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The German car industry in times of decarbonisation

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THE GERMAN CAR INDUSTRY IN TIMES OF DECARBONISATION

Carlo Jaeger, Jonas Teitge, Jan-Erik Thie, Antje Trauboth¹

ABSTRACT

Long after the debates about tertiarisation and post-industrial society, deindustrialisation is a hot topic again. An important example is the future of the German car industry. Some people believe that the forces of climate policy and digitalisation will lead to a smooth shift from selling internal combustion cars to battery electric ones. We show that things are much more difficult by distinguishing three different futures. First, a pink scenario of global industrial expansion based on electric cars and renewable electricity (1), then, a black scenario of a shrinking market for German cars and a global car fleet far from reaching climate neutrality by 2050 (2), finally a green scenario where carbon neutral self-driving robotaxis and shuttles on demand help realise the goals of the Paris accord and where the German car industry embraces digitalisation to sell mobility as a service, bridging the divide between private and public transport (3). Moreover, the pattern of incremental innovations the German innovation system is locked in is a problem. Germany needs to renew the creative capacity it had when the invention of the automobile planted the seed of the German car industry. This will require patient research able to analyse and foster an unprecedented economic transition. We explain and propose the multisectoral approach to economic dynamics developed at the interface of mathematics and economics by John von Neumann because it offers an adequate starting point for this indispensable effort.

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The German Car Industry in Times of Decarbonisation*

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October 18, 2023

Abstract

Long after the debates about tertiarisation and post-industrial society, deindustrialisation is a hot topic again. An important example is the future of the German car industry. Some people believe that the forces of climate policy and digitalisation will lead to a smooth shift from selling internal combustion cars to battery electric ones. We show that things are much more difficult by distinguishing three different futures. First, a pink scenario of global industrial expansion based on electric cars and renewable electricity (1), then, a black scenario of a shrinking market for German cars and a global car fleet far from reaching climate neutrality by 2050 (2), finally a green scenario where carbon neutral self-driving robotaxis and shuttles on demand help realise the goals of the Paris accord and where the German car industry embraces digitalisation to sell mobility as a service, bridging the divide between private and public transport (3). Moreover, the pattern of incremental innovations the German innovation system is locked in is a problem. Germany needs to renew the creative capacity it had when the invention of the automobile planted the seed of the German car industry. This will require patient research able to analyse and foster an unprecedented economic transition. We explain and propose the multisectoral approach to economic dynamics developed at the interface of mathematics and economics by John von Neumann because it offers an adequate starting point for this indispensable effort.

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Abbreviations

BBSR	Federal Institute for Research on Building, Urban Affairs and Spatial Development
BYD	BYD Company Limited
EV	Electric vehicle
GCF	Global Climate Forum
GM	General Motors Company
IC	Internal combustion
ICE	Intercity-Express
IMK	Macroeconomic Policy Institute
IPCC	Intergovernmental Panel on Climate Change
IPO	Initial public offering
SUV	Sport utility vehicle
TGV	Train à grande vitesse
UN	United Nations

1 The new deindustrialisation challenge

Starting in the 18th century, Europe has led the world into carbon-based industrialization, with two long-term consequences: long-lasting economic growth in industrialized countries, and anthropogenic climate change worldwide. The industrial revolution started in the UK around 1760, taking advantage from the vast coal resources available on the British isles. The polities that would later become Germany followed suit roughly a century later, again taking advantage from rich coal resources, that were later complemented by imported oil and natural gas. As a result, Germany became the first industrial power of Europe.

Industrialization in the US started with increasing productivity in agriculture that led to shrinking employment in that sector (see figure 1). Employment in manufacturing gradually expanded, but reached a peak in the US after WW II, in the UK however in the 1960ies, when the fraction of employment in the so-called secondary sector had reached about 40%.

