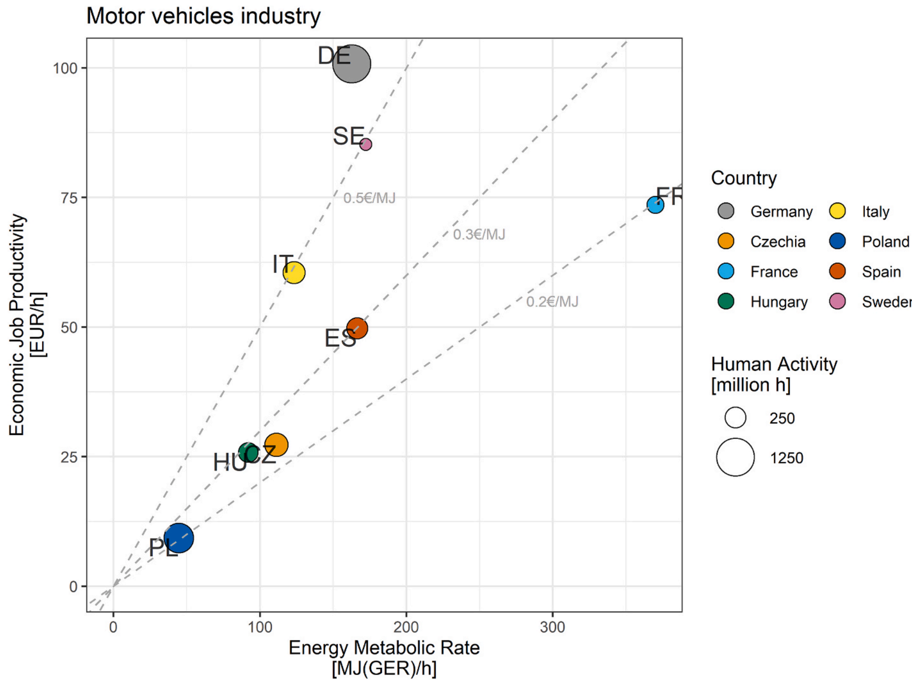

Fig. 5. Energy Metabolic Rate and Economic Job Productivity for the motor vehicles industry (2018). Dotted lines indicate different levels of Economic Energy Efficiency (€/MJ). The size of the circles is proportional to the size of Human activity.

Economic Job Productivities are higher or lower depending on the economic value of the outputs. The production of a high-end car will imply higher value added than a smaller car. The allocation among countries of activities and thus their value capture depends on path dependency, power relations, and hierarchies established by the current international division of labor. We can see differences among EU countries here, but at the same time the EU industry has a relatively higher value added than the rest of the world, representing a relatively high share of its exports [43].

There is a large range of values both for EMR and EJP. Poland has the lowest EMR (14 MJ/h electric and 9 MJ/h thermal), and EJP (11 €/h). France has the highest EMR by far (electricity 101 and thermal 107 MJ/h), which is 7 and 12 times those of Poland and more than doubling the second highest, that of Sweden (55 and 28 MJ/h). On the other hand, France has only the third EJP (74 €/h). The value of French EMR might be affected by the choice of selecting purely industrial activity in national accounts by its national statistical office (explained in the Supplementary material).

Germany, Sweden and Spain have similar Energy Metabolic Rates, all over 160 MJ/h (when measured in GER). However, they do this at totally different levels of EJP. These range from 101 €/h in Germany, to 85 €/h in Sweden, to 50 €/h in Spain. While there is this set of countries that share EMR but not EJP, Hungary and Czechia have very similar EJP and EMR (around 25 €/h and 100 MJ/h).

Economic energy efficiency (EEE) is a very common indicator for economic and environmental analysis, despite its problems for assessing the multidimensional performance of countries and sectors [12,23,44,45]. This indicator simplifies the information referring to two metabolic rates (EMR and EJP) whose value depends on different factors determining the technological and value-added intensity of the sector. These two indicators referring to non-equivalent narratives and descriptive domains have a clearer and more intuitive meaning than EEE: the type of activity and the technology used vs the amount of value added generated by the activity. In this example, countries with different EMR and EJP end up having the same EEE, such as Italy and France (around 0.5 €/MJ) and Spain and Hungary (around 0.3 €/MJ, Spain doubling Hungary's EJP).

