New Political Economy

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/cnpe20

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To cite this article: A. Katharina Keil & Julia K. Steinberger (2023): Cars, capitalism and ecological crises: understanding systemic barriers to a sustainability transition in the German car industry, New Political Economy, DOI: 10.1080/13563467.2023.2223132

To link to this article: https://doi.org/10.1080/13563467.2023.2223132

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Published online: 20 Jun 2023.

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NEW POLITICAL ECONOMY
https://doi.org/10.1080/13563467.2023.2223132

Routledge
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RESEARCH ARTICLE

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Cars, capitalism and ecological crises: understanding systemic barriers to a sustainability transition in the German car industry

A. Katharina Keil and Julia K. Steinberger

Institute for Geography and Sustainability, Faculty of Geosciences and Environment, University of Lausanne, Lausanne, Switzerland

ABSTRACT
In the face of climate and ecological crises, it is vital that car use be reduced, while simultaneously shifting towards different powertrains and reducing the size, weight and energy demand of vehicles. This poses a challenge to the global car industry, as its business model historically centres on selling more and larger cars. In this context, the purpose of this paper is to examine the social-ecological limits of industrial restructuring in Germany. A narrative literature review through the lens of Marxian political economy sheds light on intertwined system-immanent barriers to achieving social and ecological sustainability at the sectoral level. Consequently, powertrain electrification is structured by technological dynamism, which fuels appropriation in the quest for metals and rare earths, with significant social and ecological disadvantages. This generates an impasse for the industry's transition strategies. Understanding how capitalist tendencies generate interlaced and mutually re-enforcing barriers to achieving social-ecological sustainability is key to understanding why industrial transitions are insufficient from a social-ecological perspective.

ARTICLE HISTORY
Received 10 October 2022
Accepted 6 June 2023

KEYWORDS
Automobile industry; powertrain electrification; capitalist tendencies; appropriation; technological dynamism

Introduction

With the increasing palpability of multiple ecological crises, much attention has been turned to the future of emission-intensive and highly polluting sectors of the economy. In the case of transport, calls for greening personal mobility are gaining strength. Proposals range from the electrification of cars to a thorough transformation of the transport system, including a drastic reduction in car traffic (Blanck *et al.* 2017, Becker *et al.* 2019). From the perspective of social-ecological sustainability, understood as socially just and ecologically viable, proposals of this type are promising (Brand *et al.* 2021). Yet car-dependent transport systems continue to be characteristic of industrial societies for political, economic and cultural reasons. These include state dependency on tax revenue generated by car manufacturers, car-centred mobility policies and car culture (Mattioli *et al.* 2020).

One key actor upholding car dependency is the automobile industry,[1] which is often of high economic and political importance to its host states (Mattioli *et al.* 2020). Germany, the case under consideration in this paper, hosts the headquarters of three original equipment manufacturers: Volkswagen, Daimler and BMW, who are all in the top 10 of the world's biggest car manufacturers

CONTACT A. Katharina Keil katharina@keil-gruenberg.de Institute for Geography and Sustainability, Faculty of Geosciences and Environment, University of Lausanne, Lausanne, Switzerland
Supplemental data for this article can be accessed https://doi.org/10.1080/13563467.2023.2223132.

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in terms of revenue (*Größte Autokonzerne nach Umsatz bis 2020* no date). While car manufacturers now portray themselves as embracing ecological goals, their business strategies fail to follow suit. For example, Volkswagen promises to be climate neutral by 2050, while centring the sales strategy for its biggest brand, VW, on sport utility vehicles (SUVs), which are highly pollutive in use and resource intensive in production due to their size and engine power (Beutnagel 2021, Groneweg and Gehrs 2021). Against the backdrop of interconnected social-ecological crises, notably climate change, such a mismatch merits investigation. Discounting it as simple greenwashing would overlook changes that genuinely are made (Becker *et al.* 2019). However, to what extend can these changes be expected to help tackle the social-ecological crises?

We argue that it is necessary to mobilise a systematic understanding of the German car industry as embedded in the global capitalist economy to assess this. Therefore, we employ a framework at the intersection of Marxian political economy and ecological economics, developed by Elke Pirgmaier (2018, 2022), in order to answer the following research question: How do the endogenous tendencies of capitalism shape the automobile industry's transition away from internal combustion engine vehicles? We are not interested in the potentials of technology's contribution to sustainability from an engineering perspective, but in delineating how the functioning of the capitalist system structures industrial transitions. We show how this functioning generates barriers to achieving social-ecological sustainability, even if new technologies could have a positive impact.

This paper makes three contributions. First, as explained in section 'Approach', it brings disparate strands of research on the car industry together to theorise how 'the mutual interaction of tendential forces' contribute to the car industry's failure to transition towards sustainability (Wells and Nieuwenhuis 2012, Reuten 2014, p. 258). Second, section 'On the way towards ecologically sustainable cars?' summarises current developments surrounding vehicle electrification and offers an integrated and concise overview of the trajectories of German car companies. Third, section 'How industrial developments are shaped by the tendencies of capitalism' shows how capitalist logics, tailored towards maximising profit, create an impasse for industrial sustainability strategies and innovations. Here, the focus will be on technological dynamism, that is, the way that technology develops under capitalism; and appropriation, i.e. the spiralling exploitation of human and non-human nature for capitalist production (Pirgmaier 2022). These insights will be synthesised and discussed in Section 'Discussion' with regard to the ways in which the tendencies are interlinked. Section 'Conclusion' concludes.

Approach

The links between capitalism, exploitation of labour and ecological destruction were considered by Marx (1867) in the context of the consequences of urbanisation and industrial agriculture, and have received attention since from Marxist scholarship, most notably from the school of metabolic rift (Schmidt 2014, c.f. Saito 2020). The analyses vary but depart from the common tenet that capitalist production is based on the simultaneous exploitation of human labour and non-human nature (Marx 1867, Foster 1992, Moore 2015). Moreover, 'the greater the social wealth, […], the greater are capital's ecological demands, and the level of environmental degradation' (Foster 1992, p. 79).

For the research at hand, understanding the channels through which these detrimental effects are actualised is key. Our work builds upon the analytical framework developed by Elke Pirgmaier (2022), who outlines how eight dominant tendencies arise from the functioning of capitalism: overproduction, technological dynamism, appropriation, commodification, overconsumption, acceleration, alienation and financialisation. They manifest at different points of the circuit of capital, as shown by Figure 1, and engender adverse 'environmental impacts and barriers to societal change' (Pirgmaier 2018, p. 130).