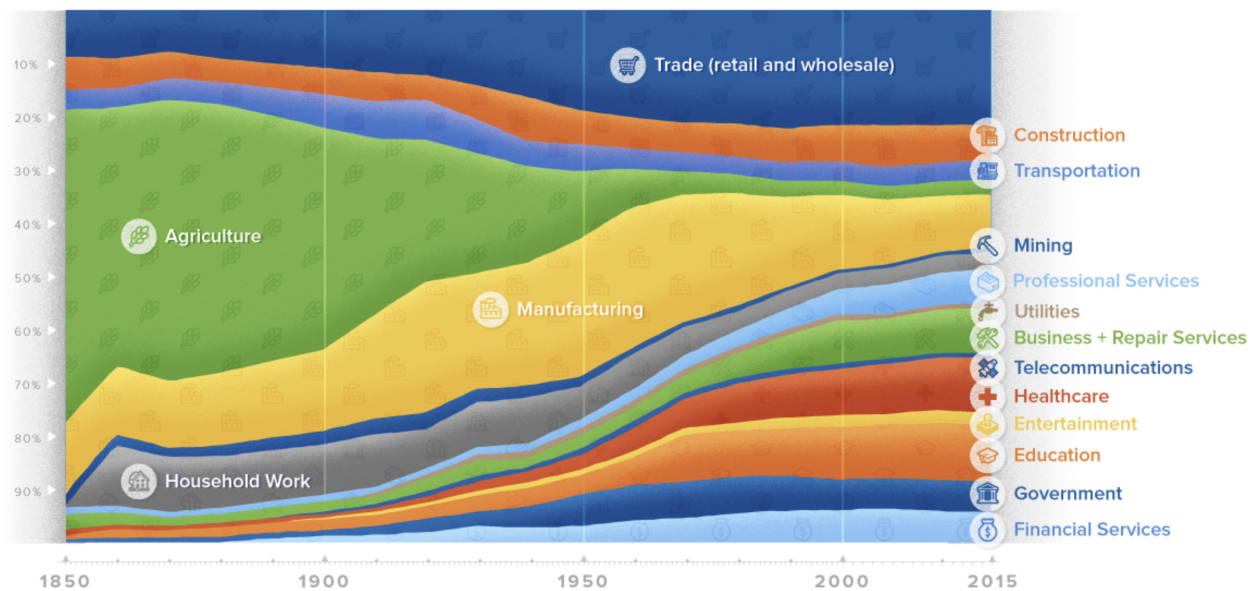


Figure 1: US employment fraction of different sectors, 1850-2015 (Desjardins, 2019).

In the German economy, the peak of employment in the secondary sector was reached in 1965 at a level of 49% (see figure 2). Meanwhile, employment is dominated in Germany as elsewhere by the so-called tertiary sector - a mixed bag of activities illustrated in figure 1.

The shift from manual labour typical for manufacturing to work typical for the so-called service sector has triggered fruitful research and important debates about the opportunities and dangers connected with the "post-industrial society".