3.2. Subsectors (level n-1)

The Vehicle Production Rate at the MVI level provides some insights into the specialization in the production of parts or vehicles. In this section, we are getting down another level (level n-1), analyzing the subsectors in the Structural Business Statistics [33]: *C291 – manufacture of motor vehicles* (henceforth Manufacture of vehicles), *C292 – manufacture of bodies, trailers and semi-trailers* (henceforth Manufacture of bodies), *C293 – manufacture of parts and accessories for motor vehicles* (henceforth Manufacture of parts). Manufacture of vehicles includes

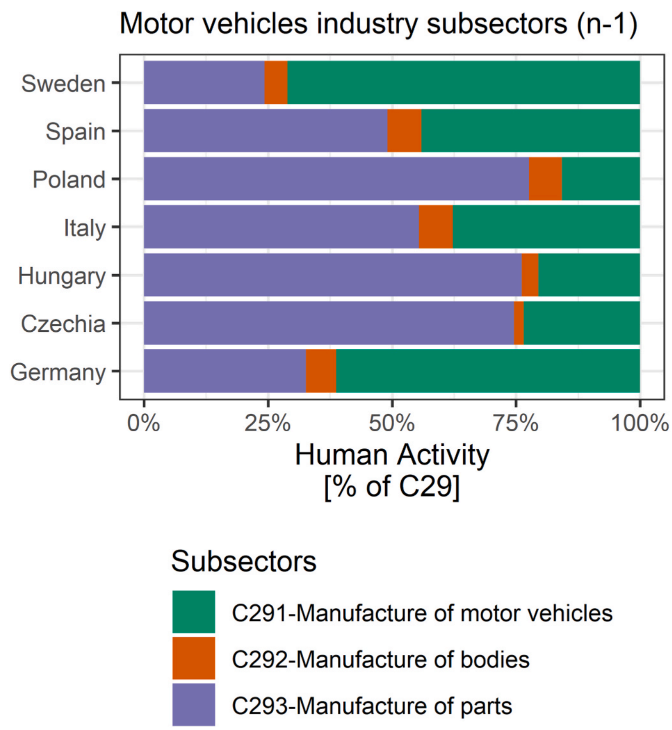

Fig. 6. Shares of Human activity in the subsectors of the Motor vehicles industry (2018).