To avoid confusion, the understanding of tendencies should be clarified.[2] In Marxian economics, laws are conceived of as tendencies rather than as continuous empirical conjuncture. Tendencies are transfactual. Whether a tendency exists is not determined by how regularly or continuously it occurs

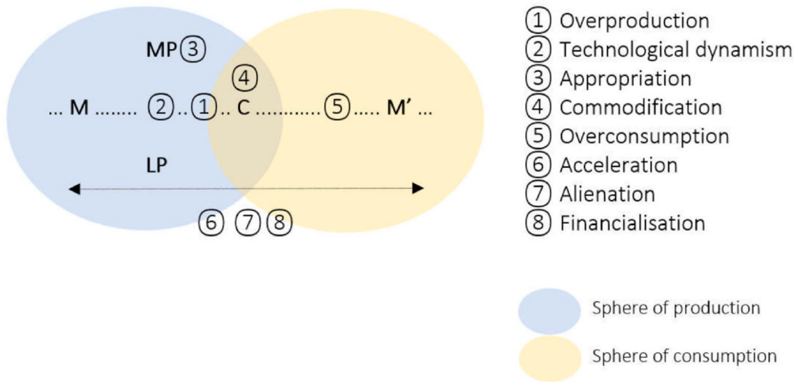

Figure 1. Systemic tendencies in the circuit of capital. Source: Pirgmaier (2018).

or by a mathematical question that can be formalised (Fleetwood 2012). It is not to be expected that all tendencies manifest themselves to the same degree at any given point in time. Their manifestation, or absence thereof, is linked to historically contingent configurations. In the long term, however, each of the tendencies must materialise at some point for the system to persist (Pirgmaier 2022). Inquiring into the tendencies structuring innovation in the German car industry therefore requires synthesising different strands of research regarding the industry.

Pirgmaier's (2018, 2022) work on tendencies draws on systematic dialectics, which also informs our approach. According to Reuten (2000, p. 142) 'systematic dialectics aims to "show" its object of inquiry'. In other words, its goal is to arrive at an understanding of the functioning of a whole, in this case of the capitalist system, by critically appropriating and connecting disparate, partial knowledge about that whole (Reuten 2014). In this iterative investigative process, there are no 'hard-and-fast rules or guidelines for investigation – there are no criteria other than the content of the argument' (Reuten 2014, p. 266). While sticking with the epistemological and ontological assumptions of systematic dialectics, we choose a subsection of a system, the German car industry, as our unit of analysis. We expand the approach by drawing on it to advance understanding of a specific industry that is embedded within global capitalism.

To our knowledge, the approach taken in this paper is novel in the sense that, while we stick with systematic dialectics' aim of generating holistic understanding, we do so for a specific industry. Yet is not possible to focus on the *German* car industry without considering the *global* context to the degree necessary to the argument. We aim to advance a theoretically informed assessment of the processes behind the dynamics that can currently be observed (see section 'The ecological footprint of cars and the impact of powertrain electrification'). Understanding the role of capitalism's tendencies in the development of the German car industry allows us to shed light on the mechanisms through which a social-ecologically unsustainable system reproduces itself in a specific moment and context (Reuten 2000).

On a practical level, answering the research question requires engaging with different sets of sources. Section 'The German car industry' presents stylised facts about and current developments in the German car industry, based on primary data taken from annual reports and strategy documents. Sections 'Regulatory push for electrification', 'The ecological footprint of cars and the impact of powertrain electrification', 'A limited role for shared car use' and 'How industrial developments are shaped by the tendencies of capitalism' synthesise an interdisciplinary body of literature on the car industry, including ecological economics, history, political science and sociology, as well as policy papers and reports by applied research institutes (cf. Marscheider-Weidemann *et al.* 2021) and grey literature, for example from non-profit organisations (cf. Groneweg 2020). This literature was found by a systematic and iterative keyword search via science websites, publisher websites and journal websites, as well as search engines. The second part of the research process is analogous to what Sovacool *et al*. (2018) classify as narrative review, serving to bring disparate strands of literature in conversation with each other.

On the way towards ecologically sustainable cars?

This section gives a brief overview of the regulatory framework of the current transition, cars' ecological footprint, the impact of shared car use and current trends in the German car industry. The insights of this empirical section are the basis of the theoretically informed analysis in section 'How industrial developments are shaped by the tendencies of capitalism'.

Regulatory push for electrification

Vehicle electrification has become a policy priority on the German and European level, as well as for countries that are significant markets for car manufacturers, notably China (Mazur *et al.* 2015a, 2015b, Schüler-Zhou 2019, Pichler *et al.* 2021). In 2020, new fleet emission limits entered into force which incentivised car manufacturers on the European market to decrease emissions to avoid being fined (European Parliament and Council of the European Union no date). As a result, average CO_2 emissions of new cars fell from 140 g/km in 2020 to 122 g/km in 2021 in Germany, according to in-lab measurements. Another result of the restrictions was that sales of plug-in hybrid vehicles (PHEV) and battery electric vehicles (BEV) increased from three per cent of total car sales in 2019 to 26 per cent in 2021, with an increasing share of BEVs in relation to PHEVs. In September 2021, 17 per cent of new cars sold were BEVs, while 12 per cent were PHEVs (International Council on Clean Transportation 2022).

Real fleet emissions, however, are higher than this data suggests. In 2018, an average gap of 39 per cent between real-world and lab emissions persisted. New regulations to address this gap entered into force in 2021, but evaluations of their effect were not available at the time of writing (Transport & Environment 2020a). Moreover, the EU regulation leaves loopholes for greenwashing. First, it stipulates a 'super credit system'. In 2020, all cars with lab emissions lower than 50 g CO_2/km contributed double to the calculation of carmakers emission reduction (European Parliament and Council of the European Union no date). The second critical loophole in current regulations are PHEVs. Their real-world emissions are on average three to five times higher the approval values, on which classifications and emission statistics are based. This is because, on average, private PHEVs are only driven as electric vehicles 45–49 per cent of the time, while for company cars this is as low as 11–15 per cent, rendering their classification as EVs questionable (Transport & Environment 2020b, Plötz *et al.* 2022). The European Commission proposed a first step towards addressing this gap in its 2022 update to vehicle classification. (Transport & Environment 2022).

The ecological footprint of cars and the impact of powertrain electrification

The regulations mentioned above have clear effects when it comes to market and industrial developments. However, the understanding of sustainability underpinning them is limited. First, because only in-use CO_2 emissions are considered, while the CO_2 emissions of EVs are indirect and arise through the energy mix used in vehicle production and electricity generation. In production, EVs incur higher CO_2 emissions than other vehicles due to their batteries, which are mostly produced in economies with a high share of coal in their energy mix (Helms *et al.* 2019). Due to the coal intensity of the German energy mix, a BEV is estimated to be only about 20 per cent less CO_2-intensive in use than a petrol-based otto engine. The balance is on par for diesel engines (Helms *et al.* 2016). Over the vehicle's lifetime, the estimated distance at which combustion engines and BEVs break even in terms of CO_2 emissions ranges from 29,000 to 150,000 km, depending on the grid decarbonisation scenario (Helms *et al.* 2019, Leßmann and Steinkraus 2019).