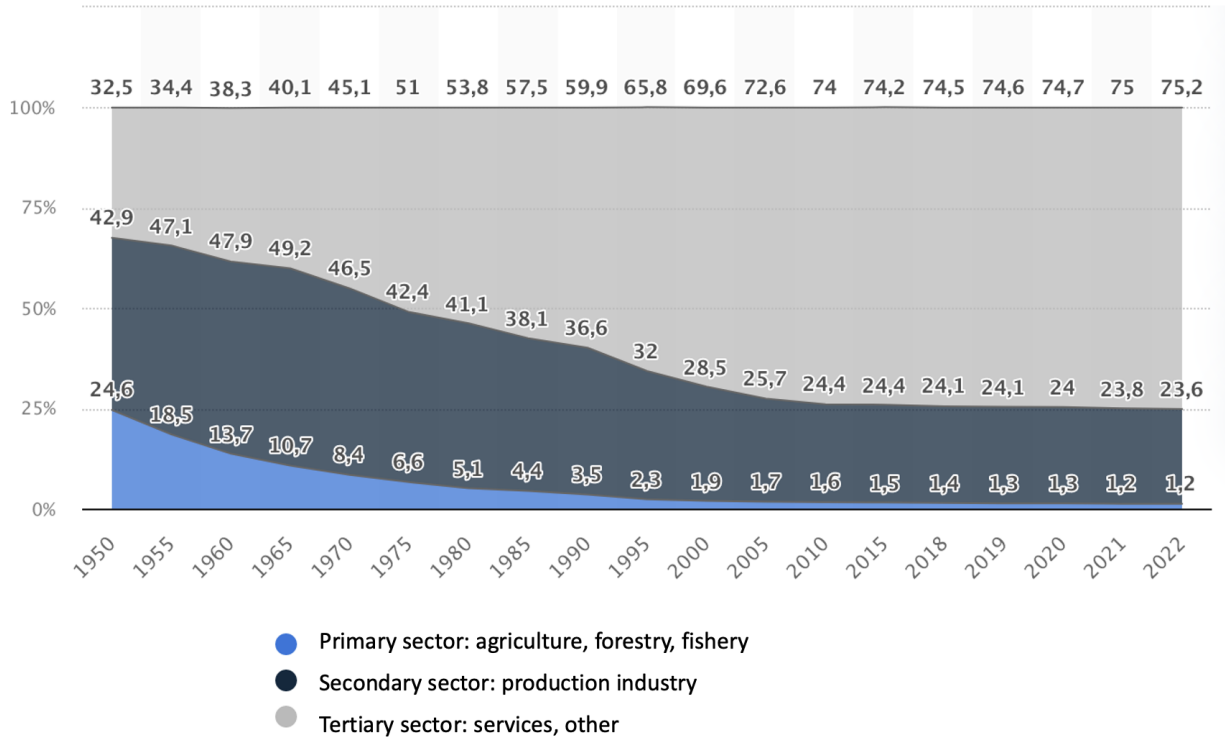


Figure 2: Employment fractions in primary, secondary, and tertiary sectors of Germany, 1950-2022 (Statista, 2023).

However, in terms of gross added value, traditional industry is still extremely important for the German economy and society. In 2021, the German industry contributed 26.6% of gross added value to the economy as a whole. In comparison, that fraction was 16.8% in France and 18.4% in the US, while in Japan it was about 29%. In 2020 industrial businesses in Germany had a turnover of about 2 trillion €, with the car industry on top with 459 billion € (Orth, 2023).

That said, the fraction of industry as part of total gross value added is declining in Germany as in other leading industrialised economies (see figure 3).

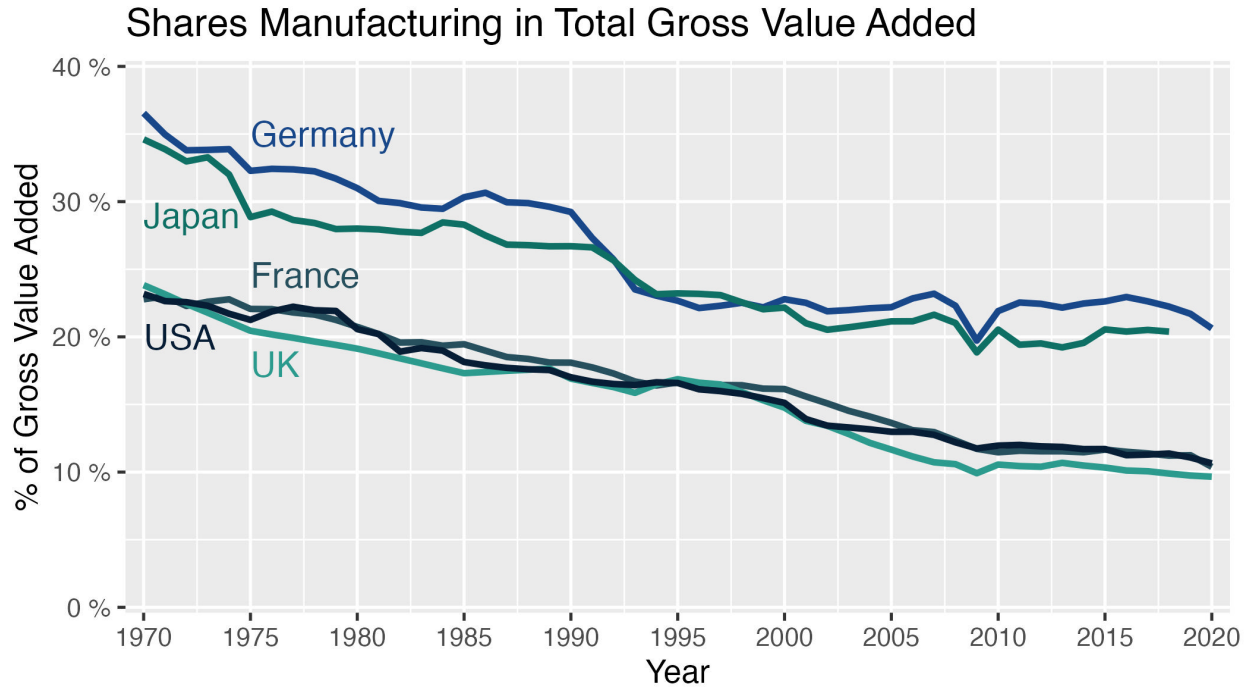


Figure 3: Shares Manufacturing in total gross value added, Germany and more, 1970-2020 (AMECO, 2023).