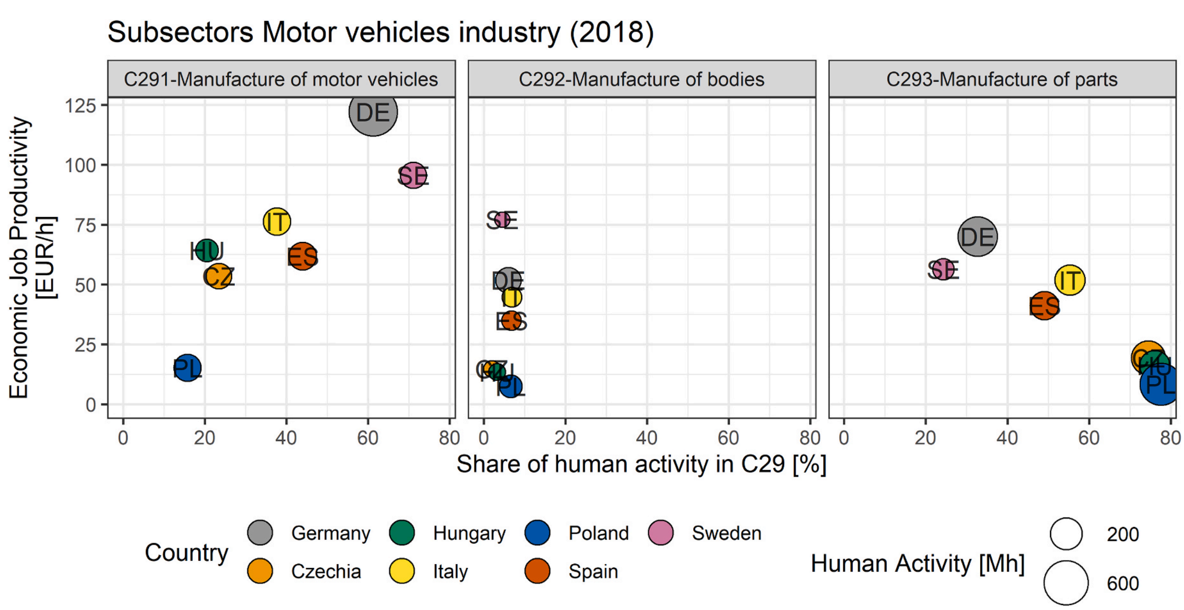

Fig. 7. Economic Job Productivity by share of human activity of subsectors in the motor vehicles industry (2018). The size of the circles is proportional to Human Activity in the subsector.

motor vehicle engines and chassis [40]. We have data on Human Activity, and Value added at factor cost for these subsectors.

Fig. 6 shows the different internal configurations of the MVI in the different countries: the profile of allocation of Human Activity in the three different subsectors. The subsector "Manufacture of bodies" seems to be the less relevant with less than 10% of Human Activity in the different countries of the sample. The subsectors Manufacture of parts or of vehicles determines largely the sector's overall metabolic patterns at the level n. According to the shares of these subsectors, we can classify countries into three types: (i) oriented to Manufacturing of vehicles (higher than 60% for motor vehicles: Sweden and Germany); (ii) intermediate (between 40% and 45%: Spain and Italy); and (iii) oriented to parts (Hungary, Czechia, and Poland: around 75% for parts).

Fig. 7 shows the EJP by the share of working time in each subsector. Different levels of EJP are related to the different subsectors but also to the specific country. Whereas Manufacture of motor vehicles for each

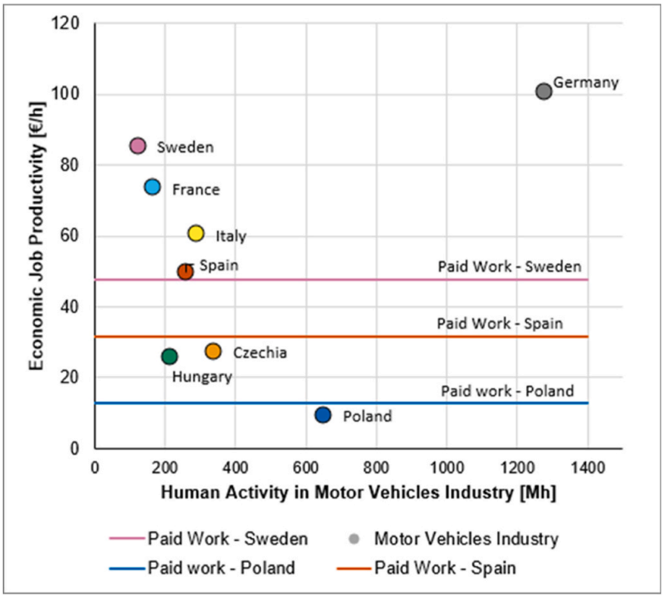

Fig. 8. Comparing the Economic Job Productivity in the motor vehicles industry (2018), with the EJP of the Paid Work Sector in Sweden (the largest of the set of countries), Spain (intermediate) and Poland (the lowest in the set of countries).

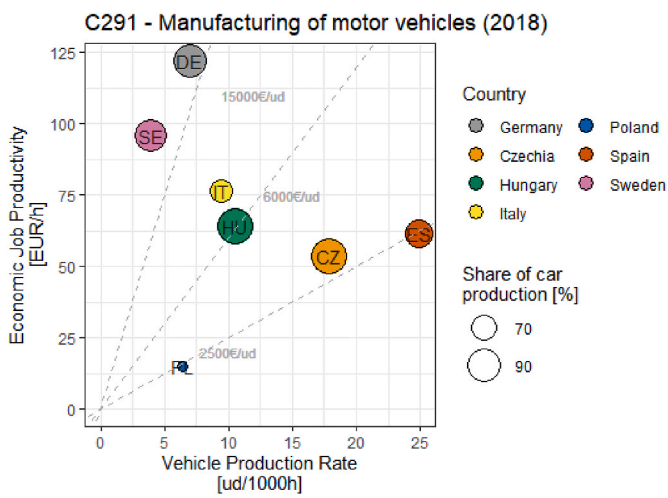

Fig. 9. Economic Job Productivity against Vehicle Production Rate for the subsector C291 (level n-1) – Manufacturing of motor vehicles. Dotted lines indicate different levels of Value added at factor cost by vehicle. Size of circles proportional to share of car production in relation to vehicle production [%].