Second, assessing the ecological impacts of EVs relative to conventional vehicles requires widening the scope beyond CO_2 emissions. The production of cars is very resource intense and uses many virgin raw materials, such as rubber for tyres, leather for seats, and metals and rare-earth elements for chassis and powertrains. The sourcing of each of these materials comes with its own ecological and social impacts (Betz *et al.* 2021, Fritz 2022, Riofrancos *et al*. 2023). As regards quantity, aluminium and steel, derived from bauxite and iron, are the most important metals to consider, making up between 50 and 60 per cent of a car, independent of the powertrain (Groneweg 2020). Globally, the German car industry is the fifth biggest user of raw materials, and its resource needs will increase with powertrain electrification (Groneweg *et al.* 2021).

Furthermore, each EV comes with a large battery that needs a novel set of resources, most notably lithium, cobalt and nickel, but also rare earths (Kalt 2020). The metals used in battery production are primarily found in the Global South: lithium in Chile, Argentina and Bolivia; cobalt in Congo; and nickel in Indonesia and the Philippines. Moreover, rare earths are mainly sourced and processed in China, which supplies over half of the global output and dominates the processing of critical components for electrification: in 2019, 94 per cent of rare earth magnets, needed in each EV, were made in China (Bundesanstalt für Geowissenschaften und Rohstoffe [BGR] 2021; Gauß *et al*. 2021). The mining of all these resources incurs severe ecological degradation, such as sinking ground water levels, resulting in desertification, and (radioactive) pollution (Margonelli 2009, Groneweg 2020, BGR 2021, Rushdi *et al*. 2021). The challenges associated with the extraction of primary resources can be expected to increase, especially since used materials are rarely recycled (Busch *et al*. 2014). The ecological and social consequences of this new frontier in resource extraction will be further elaborated on in section 'How industrial developments are shaped by the tendencies of capitalism' below.

In addition to electric cars, fuel cell-powered cars using hydrogen are frequently put forward in the name of 'greening' the car, in the German case by BMW, which started to manufacture a hydrogen SUV on a small scale in late 2022 (Wermke 2023). Hydrogen has been put forward as green and carbon neutral. However, hydrogen cars are very unlikely to be an ecologically sustainable choice: they are two and a half times less energy efficient than electric vehicles. Moreover, 82.4 per cent of hydrogen was produced using fossil fuels, mostly gas, in 2021(Evans and Gabbattis 2020, International Energy Agency 2022). The production of green hydrogen hinges on the availability of renewably generated electricity on an unprecedented scale. Satisfying current demand for hydrogen with electricity would already require an equivalent of the annual electricity use in the EU (Evans and Gabbattis 2020).

Under these auspices, the proposal to use hydrogen to power cars should be treated with utmost caution, as it is not only an inefficient way of burning fossil fuels but also yields the danger of new forms of so-called green colonialism (Van de Graaf *et al*. 2020). The market share for these vehicles is presently small and experts expect that, given the regulatory framework outlined above, electric vehicles will outrival hydrogen (Evans and Gabbattis 2020). Therefore, the remainder of this paper focuses on electrification. In summary, a better ecological balance does not equate to an 'ecological' mode of transport. Regardless of their powertrain, cars are resource intensive and inefficient compared with active mobility or collective motorised forms of transport (Helms *et al*. 2016).

A limited role for shared car use

Carsharing, preferably electrified, is often raised in connection with sustainable mobility and features prominently in manufacurers' strategies (see section 'The German car industry'). Other commercial forms of shared car use, such as ride hailing (e.g. Uber) and ride sharing (e.g. BlaBlaCar) are also often invoked as more sustainable forms of car use. While some ecological benefits can be found, for example in the higher occupancy rate of BlaBlaCars vis-à-vis regular cars, none of the commercial sharing models is intrinsically ecological (Acquier *et al*. 2019, Beverland *et al*. 2022). Their use can have a positive impact if replacing less sustainable mobility options, but the empirical evidence is mixed (Beverland *et al*. 2022).

The promise that carsharing will lead to less crowded city roads, lower car ownership, multimodal mobility and lower emissions has not yet materialised (Becker *et al*. 2018, Jung and Koo 2018, Amatuni *et al*. 2020, Zhou *et al*. 2020, Arbeláez Vélez and Plepys 2021). Studies on commercial carsharing in German cities found minor reductions in individual car ownership, no reduction of the number of cars in the city, limited evidence for an associated modal shift to public transport and an increase in personal car use, and thus a modal shift away from the use of public transport (Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit 2015, Giesel and Nobis 2016).

For carsharing to have a positive impact, contextual factors need to be adjusted, notably via additional measures to reduce car use and ownership, as well as a focus on small, electrified fleets (Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit 2015, Schreier *et al*. 2015, Hülsmann *et al.* 2018, Doll *et al.* 2019, Shaheen *et al*. 2019). Without accompanying policy measures, carsharing, ride sharing and ride hailing are unlikely to render personal transport significantly more sustainable.

The German car industry

The automobile industry is a cornerstone of the German economy, not only because of its importance to the country's export-reliant business model but also because of the narrative of Germany's economic success being founded on car manufacturing (Wentland 2017). BMW and Daimler own upmarket brands: BMW, Mini, and Rolls-Royce for the former, Mercedes and Smart for the latter. The Volkswagen group owns 12 brands, catering to consumers across the board, from Porsche and Audi to Skoda. At present, around 800,000 people are directly employed in the industry, which in 2019 generated €436 bn of revenue one-third of all export-related revenues (Bundesministerium für Wirtschaft 2020). Accordingly, the industry's interests have considerable political clout (Brand and Wissen 2021). This has led to a lock-in of political support for the system of automobility, upheld by numerous actors (Walks 2015, Brand and Wissen 2021): As Brand and Wissen (2021) note:

> Automobility's infrastructural, institutional, and subjective entrenchment [...] can also be attributed to the interests of workers, employees and trade unions, who perceive a fundamental restructuring of the industry as a threat to their associational power. (Brand and Wissen 2021, p. 127)

This associational power is rooted in the era of Fordism, which is intrinsically connected to the rise of automobility and increased union organising (Walks 2015). The core workforce of German car manufacturing companies is well paid, well trained and a stronghold of the German union for metal workers (Iwer 2018). Consequentially, the union and car manufacturers often have similar positions in the negotiation of industrial policies concerning the sector.

Sectoral development

To understand recent sectoral developments, key data from 2010 to 2020 for BMW, Daimler and Volkswagen was extracted from their annual reports (Table 1). First, it should be noted that falling

Table 1. Earnings before interest and taxes (EBIT, million €).

Year	Volkswagen	BMW	Daimler
2010	7141	5111	7274
2011	11,271	8018	8755
2012	11,498	8275	8820
2013	11,671	7978	10,815
2014	12,697	9118	10,752
2015	−4069	9593	13,186
2016	7103	9386	12,902
2017	13,818	9899	14,348
2018	13,920	8933	11,132
2019	16,960	7411	4313
2020	9675	4830	6603

profitability, indicated by EBIT, precedes the COVID-19 pandemic, starting in 2017 for BMW and Daimler. Volkswagen recovered from its 2015 dip (a consequence of the revelation that the company had manipulated emission data for its diesel-powered engines [Brand and Wissen 2021]).