Recently, two connected global developments have drastically modified the perspective of a post-industrial society, leading to a new deindustrialisation challenge. The first development is the dynamic of global climate policy. The goals of reducing greenhouse gas emissions at great speed, advocated by the IPCC, implied by the Paris accords, formally declared by the European Union and by the German government, are pretty much unreachable with the global industrial system that has been established world wide over many generations. Implementing these goals may lead to a smooth transformation of core industrial structures of today’s world economy, but it may also lead to a dismantling of those structures without replacing them fast enough with large-scale climate friendly systems of industrial production. Among other things, this danger is highly relevant for global inequality, as experience has shown that industrial development is key for realistically reducing poverty and overall inequality (Kniivilä, 2007).

The second development is the increasing tension between the US and China. In the past decades, the US has imported more and more industrial products from China, thereby eroding important parts of the industrial base of the national economy. The Biden administration has expanded the protectionist intentions of Trump with large-scale measures, combined with policies

that shall restore the US industry as a global leader in green, digital, and military technologies. At the same time, the US is combining the goal of weakening the still very strong industrial base of the Chinese economy with protectionist intentions that are bound to weaken competition from the European industry, too.

China is reacting to this situation with measures of its own, combining massive government support for new industries with export limits on rare earths like Gallium and Germanium. These metals are critical for producing electric vehicles, microchips, and more; China in turn has a dominant position in rare earth supply.

Given Germany's formal commitment to the goal of carbon neutrality by 2045 and the outstanding importance of its car industry, new deindustrialisation dangers are a first rate challenge. The situation is especially delicate because the shift from fossil fuels to renewables is now happening in a situation of significant increases of energy costs on international markets. And it would be naive to think that the car industry, the jewel of German industry, will have an easy path to follow under these conditions.

Therefore, in section 2 we will look at different plausible futures for the German car industry. In section 3 we will discuss the deep contrast between the futures this industry is faced with and its amazing success story of the past. Carefully analysing the challenges and options the German car industry is confronted with requires innovative scientific concepts and methods. We will introduce them in section 4, building on the revolution in mathematical economics introduced by the outstanding mathematician and father of game theory, John von Neumann. We will pay special attention to the connection between the von Neumann approach and the widely used Input-Output methodology pioneered by Leontief. In the final section 5 we conclude by flagging opportunities and pitfalls one has to be aware of when trying to bring about a promising and successful transformation of the German car industry along with urban mobility way beyond Germany.

2 Three futures for the German car industry

In Germany, the political and socio-economic conditions relevant for the car industry have changed over the course of decades and more (see section 3), but since 2009 things are moving much faster. In that year the German government launched an economic stimulus plan to counteract the international financial crisis that started 2007 in the US and was later prolonged in Europe until 2013. The stimulus plan included measures to foster the transition from conventional cars to electric ones. Government and mass media considered this not only as a measure to overcome the economic crisis, but also as an essential pillar of German climate policy.

In the same year 2009, China - by far the greatest car market in the world - began handing out financial subsidies to companies producing so-called new energy vehicles companies. Already in 2001 China had decided in its five year plan to support a transition from traditional cars to new energy vehicles (NEVs).¹ NEVs could mitigate urban air pollution, reduce China's need for imported oil, and as a new business, help overcome the shock of the international financial crisis. In 2007 Wan Gang, an auto engineer who had worked in the German car industry for years, became China's minister of science and technology. He believed that the future belonged to NEVs, tested a Tesla Roadster in 2008, and prioritized NEV development as minister. Later on, China heavily supported the new Tesla Gigafactory in Shanghai, that started its production in 2019, in order to set up a learning ecosystem with fierce competition. In 2022, the Chinese carmaker BYD beat Tesla in global EV sales.

In 2009 Tesla got out of financial trouble thanks to several loans, including one from the Daimler AG worth 10% of the Tesla shares (that in 2022 became the Mercedes-Benz group). The year before, Tesla had presented its Roadster, the first electric sports car, that helped create the Tesla hype. In 2009, Tesla doubled down by announcing the Model S, to great acclaim by specialized media. Sales of Model S began only in 2012, but in 2010 Tesla went public with an offering worth \$ 226 million. On the day of the IPO, the stock closed 40% higher. Two decades later, the market capitalisation of Tesla was much bigger than that of GM, Ford, Volkswagen, Toyota, and Fiat Chrysler combined.

As a matter of fact, since 2009 the German car industry, mass media and the federal government

¹This included battery electric and hydrogen or e-fuel driven cars as well as hybrid cars combining an electric with an internal combustion engine. It is worth noting that China had started to replace internal combustion motorcycles with battery electric ones.

operate as allies in efforts to phase out cars driven by internal combustion engines and replace them with battery electric vehicles. Understandably, this goes hand in hand with a narrative according to which the German automotive industry will master this global transition unscathed, assuming a global leadership role in the production of battery-electric vehicles and thus also strengthening Germany's pioneering role in climate policy.²

Attractive as the future described by this narrative may be, it does not describe the one and only future for the German car industry. Even an alliance formed in Germany by at least the car industry, mass media, trade unions, and the federal government would not be a benevolent planner that could control the domestic car market. The decisions of dozens of millions of German citizens will influence demographic developments, car sales and car use as well as room for governmental manoeuvres. Even more relevant are the developments of international markets, because nowadays around 76% of all domestically produced German cars are exported (VDA, 2023).