country has larger EJPs than Manufacture of parts, the German Manufacture of parts has larger EJP than the Czech Manufacture of motor vehicles. This point shows that the differences in the national economic context matter.

For example, as indicated by Fig. 8, the EJP of the sector (at the level n) can be above or below the average EJP of the Paid Work sector. In this example, the EJP of MVI in 5 countries are higher than the EJP of the Paid Work in Sweden (48 €/h), the largest of the set of countries, whereas only Poland has a lower EJP in MVI (9 €/h) than in the average of Paid Work (13 €/h).

3.2.1. *Manufacturing of parts*

The specialization in the subsector inside MVI (% of HA in Manufacturing of parts) is inversely proportional to EJP. Sweden and Germany are around 60 €/h and 30% of Human Activity in the Manufacture of parts. Italy and Spain around 45 €/h and 50%, and Czechia, Hungary, and Poland around 15 €/h and 75%. This large variability can be given by the great number and diversity of parts in vehicles. Domański et al. [46] classify them by value-added: high (e.g., engines and transmissions), medium, and low (e.g., wire harnesses and seats).

3.2.2. *Manufacture of motor vehicles*

The broadest variability among countries in Economic Job Productivities is in the subsector Manufacture of motor vehicles. For example, the EJP of Germany (122 €/h) doubles that of Italy (76 €/h). Sweden and Germany have the highest EJPs (122 and 95 €/h, resp.). Italy, Hungary, Spain, and Czechia have similar values for EJPs at around 50–75 €/h.

Apart from technology, these discrepancies might happen principally for two reasons: the differentiation of the product (production of higher-end vehicles) and the weight of the development of vehicles (engineering activities). Vehicle design is primarily developed in the main headquarters of Original Equipment Manufacturers (OEMs), and the value capture of these activities is higher. These stages are at the initial peak of value added of the smile curve [47–49], which indicates that preproduction (design and engineering) and final production and services (marketing, sales, etc.) get a larger proportion of value added than the rest of activities in the value chain. The production of premium vehicles and the core development of vehicles are activities with limited demand and require a certain reputation associated with particular companies.

Fig. 9 shows the Vehicle Production Rate and Economic Job Productivity specific to subsector *C291 – Manufacturing of motor vehicles*. The size of circles is proportional to the share of car production in relation to vehicle production (cars, buses, trucks, etc.) to consider the product mix. The VPR is the lowest in Sweden, Poland, and Germany (around 5 veh/1000 h). There is a wide range of VPR. The Spanish one is more than 5 times larger than that of Sweden. We can also see that a high labor productivity in monetary terms is not necessarily related to higher productivity in material terms. Sweden and Germany have the lowest level of VPR and produce the highest value added per hour of work.

At this level, we can identify a few factors affecting the performance of VPR without the distortion of the production of parts. This subsector includes the production of engines and chassis [40]. Therefore, a larger production of engines and chassis to export for other countries to assemble will imply a lower VPR. In the same way, a high share of white-collar workers in core engineering and other ancillary activities results in a lower VPR. This might be the case for Sweden and Germany, which have the lowest Vehicle Production Rates but the highest Economic Job Productivity. In these countries, labor productivity is high in terms of value added, but it is not in terms of vehicle production. This is a sign that they might be capturing the value added in the whole production chain of cars in the core engineering design processes in OEMs headquarters.

Another factor could be the organization of tasks in the value chain, also related to the designs. This modularization is intrinsically linked to vehicle design, company relations, outsourcing, and production processes [50,51]. However, this would require an analysis of the specifics of manufacturing processes at the lower level (level n-2) based on different data sources.