As a result of (1) the regulations outlined in section ‘Regulatory push for electrification‘, (2) new competition with firms like Tesla, and (3) market saturation, the German car industry, like its global competitors, is under pressure (Köhnke 2022). Car manufacturers have responded with mid- to long-term strategies published through various channels such as websites, annual reports and sustainability reports. In accordance with their main source of revenue, they envision a future that continues to centre on the car, despite reframing the companies’ roles as mobility providers. VW’s strategy, ‘NEW AUTO - Mobility for Generations to Come’ is built around digitalisation, powertrain diversification and new forms of car use, notably carsharing and autonomous driving, but the ultimate idea remains to have as many people as possible using a car that carries one of the company’s brand labels Volkswagen Konzern (no date). Similarly, BMW proclaims that it will ‘stand for first class individual mobility and contribute to the sustainable development of our planet’ (BMW Group no date), while Daimler’s main brand, Mercedes-Benz, promises to build ‘outstanding, fascinating vehicles’, alongside achieving carbon neutrality by 2039 (Mercedes-Benz Group no date). Overall, the business strategies aim at safeguarding continuous car use, while the sustainability strategy hinges on reducing GHG emissions, which as outlined above is an insufficient sustainability indicator.

Vehicle electrification

While some car manufacturers have communicated global (e.g. Jaguar, Volvo) or European phase-out dates for combustion engines (e.g. Ford, Stellantis), none of the German companies had done so for all brands at the time of writing. Volkswagen announced that it would phase out sales in Europe by 2035, with more specific dates for some brands. BMW has not yet communicated a definite phase-out plan, but announced that its daughter, Mini, will be fully electric by the early 2030s. Similarly, Daimler has yet to communicate an exit date for Mercedes, but Smart, which Daimler co-owns with the Chinese manufacturer Geely, is the company’s first fully electrified brand (Köllner 2021). Simultaneously, all three companies communicate sales targets: Daimler aims for 50 per cent of its sales to be electric or hybrid by 2025, BMW for 50 per cent of global sales to be fully electrified by 2030, and Volkswagen for 70 per cent of European sales to be electric by 2030.

Considering current shares of electrified vehicles, reaching these sales goals does not seem evident. Figure 2 gives an overview of the global share of all three companies’ EV sales from 2015

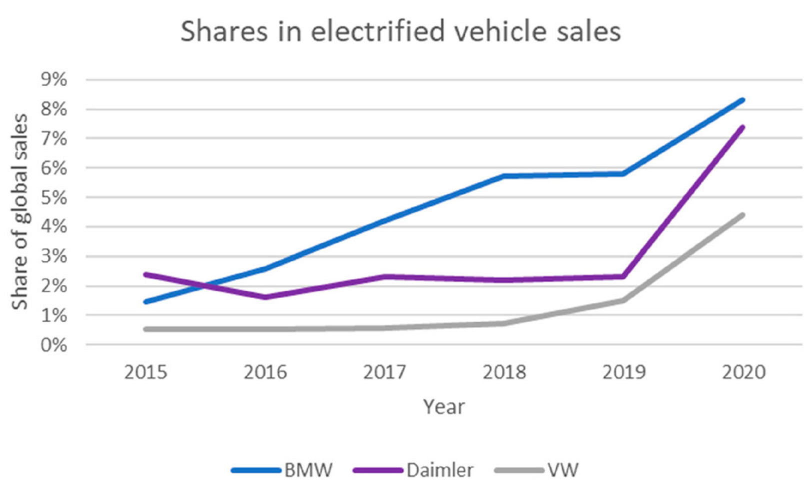

Figure 2. Shares in EV sales, 2015–20.

to 2020. Note that the VW group publishes this data only as an aggregate of brands: Volkswagen cars, Audi, Skoda, Seat, Volkswagen light duty vehicles. BEV and PHEV are combined due to limited data availability. Even for BMW, which has the highest share in global EV sales, only eight per cent of the cars sold in 2020 were electrified. All three companies' EV sales figures are mirrored in the drop in respective fleet emissions on the European level, which were on the rise after 2015 as sales of SUVs picked up (European Environmental Agency 2021).

What is more, one needs to remember that EV sales include PHEVs, which, as explained in section 'The ecological footprint of cars and the impact of powertrain electrification', have substantially higher emissions than BEVs. Volkswagen is the only company providing longitudinal disaggregated data, shown in Figure 3. Until 2018, more PHEVs were sold. BMW and Daimler provide disaggregated data for 2019 and 2020, when both companies sold two to three times as many PHEVs than BEVs. As the former still largely use fossil fuels in real-world usage (see section 'The ecological footprint of cars and the impact of powertrain electrification'), even the modest share in EV sales should be treated with caution. German car manufacturers profit from both the double accounting and the PHEV loophole in the current EU regulation (European Environmental Agency 2021).

Vehicle size

The final trend to be considered is vehicle size. The trend towards bigger, heavier cars with more powerful engines is continuous and unbroken both globally and nationally, but has a negative impact on ecological goals. Between 2005 and 2020, the average horsepower of newly admitted cars in Germany went from 123.3 to 160.2 (Kords 2022). For reference, the original VW beetle had 34 horsepower (Petersen and Diaz-Bone 1998). This trend has been exacerbated by the rise of heavy, fuel-intensive SUVs (Brand and Wissen 2021). In 2019 and 2020, SUVs had the highest shares in newly registered cars – around 21 per cent in both years (Kraftfahrt-Bundesamt 2020, 2021). From a producer's perspective, the sale of SUVs is attractive, with a low production cost relative to the sales price, allowing for a high mark-up (Köhnke 2022). Yet, as shown by Groneweg and Gehrs (2021), Volkswagen's aim to boost its SUV sales to 50 per cent by 2025 undermines climate goals.

Building upon the report by Groneweg and Gehrs (2021), Figures 4-6 show car sales between 2015 and 2020 for the three car manufacturing companies under consideration. Figure 6 is adapted from Groneweg and Gehrs's report, while Figures 4 and 5 were done analogously by the authors. Vehicles were classified according to the EU commissions and ACEA classification

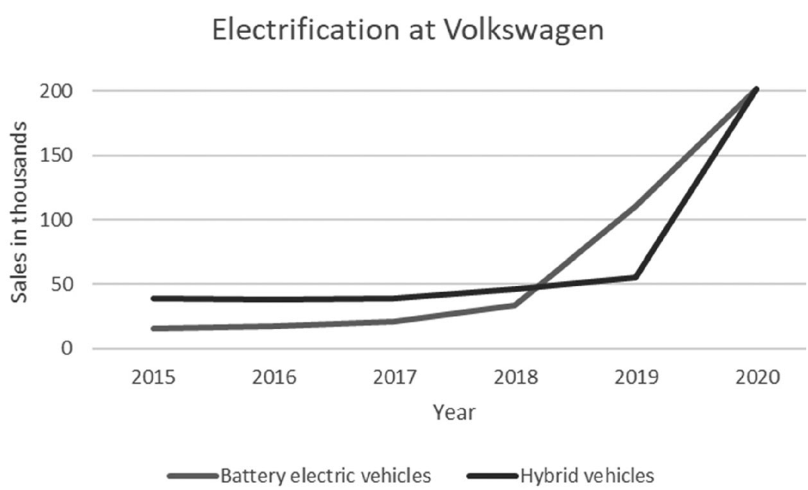

Figure 3. EV sales, Volkswagen, 2015–20.