Finally, we must always consider the diversity of vehicles, which are all summed up for the VPR regardless of the type. Countries like Italy and Poland have a VPR between 5 and 10 veh/1000 h but have the lowest car production shares (67% and 56%, respectively). LCVs, heavy trucks, and buses are larger than passenger cars; therefore, more time might be needed for their production. The product mix inherent to any sector at this level hinders the interpretation of VPRs.

4. Discussion

4.1. Metabolic patterns, roles, and hierarchies

Our analysis shows that the MVI is not a homogeneous sector in terms of its structural and functional characteristics. We can cluster the countries in three groups regarding specialization in subsectors: specialization in vehicle production (Sweden and Germany), in manufacturing of parts (Eastern countries: Poland, Czechia, and Hungary), and the rest of the countries (Spain, France, and Italy), which have an intermediate position and more heterogeneous metabolic patterns. It is not only companies that are hierarchically ordered depending on their tier but also countries. A hierarchy of countries emerges parallel to that of companies, which depends on the type of companies they have and functions they carry out. The differences in metabolic patterns are related to the roles played within the EU27 auto industry division of labor.

Germany is the largest producer in terms of human activity, value added, and production, with the highest EJP. The relatively high Energy Metabolic Rates are explained by the fact that production processes are: (i) more energy intensive than in other countries due to automatization; and (ii) aimed at specific activities such as engine production.

Sweden has the lowest population of the set of 8 countries, the lowest production of vehicles, and the lowest share and amount of working time in the MVI. Regarding subsectors, it has the highest percentage of working time in Manufacture of vehicles of all countries but with the lowest Vehicle Production Rate. This lower VPR can be affected by the importance of larger vehicles such as heavy trucks: 37% of the employees in MVI in Sweden were devoted only to heavy vehicles in 2015, and 29% to both light and heavy vehicles [52].

These observations show the possibility of exploring and explaining the differences in metabolic performance considering a variety of factors. Something that flags the simplistic approach of the indicator of Economic Energy Efficiency applied at the level n (MVI). Both Sweden and Germany have high EJP and EMR despite having low VPRs. They also have the highest shares of employment in the subsector Manufacture of vehicles. At this n-1 level, we can see how these low VPRs are compensated by the large value added per vehicle produced. That is, lower productivity in vehicle production does not necessarily translate to lower economic labor productivity. They have the highest EJP in Paid work, manufacturing and MVI of all the 8 selected countries, showing the value capture of their whole economy. Within the same economic subsector, higher-income countries tend to specialize in those activities providing higher economic returns.

On the other end, Poland has the lowest metabolic ratios across all dimensions and levels. This indicates a low automatization possible because of low labor costs. Despite having the second largest workforce in the analyzed countries, they are only the 6th producer of vehicles. Most Polish Human Activity in MVI is allocated to the subsector Manufacture of parts, which makes it a supplier country to other MVI that assemble the final products.

The location of the headquarters of Original Equipment Manufacturers is strategic. Outsourcing activities to suppliers from these OEMs generates a hierarchical supply chain with a pyramid form with the diverse tier levels controlled at the top by the OEMs [53]. On the one hand, automobile nationalism and political pressure exist to maintain the final assembly of higher-end vehicles and headquarters in core countries and close to final markets. On the other hand, chains are getting more fragmented in a search for decreasing costs and maximizing profits. Control is increasingly centralized in a reducing number of companies (from 42 independent automobile assemblers in North America, Japan, and Western Europe in 1960 to only 12 in 2005) [54]. Factories and engineering development represent large fixed costs and economic barriers to entry for new brands or companies to take over. A fact that is locking in the existing hierarchies. Given the different degrees of power and infrastructure, there is no level playing field and no easy chance to catch up or upgrade for the actors at the periphery.

The fall of communism and, afterwards and most importantly, the integration of Eastern countries in the European Union generated the conditions for the outsourcing of lower value-added activities through foreign investments to countries like Poland and Czechia due to their lower operating costs [55–58]. This has been chiefly in terms of labor-intensive component manufacturing and the production of sub-compact cars and lower segment vehicles [57]. The peripheral actors of the auto industry in the EU have shifted from Southern to Eastern countries [59,60] and generated a new spatial division of labor. Countries like Spain still produce more vehicles than Czechia and Poland despite the larger employment in the sector of the latter. This is mainly due to the different specializations in subsectors. Spain has a larger share of employment in the subsector Manufacture of vehicles, whereas Czechia, Hungary, and Poland have it in Manufacture of parts.

Czechia and Hungary are the countries whose MVI represent the largest share of employment in their national economies of the selected countries. These two countries are at the system's periphery and have the most similar metabolic patterns. Compared to most of the rest of countries, they have low GHG Emission Rates and Energy Metabolic Rates. Since wages are lower (also related to the lower EJPs), more labor-intensive activities are viable in those countries.

Spain and France have the second and third-largest vehicle production in the set of countries. France and Italy have been part of Europe's industrial heartlands, with two of the main historical regions of vehicle assembly: the Paris region and Piedmont. French and Italian carmakers have offshored the full production to Eastern European countries, while Germany has fragmented production internationally [61]. While France and Italy struggle to maintain their position as core countries, Spain has upgraded from its previous peripheral position.

In fact, until the 1990s, Spain was the major low-wage periphery in the European auto industry. Foreign investments started in the 1970s and 1980s due to the relatively low wages compared to core countries in Central Europe [62]. The rise in costs and the integration of Central Eastern European countries shifted the periphery eastwards [57], and Spain has thus become an intermediate or pericentral player [60,63]. Lampón et al. [64] show the relocation of component production plants during the period 2001–2010 from Spain to mainly Eastern Europe (48% of total relocated jobs) and the increase of value-added, capital, and skill-intensive activities (e.g., mechanical systems for motorization, transmission, and braking). This might explain the relatively high Energy Metabolic Rates. Spain is the second country in vehicle production and GHG emissions after Germany and in GHGER and VPR after France.

This point shows the importance of studying the evolution of the dynamic of economic relations in the global MVI, which is nowadays heavily affected by trade across open economies having different regional characteristics. For this study, it is necessary to consider additional levels of analysis above the ones considered in this study. That is, the analysis presented here should be complemented with a study of the global supply chain perspective, not assessed here but available in the literature [65–67]. The auto industry is a final products industry. This entails that most of the GHG emissions and energy carrier consumption in the production of vehicles happen in upstream sectors [68–71], while large shares of value added and employment are allocated in the automotive industry.

4.2. Methodological implications

Our results flag three key points for economic analysis relevant to sustainability: (i) the heterogeneity of metabolic patterns of auto industry sectors is due in large part to functional and range specialization given by core-periphery relations and not to the state-of-the-art of technology; (ii) the metabolic patterns of MVI may produce the illusion of decoupling within the national economic structure because of the specialization in certain activities that entails the externalization of resource-intensive processes elsewhere; (iii) the limits of reductionism when dealing with the analysis of complex systems. Complex concepts such as energy and material efficiency cannot be handled using simplistic indicators. Instead, they require the adoption of a multidimensional and multilevel analysis. The different relevant characteristics on the technical, social or economic dimension must always be observed within a hierarchy of contexts at different levels in different dimensions. In complex adaptive systems, there is a deep entanglement between structural (e.g. technology) and functional elements (e.g. mix of activities carried out with the technology) that have to be identified and studied in terms of relational analysis. The application of MuSIASEM presented here clearly illustrates the importance of combining structural and functional information across different levels of analysis to avoid simplistic misinterpretations, even if it requires processing more detailed information at lower and upper levels to have a richer picture of the overall social-ecological system [14].

Methodologies used to analyze the performance of the MVI should be able to capture the diversity of fragmented production stages or functions within the value chain, making a distinction between the differences in technologies, efficiencies, or productivity improvements (how the production is made) and the stages within the same value chain (what type of product or activity is carried out), including the financialization and servicification of the auto industry. Moreover, depending on the research question, we should consider an even lower sectorial disaggregation in manufacturing of vehicles or parts (at the level n-2). Certain metabolic patterns might be explained by the level of specialization in higher-end products or different types of vehicles and parts. This entails that the NACE classification at the division level is still too broad to capture intra-industry heterogeneity, and segment and functional specialization related to intra-industry hierarchies and core-periphery relations.