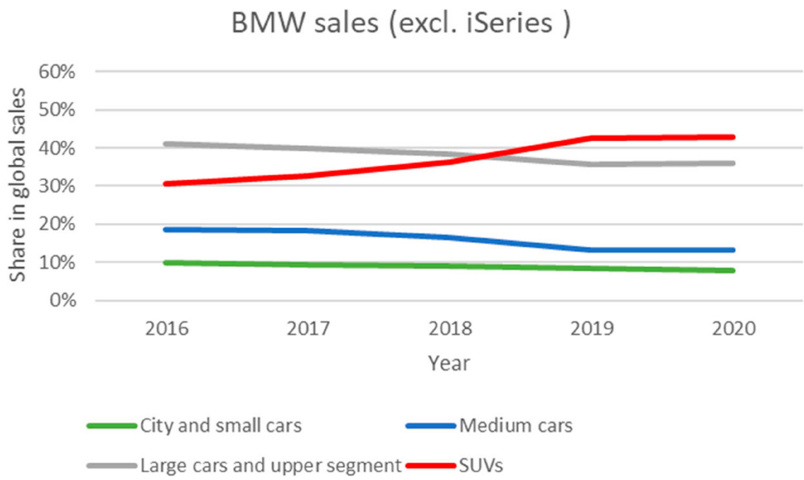

Figure 4. Sales by vehicle type, BMW, 2016–20.

schemes, which consider car size, engine power and consumer target group (Commission of the European Communities 1999, ACEA 2022). For Volkswagen, only the brand, and not the whole company, was analysed, since the SUV strategy was announced on a brand level. As Daimler's Mercedes and BMW do not have small cars in their portfolio, sales numbers for the enterprises' brands of smaller cars, Smart and Mini, were included. The Mini countryman is classified as an SUV despite being relatively small, as it has a design typical of an SUV. The BMW iSeries could not be included as sales numbers are not disaggregated by model and fall into different categories. While Volkswagen's sales target is a drastic example, the figures show that BMW and Daimler are following suit.

This Section outlined the most important factors to consider when evaluating the ecological potential of current transitions. Car manufacturers' business model continues to rely on increased car use (section 'Sectoral development'), albeit with changes to the powertrain (section 'Vehicle electrification') that on their own are insufficient to tackle the multiple ecological crises (section 'The ecological footprint of cars and the impact of powertrain electrification'). At the same time, the ecological potential of electrification runs danger of being undermined by continued growth in

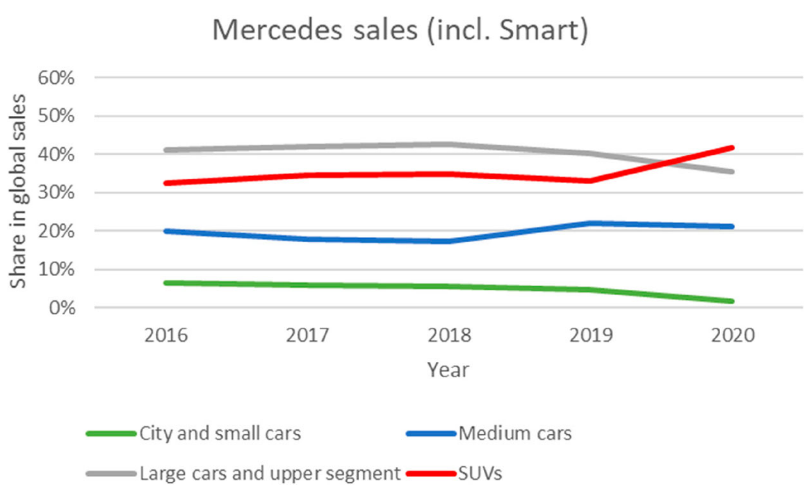

Figure 5. Sales by vehicle type, Mercedes, 2016–20.

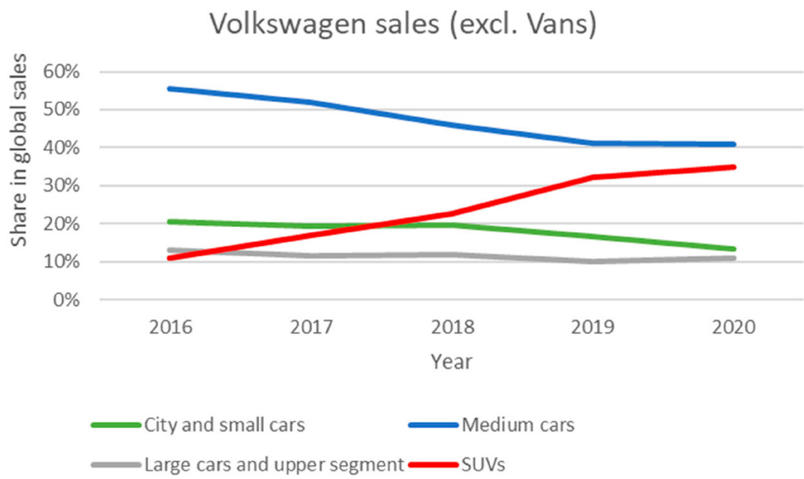

Figure 6. Sales by vehicle type, Volkswagen, 2016–20.

vehicle size (section 'Vehicle size'). To assess these industrial developments in the context of regulation (section 'Regulatory push for electrification'), social-ecological concerns (section 'The ecological footprint of cars and the impact of powertrain electrification') and proposals for supposedly more sustainable forms of car use (section 'A limited role for shared car use'), we need a framework that allows for a systemic approach focusing on the interlinkages between the different observable phenomena. Therefore, the next section explores to what extent these indicators of a transition towards *unsustainability* are rooted in systemic tendencies (Antal *et al*. 2020) (Figures 5 and 6).

How industrial developments are shaped by the tendencies of capitalism

Currently, technological innovation in the form of powertrain electrification has the most direct bearing on the social-ecological impact of vehicle production. Our analysis will thus centre on two of the eight dominant tendencies of capitalism that unfold in the sphere of production: technological change and appropriation. The focus on these two tendencies is itself an outcome of the research process. After reviewing literature and assessing it from the viewpoint of the eight tendencies outlined by Pirgmaier (2022) and described in section 'Approach' of this paper, we argue that these two tendencies are most pertinent to understanding why the possibilities of ecological innovation appear to be so limited in the context of car manufacturing. However, as Pirgmaier (2022) and Reuten (2014) explain, all eight tendencies co-exist and have a bearing on current dynamics. Therefore, we are providing brief descriptions of the remaining six tendencies and situate them in relation to our research.

- **Acceleration**: the transport system in which cars are embedded has been a key driver of the acceleration in economic activity and personal mobility, on which the current economic system relies. This acceleration engenders social-ecologically detrimental effects (Grübler 1998, Steffen *et al*. 2015, Rosa 2016). The transport system is highly intertwined, characterised by path dependency and incremental change oriented towards the status quo (Grübler 1998).
- **Alienation** in the Marxist sense comes in four forms: from 'work; our produce; other human beings, and nature' (Pirgmaier 2018, p. 140). Car use is associated with alienation from humans and nature. Currently, it is most expressed in the interior design focused on cocooning, which shields the driver from the outside world, and the SUV-style exterior design, which aims at a dominant position vis-à-vis other drivers as well as nature (Sachs 1992, Gunster 2004, Wells and Xenias 2015, Newman 2016a, 2016b).

- **Commodification** is the incorporation of something into the logics of market exchange. It can currently be observed in the increasing popularity of commercial carsharing, ride sharing and ride hailing (section 'A limited role for shared car use'). While car manufacturers were not frontrunners in this development, they are widening their portfolio in this direction and focusing on these forms of mobility in their strategic business communication (section 'Sectoral development') (Canzler and Knie 2018, Pirgmaier 2018, Wissen 2019). As outlined in section 'A limited role for shared car use' commodified shared car use is likely to stabilise or increase car use, thus posing a barrier to social-ecological sustainability.
- **Overproduction** is endemic to the car industry. The industry is characterised by capital intensity, increasing returns to scale, high long-term investments and the need for high-capacity utilisation (approximately 85 per cent on the plant level) in order to be profitable. Presently, this results in global competition for shares in a saturated market, mainly by introducing 'new' product ranges at lower prices, and is reflected in recurring sales crises and permanently higher production than sales numbers (Kaufmann 2011, Mattioli *et al*. 2020, Köhnke 2022).
- **Overconsumption** is linked to alienated lifestyles, in which consumption has become a way to compensate for the demands of daily life (Hickel 2020). One example thereof is the uptake of ever larger cars, as described above. In Germany, overconsumption is bolstered by privileges for company cars, which make up half of new admissions, and early scrapping schemes in times of economic crises (Boston and Barnett 2020, Hickel 2020, Brand and Wissen 2021, Stephan and Gehrs 2021, Candeias and Krull 2022).
- **Financialisation** unfolds through various channels in the industry and is not new. Its expansion is, however, notable. Of all vehicles delivered by Volkswagen, over a third (34.2 per cent) is either financed or leased (Volkswagen Konzern 2020), and in the case of Daimler, every second vehicle delivered in 2019 was either financed or leased (Daimler 2020, p. 177). For BMW this share was even higher, at 65.9 per cent (BMW Group 2020). Thus, profit generation is increasingly dependent on demand induced by financing options rather than direct sales, especially for upmarket brands (Kädtler and Sperling 2002, Dietl *et al*. 2009, Scheuplein 2021, Köhnke 2022, Haines-Doran 2023).

Powertrain electrification unfolds against the backdrop of these six tendencies. An exhaustive discussion of their interrelations is beyond the scope of this article, but can be briefly summarised as follows: Acceleration, alienation and commodification are most important for understanding the transport system in which cars are imbedded. They incentivise continued car use, either privately owned or via carsharing. Independent of power train, car manufacturers can stimulate demand through increasingly complex financing schemes, which act as a lubricant upholding overproduction and overconsumption, which structures the industries business model.

Technological dynamism

The industrial restructuring following market logics (section 'The German car industry') unfolds as a specific instance of technological dynamism, a defining feature of capitalist production which is a priori steered towards 'the acquisition and augmentation of exchange-values' (Marx 1867, p. 739). In other words, the profit generated by production rather than the use value of the product is of interest. This valorisation imperative steers the direction of technological change towards lowering production costs and increasing profits via the deepening of the division of labour and increasing output at the cost of humans and nature, who are exploited in the process (Foster *et al*. 2011, Smith 2012, p. 262). Consequentially, technological dynamism does not lead to lower environmental impacts of production, even though innovations often lead to greater efficiency. The Jevons Paradox, which states that improvements in efficiency are offset by a higher output, is not paradoxical from this perspective (Binswanger 2001, Hertwich 2005, Font Vivanco *et al.* 2016, Moshiri and Aliyev 2017, Pirgmaier 2022).

The tendency towards labour-saving, efficiency-increasing technological developments has unfolded throughout the history of the global and German automotive industry (Köhnke 2022, p. 145 ff.). In the period of economic recovery after World War II, the industry embraced Fordist production based on product standardisation and semi-skilled labour at the assembly line (Boyer 2018). As a production principle, this underpinned the commercial success of the car, as it lowered production costs while increasing profit and output. This is characteristic of innovation under capitalism (Pirgmaier 2018). Subsequent developments have continued this trend. Most notable is a 'platform-based' production principle, used throughout the industry, which standardises the main invisible components of the car while catering to consumer demand for diversity through a variety of chassis and options for interior design (Mattioli *et al.* 2020). The thus emerging production regime is tailored to sell cars that are largely standardised but can be sold with a relatively high mark-up. It is therefore not surprising that firms like VW make the sale of SUVs a cornerstone of their business strategy.

Alternative powertrains and ecological innovations, in turn, have a history of being driven out (Høyer 2008). The industry lobbies systematically against more stringent environmental regulations and aims for voluntary agreements (Rennings *et al.* 1997, InfluenceMap 2021). The development and demise of the three-litre car (consuming three litres of gasoline per 100 km driven) illustrates how voluntary agreements fail to have positive ecological impacts and shield car manufacturers from regulation-induced innovation pressure (Rennings *et al.* 1997, Wells *et al.* 2013). In 1995, Greenpeace presented SMiLE: the first three-litre car based on a Renault Twingo. The development of this prototype spearheaded debate on the commercial production of such cars in the context of environmental and climate protection (Petersen and Diaz-Bone 1998). Instead of new governmental regulations to this end, a voluntary agreement was reached. Volkswagen and Daimler would produce their own three-litre cars by 2000. In return, the government would not introduce binding quotas for fleets' gasoline use or CO_2 emissions. The only accompanying measure was a tax incentive. The cars that were finally marketed used technology that rendered them more expensive than Greenpeace's prototype and had a high retail price compared to similar, less fuel-efficient vehicles (Rudolph 2003, Knödler 2015). Despite being lauded as 'car of the future', market diffusion was not achieved, while vehicle emissions and gasoline use rose unhindered until 2015 (Petersen and Diaz-Bone 1998, Rudolph 2003, Deutsche Umwelthilfe 2021).