These core-periphery relations and functional specialization limit the validity or meaning of approaches for calculating consumption-based resource use such as the technology-adjusted consumption-based emissions [72] or the domestic technology assumption in single-country IOT. Due to functional specialization, applying a sectoral performance indicator of a certain country to all countries would represent only a part of the activities that are required for vehicle production. The activities in MVI are in fact related and dependent on one another across countries to get the final product, in this case, vehicles and replacement parts. This critique is in line with existing literature in Input-Output Models on sector aggregation bias and the pitfalls of domestic technology approaches [73–79].

Despite this sectorial metabolic pattern variability among countries, the auto industry is a light industrial sector of final products, with lower impacts and higher value added compared to other industries and primary sectors. Simplistic analysis of emissions may indicate that the emission intensity of a country decreases when it invests in MVI, similar to what happens to services [80,81]. However, this conclusion depends on a narrow production-based analysis that leads to flawed conclusions on decoupling, the environmental Kuznets curve, and structural change for sustainability due to the cost shifting of upstream processes and the higher value capture of MVI. These ideas have been debunked previously in literature [44,82–86]. The inverted-U shape of the Environmental Kuznets Curve is related to the fact that developed countries specialize in the upper sectors in the smile curve, including MVI and other management and office work. These activities have low impacts compared to the more basic processes from which the auto industry gets inputs to function. That is, while the activity of this sector in the national economy might be favorable in value-added terms compared to the average performance of the paid work and manufacturing (expressed in metabolic rates), it induces impacts in other sectors, generally externalized to foreign countries. Moreover, the production of internal combustion vehicles commits further emissions in the mid-term during the lifespan of the vehicles. Therefore, the existence and growth of this sector in a country provide value added with a relatively low environmental cost at the expense of leaking impacts to foreign suppliers with lower salaries and the commitment of longer-term emissions in the use of vehicle fleets. This is another perspective of unequal exchange [87–89]. The whole value-chain impacts of vehicle production might not even appear in local consumption-based accounts since the final products and parts are in part exported to global markets, while value added and higher-paid jobs remain in the country. The spillover effect in upstream processes must also be analyzed carefully. Further work should explore the linkages between countries in terms of trade to understand more fully the dependencies and the complete picture of the distribution of impacts and profits in the supply chain of the MVI in the EU.

When comparing the mono-scale indicator of Economic Energy Efficiency with the relational analysis across dimensions and levels of analysis provided by MuSIASEM we can observe that the EEE indicator can only be used one scale at a time and mix in a single indicator with does not have any meaning in relation to a semantic dimension of analysis. In fact, EEE is a flow/flow indicator (comparing the size of a flow A with a flow of B) without acknowledging the existence of non-equivalent processes determining the value of A and B. The EEE is a simplification (a ratio) of two metabolic rates: EMR and EJP (flow/fund indicators). Each one of these two flow/fund indicators refers to concrete typologies of biophysical and added value production, with a specific biophysical or political meaning: (i) EMR reflects the level of mechanization of economic activity; (ii) EJP shows the ability to capture added value per hour of work. As illustrated in Section 3, the values of these two indicators depend on the core-periphery relations and functional specialization. Therefore, these indicators do have external referents that can be studied in relation to known factors, i.e. they are meaningful. In our analysis, we have shown that completely different EJPs and EMRs can give place to the same values of EEE. Therefore, EEE does not have a meaningful external referent, it is just a ratio over two numbers. This entails that it does not provide relevant information for analyzing the reasons why a certain country or sector is apparently improving their sustainability. Moreover, this indicator understands sustainability in a decoupling framework, i.e., the possibility of generating additional value-added with less energy carrier consumption. On the one hand, we can question whether this is enough or necessary for sustainability. On the other hand, constant or increasing energy consumption can be counterbalanced by larger increases in value capture. What is more, activities less related to direct energy consumption are those capturing more value added (management and engineering).