How do these historical trends inform current developments? Arnulf Grübler's (1998) work on technological transitions helps to shed light on this question. First, complex technological systems are sticky, and their development can take up to a century in the case of transport infrastructures. Second, new technologies that can be integrated into an existing technological system are easier to implement. Third, any new technological regime needs an enabling social and institutional context – which was not given for the three-litre car. As new regulations regarding the decarbonisation of transport (section 'Regulatory push for electrification') change the institutional regime, BEVs are a relatively convenient technology. They use the same roads as other cars, while new charging points can be comparatively easily integrated into present infrastructures. In this enabling context, BEV technology, hitherto deemed unattractive, becomes competitive. The trouble is that non-disruptive change also heightens the likelihood that the tendency to tailor innovation towards profit maximisation will persist – just in an electrified version. This is precisely what seems to be unfolding: while early BEVs, like BMW's i3, were relatively small, car manufacturers are now expanding their product range to include electric or hybrid SUVs and are phasing out smaller series such as the i3. As the former have high resource requirements in production and are energy intensive in use, e-SUVs do not contribute to making cars more sustainable. The characteristics of technological dynamism shed light on the system-immanent drivers of ecological unsustainability.

Appropriation

The expression of technological dynamism as a trend towards electric SUVs implies a resource-intensive trajectory for vehicle electrification, which is fuelling a second tendency: appropriation

(Pirgmaier 2022). Appropriation in the early stages of capitalism was discussed by Marx in Capital I. He laid out how primitive accumulation, that is, the dispossession of the landless classes through enclosure, was a cornerstone of capitalist development in England (Marx 1867). Subsequent Marxian scholarship, spearheaded by Rosa Luxemburg's work on capitalism and imperialism, developed an understanding of appropriation as a continuous process of expanding and deepening the frontier of capitalist development (Luxemburg 1913, Pirgmaier 2022).[3] Luxemburg emphasised that it 'is illusory to hope that capitalism could ever be satisfied with the means of production that it is able to procure by means of the exchange of commodities' and postulated the violent process of appropriation as a cornerstone of capitalism's functioning (Luxemburg 1913, p. 394). Presently, David Harvey's work on accumulation by dispossession sheds light on the unfolding thereof, while Jason Moore's conceptualisation of the exploitation of the web of life integrates the ecological side of appropriation (Harvey 2014, Moore 2015).

Appropriation does not denote resource extraction per se, but the continuous, violent expansion and deepening of the extractive frontier, which engenders a spiralling dynamic of human and non-human exploitation (Lessenich 2020). Many of the materials used in car production (section 'The ecological footprint of cars and the impact of powertrain electrification') are sourced under circumstances resembling appropriation (Betz *et al.* 2021, Fritz 2022). To keep the discussion concise, we will exemplarily discuss four metals from two component groups: bauxite and iron, as those metals account for most of a car's weight, and lithium and nickel, two battery components for EVs for which demand is expected to rise drastically.

The sourcing of Bauxite and Iron illustrates present appropriation dynamics unfolding. More than 90 per cent of bauxite used in Germany comes from a single Guinean mine- the Sangaredi-Mine. Guinea does not host mines that are certified in line with independent social and environmental standards (Groneweg 2020). The non-governmental organisation PowerShift e.V. reports on the human rights violations and environmental impacts of mineral extraction. For the Sangaredi-Mine, they report the relocation of a village to an area that lacks fresh water and arable land in 2021, along with land grabbing, water pollution and ecological degradation. These dynamics, as well as the structural factors facilitating them, are characteristic of modern appropriation, which is intimately linked to neo-colonial north-South relationships. Guinea is rich in resources and economically dependent on bauxite mining. The mines, however, are owned by foreign multinationals disposing of political power, while social insecurity is widespread (Knierzinger 2014, Diallo 2019). The situation is similar in Brazil, Germany's main supplier of iron ore. In the context of ore mining, frequent dam bursts destroy ecosystems and kill people (Groneweg *et al.* 2021).

Powertrain electrification adds a new dimension to the resource needs of an industry that is already classified by the German Ministry of Labour as at risk of violating human rights (Bundesministerium für Arbeit und Soziales 2020). Analysts across the board expect substantial increases in demand for raw materials due to powertrain electrification. For instance, in 2018, McKinsey estimated global demand for lithium at 700,000 tons by 2025, while the German Resource Agency's estimate in 2019 was 111,000–150,000 tons by the same date. (McKinsey&Company 2018, German Mineral Resources Agency 2019). Moreover, the global demand for rare earths is expected to have risen by 43 per cent by 2030 (BGR 2021). This rising demand without decreasing demand for other raw materials used in car production leads to an overall increase in resource exploitation and highlights the spiralling nature of appropriation.

The second aspect are the circumstances of resource extraction. For example, the extraction of lithium in the Chilean Atacama Desert, the world's biggest lithium reserve, comes at the cost of water shortages for indigenous populations and severe disturbances of the local ecosystem (Riofrancos *et al*. 2023). In the Philippines, where nickel is sourced under deleterious conditions, killings of anti-mining activists are a common occurrence (Holden 2014). For a detailed account of the social and ecological consequences of lithium extraction in Chile, see Schlosser (2020). See Kalt (2020) for the value chain of cobalt, lithium and nickel. In the process of vehicle electrification, the extractive frontier is expanded and deepened, with ensuing human and non-human exploitation.

The German car industry is not exempt from this global trend. Currently, most batteries for EVs are supplied by Asian technology firms, but German car manufacturers are building plants for battery production with various coalitions of corporations and substantial political support. The depth of engagement ranges from final assembly to plans for battery cell development, and other forms of horizontal and vertical integration of the value chain (Harloff 2021, Köhnke 2022, Schade *et al*. 2022). At the same time, none of them give full disclosure of raw material sourcing and its environmental and human rights implications. Moreover, none has comprehensive mechanisms to report infractions of human rights along the value chain, despite membership in corporate social responsibility initiatives and projects for direct, certified resource extraction by BMW (Groneweg 2020). In sum, present initiatives, both NGO- and industry-led, aimed at establishing social and ecological sourcing standards, are insufficient to establish accountability (Groneweg 2020).

The overall picture in the context of resource extraction- insufficient accountability along the value chain, socially and ecologically detrimental circumstances of extraction, and growing demand for novel materials- shows how technological dynamism (section 'Technological dynamism') fuels appropriation dynamics. It is important to understand, as mentioned above, the expansive nature of these developments. In the absence of demand reduction and efficient value chain regulation, the violence towards and disenfranchisement of local populations alongside ecological destruction is likely to increase further, thereby intensifying appropriation despite recycling initiatives that are now emerging (Schade *et al*. 2022).

Discussion

As outlined in section 'How industrial developments are shaped by capitalism's tendencies', powertrain electrification unfolds against the backdrop of a transport system marked by acceleration, alienation and commodification. As this renders car use easy and desirable, commercial carsharing is less likely to be part of sustainable multimodal transport solutions (Blanck *et al.* 2017, Ambach *et al.* 2019, Schneidewind *et al*. 2019 to name but a few). The 'collective (auto-)mobility' (Wissen 2019, p. 233) in which car manufacturers already participate to some extent yields the danger of reproducing and aggravating social and spatial inequalities that favour affluent populations and are profitable in cities but not rural areas. At the same time, the industry's own business model, which relies on a combination of overconsumption, overproduction and financialisation, is not likely to spearhead the development of small, electrified cars. Rather, the trend towards larger vehicles outlined in section 'On the way towards ecologically sustainable cars?' can be expected to continue. The industry's path-dependent business structure, governed by long-term, high up-front cost investments, incentivises a 'more of the same' approach to innovation (Canzler and Knie 2018, Köhnke 2022).

Against this background, and considering the way in which technological dynamism has been unfolding in the industry, an unsustainability transition towards fully electrified SUVs instead of small EVs used in a multimodal transport system seems probable. All German car manufacturers by now offer some form of electric SUV which, due to size, weight and energy use increases the ecological impact of EVs. Moreover, the spiralling and mutually re-enforcing nature of tendencies becomes discernible. Not only would the BEVs be more resource intensive, but the decarbonisation of the electric grid depends on a very similar set of resources, notably for solar panels. The additional demand for electricity would add to the resource extraction needed for vehicle batteries and solar panels alike (Saito 2020). The continuously increasing need for resources, aggravated by the absence of recycling schemes and the technological requirements for virgin raw materials, feeds into appropriation dynamics (Busch *et al.* 2014). The frontier of capitalist production is further expanded, and the cost is borne by local populations, surrounding environments and, ultimately, the global ecosphere (Rushdi *et al.* 2021).

Bilateral or multilateral trade agreements with resource-rich countries facilitate the development outlined above, and figure prominently in the German and EU resource strategy (Bundesregierung 2020). The car industry is a chief lobbyist for these agreements, as in the EU-Mercosur trade deal, for example (Fritz 2022). In the context of rapidly increasing demand, the race for resources fuels geopolitical tensions as nations compete for access (Riofrancos *et al*. 2023). Notably, China uses its control over rare earths to put political pressure on its trade partners (Fuhr 2014). In the absence of policies geared towards a reduction in demand for such resources, there is a high likelihood that the current practices of the mining industry, incurring ecological degradation and disenfranchisement of local, often indigenous populations, will continue unhindered and expand further (Riofrancos *et al*. 2023). It is thus unclear how the automobile industry in Germany could undergo a transition towards socially and ecologically sustainable production without disrupting the status quo.

It seems apt to expand on Kohei Saito's (2020) assessment of the socio-ecological balance of energy decarbonisation to the car industry. The author holds that in the quest of 'greening' energy production, the metabolic rift is deepening. This rift is both a spatial dislocation process of ecological destruction, as can be observed in the sourcing of metals for vehicle batteries in the global south, and a depletive process with a tendency to undermine the very basis of life. For solar energy, 'the greening of the Global North is not transforming the planet sustainably, but rather strengthening the robbery-mining processes of lithium and copper. The metabolic rift cannot be simply repaired by new technologies' (Saito 2020, p. 19). As shown above, the same applies to the car industry.

Conclusion

In conclusion, it is possible to answer the research question posed above: how do the endogenous tendencies of capitalism shape the automobile industry's transition away from internal combustion engine (ICE) vehicles? We have shown in section 'How industrial developments are shaped by the tendencies of capitalism' how technological dynamism and appropriation hinder the emergence of socially and ecologically sustainable products from within the industry itself. With a view towards social-ecological sustainability, the study allows for three main conclusions. First, focusing diversification on replacing powertrains without reducing overall output is ecologically unsustainable to begin with. Second, possible ecological improvements are at best restricted and at worst reversed by the way that technological dynamism under capitalism works. The imperative to maximise profit benefits the development of high mark-up vehicles, e.g. SUVs, while smaller cars, e.g. the three-litre vehicle, could potentially be profitable but are not taken up. It is already observable how the maxim of profit steers the industry towards electric SUVs in the absence of binding, efficient regulations. Third, the car industry is dependent on resources which are sourced at the significant social and ecological cost associated with appropriation.

The case illustrates how capitalist dynamics pose challenges for social-ecological sustainability in a mutually reinforcing way. Technological dynamism under capitalism, steered by profit maximisation, hinders the implementation of more ecological or socially efficient technologies, while fuelling appropriation, thereby shifting the cost of the supposed greening of the industry onto humans and ecosystems. Meeting one challenge gives rise to a different one somewhere else in the system unless the parameters are changed. The industry does respond to new regulations, as indicated by the drop in fleet emissions of 2020, but is unlikely to deliver based on voluntary commitments, as shown by the history of the three-litre car. To avoid a mere shift of the environmental cost hence requires a multi-level policy effort that also tackles the German car consensus, rather than reliance on industrial strategies governed by the principles of capitalist production.

Notes

1. We use the terms automobile industry, automotive industry and car industry interchangeably.
2. For a detailed discussion of the term's use in Marxian economics and its relation to the question of open and closed systems please consult, for example, Fleetwood (2012, 2017).

3. See Ince (2014) for a critique of the application of this terminology to processes of land-grabbing from a post-colonial perspective.

Acknowledgements

We thank anonymous reviewers for their thoughtful comments which helped us to strengthen the argument of this paper, as well as Elke Pirgmaier, Cedric Durand, Irmi Seidl, Guido Palazzo and Christian Arnsperger for their substantial feedback.

Disclosure statement

No potential conflict of interest was reported by the authors.

Notes on contributors

Anna Katharina Keil is an ecological economist conducting doctoral research at the University of Lausanne after obtaining a MSc in Socio-Ecological Economics and Policy at the Vienna University for Business and Economics. Her primary interest lies in understanding systemic barriers to socially and ecologically sustainable production and levers to overcoming those with a view towards work and the role of labour in transformational processes. In her PhD, she explores these topics by way of analysing the German automobile industry from the perspective of Marxist Political Economy integrating key insights from ecological economics and sustainable work.

Professor ***Julia K. Steinberger*** researches and teaches in the interdisciplinary areas of Ecological Economics and Industrial Ecology. Her research examines the connections between resource use (energy and materials, greenhouse gas emissions) and societal performance (economic activity and human wellbeing). Prof. Steinberger is Professor of Societal Challenges of Climate Change at the University of Lausanne since 2020. Before that, she worked at the University of Leeds, and was a Senior Researcher at the Institute of Social Ecology in Vienna (SEC), where she investigated sustainable cities and the links between material use and economic performance.

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