Finally, the study of metabolic rates per hour of human activity also gives the importance that working time deserves. The definition of working time as a fund gives us a definition of the size of the sector. The inclusion and centrality of working time are key to addressing employment issues that are fundamental for social and economic sustainability. Also, it is important to assess jobs in terms of hours and not per worker seeing the huge difference in hours per worker among countries. For example, working hours per year and worker in Poland are 1.5 times the German ones (Table 3). When we include only part of the dimensions that are relevant to sustainability (be it economic or environmental), we will see only part of the picture. This shows again the excessive simplicity of economic energy and emission efficiency (in MJ/€ and $kgCO_{2e}$/€) indicators when we compare them to the multi-dimensional and multi-scale biophysical performance obtained using MuSIASEM, which refers to the diverse nexus relations among different flows and funds that are established at different scales (sector, subsector). We use the word performance instead of efficiency because there are many variables at play and the crucial factor is to understand the relationships among different dimensions (that generate the nexus) and the functions performed, instead of exploring only a mono-dimensional "energy efficiency". This kind of multi-indicator analysis based on the biophysical basis of socio-economic activities has been flagged as necessary by other authors critically analysing decoupling [82,90]

5. Conclusions

This paper presents a multidimensional overview of the metabolic patterns of the EU automotive industry across scales using the MuSIASEM tool the end use matrix. This shows the key role of functional specialization, hierarchies within the sector and different metabolic characteristics from motor vehicles industry in comparison to both the other manufacturing activities and the activities in paid work. The Motor vehicles industry still represents a relatively large share of industry in some countries in the European Union. The MVI is relatively value added intensive and low emission- and thermal energy-intensive. Therefore, when looking only at the local metabolic pattern its existence in the economic structure of a country might result favorable in terms of environmental and value-added performance compared to other industries, potentially generating the illusion of decoupling.

MVI has higher value capture power compared to other industries, but there are also large intercountry variabilities which reflect core-periphery relations that arise in the metabolic patterns in all dimensions. Even when belonging to the same sector, the characteristics of the industry in each country are very different due to their specialization in subsectors or processes: the segment of vehicles and type of parts, their levels of automatization, wages, etc. This intra-industry heterogeneity limits the validity of domestic technology assumptions or the use of "the best" metabolic patterns as universal benchmarks to be used as goals for the industry. Each country is playing a different role and all of them are necessary currently to produce vehicles, regardless of the technological improvements that could still be made.

Some countries like Germany and Sweden have metabolic patterns that flag their core function in the European automotive system. Both present low vehicle production rates at the subsector level, but they have a large value added per hour of work and a large share of working time in the subsector Manufacture of motor vehicles. Germany is the center of the EU auto industry both in intensive and extensive terms: with the largest employment, vehicle production, and value added per hour of work. Poland, Czechia, and Hungary are peripheral countries. They are more specialized in producing parts and allocate less value added and energy carrier consumption per hour of work. This set of countries has some of the highest percentages of direct national employment in this industry.

Adopting this type of biophysical multi-dimensional characterization across scales we can prevent misinterpretation of decoupling effects by identifying how performance, type of production and role in the production chain affect the overall use of resources and value-added generation. The multi-scale analysis provides reflection on the functions played by each industry. Metabolic flow-fund rates from MuSIASEM provide meaningful benchmarks related to production processes and value capture of countries and production stages. Further research is required to better understand the complex entanglements between process performance, their functionalities and resource use allocation in national accounts.

CRediT authorship contribution statement

Laura À. Pérez Sánchez: Conceptualization, Data curation, Visualization, Writing – original draft. **Raúl Velasco-Fernández:** Conceptualization, Writing – review & editing. **Mario Giampietro:** Conceptualization, Writing – review & editing.

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 is available in Eurostat and the processed data used in figures is available in the supplementary material.

Acknowledgements

Laura À. Pérez-Sánchez gratefully acknowledges financial support of the Catalan administration/AGAUR (Grant number: 2019FI_B01317). The authors also acknowledge financial support by the government of Catalonia (AGAUR), through the support for research groups (2017-SGR-230). This work contributes to ICTA-UAB "María de Maeztu" Programme for Units of Excellence of the Spanish Ministry of Science and Innovation (CEX2019-000940-M). This work reflects only the authors' view; the funding agencies cannot be held responsible for any use that may be made of the information it contains.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2024.130855.

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