At the moment, China's car fleet is huge and increasing, including hybrid and battery electric vehicles. At the same time, German car manufacturers are drastically losing market shares in China. Volkswagen is being dethroned as the best-selling car company by BYD - one of the biggest electric vehicle producers worldwide (White & Nilsson, 2023). How these dynamics will further unfold in the future is crucial for the German car industry. At the same time, the Biden administration is doubling down on the protectionist, but mostly rhetoric, measures of predecessor Trump as part of a new industrial policy strategy. The so-called Inflation Reduction Act, IRA, of August 2023, e.g., offers subsidies for a battery factory in the US with about \$600 - \$800 million, while similar incentives in Germany are in the order of €150 million.³

In this situation, the future of the German car industry depends to some extent on German individual or collective agents, but to an even larger extent on matching agents in the US, China, and other parts of the world - industries, governments, millions of individuals, etc. Last but not least, in times of climate change, pandemics, and needs for rare earths, even surprising developments of the planetary biophysical environment, will shape the German car industry's future.

²This narrative is an essential part of a more comprehensive one, where not only the car industry, but Germany as a whole will successfully tackle the transition towards a carbon neutral Germany in 2045. To what extent the arguments about the car industry presented in this paper have serious implications for Germany as a whole is a challenge for further research.

³See *Financial Times* (2023); the protectionist aspects of the IRA are mitigated by exemptions, e.g. facilitating import of European electric vehicles for leasing rather than sale.

This is not to say that the future is simply unforeseeable. Human societies often follow quite stable trajectories in several dimensions over generations. But from time to time they are confronted with conditions that lead to bifurcation points such that two and sometimes even more futures become possible. It may well be that world society has reached such a branching point at the beginning of the 21st century and that the car industry will go through years, perhaps decades, of turmoil until a new stable trajectory will have been established.

Hence, for attempting to shape the future of the German car industry - be it by government, trade unions, top managers, or other agents - it is necessary to prepare for different possibilities, one of which may be realized over the next few decades. For this purpose, a description of the space of possible futures with a few selected scenarios is needed. Thus, we start in sub-section 2.1 with a "pink" scenario based on the optimistic narrative in which the German car industry brilliantly masters the challenges of domestic and global decarbonisation. Sub-section 2.2 offers a wake-up call by outlining a "black" scenario of a shrinking industry, i.e. a deindustrialisation dynamics in the car sector. Beyond the first two scenarios, sub-section 2.3 adds a perspective of breakthrough innovations leading to a third possible scenario that may deserve the label "green".

For each scenario, we draw projections about the global and the German car stock and respectively a rough approximation of the potential car production. Especially for the production projections in Germany this can only be an approximation since it depends on both domestic and global demand for German cars.

These three scenarios try to cover the alternative possible outcomes for the car industry in the next decades. We follow the decision making processes of large and globally active firms, which try to establish robust decisions based on various possible scenarios. All of our scenarios depicted are based upon a literature review and assumptions about future mobility discussed in the scientific and political arena. It goes without saying that these three scenarios are not exact projections, but rather plausible future pathways connected with reasonable assumptions.

2.1 Pink Scenario: A world leader in battery electric vehicles

From the perspective of the car industry, a "pink" scenario means that the global car stock will increase substantially within the next three decades along a further growing trend. At the same time, this scenario also suggests full climate-neutrality worldwide around 2050 and thereby having

a fully decarbonized car stock. In Germany, the car stock follows a similar path and becomes climate-neutral by 2045 as envisaged by current law.⁴

A study by Shell and Prognos (2014) projects the global car stock to increase to around 2 billion in 2050 with a world population of 9.6 billion people. Our projection for the pink scenario is slightly above that threshold with a total of 2.25 billion cars in 2050. For the global economy to become climate-neutral in 2050, as enshrined in the Paris Agreement, the transportation sector and thereby the global car stock needs to become climate-neutral as well. This means that, from mid-century on, as long as the greenhouse gases emitted by cars are not neutralised by air capture, only battery electric vehicles and cars running on E-Fuels will be on the road.

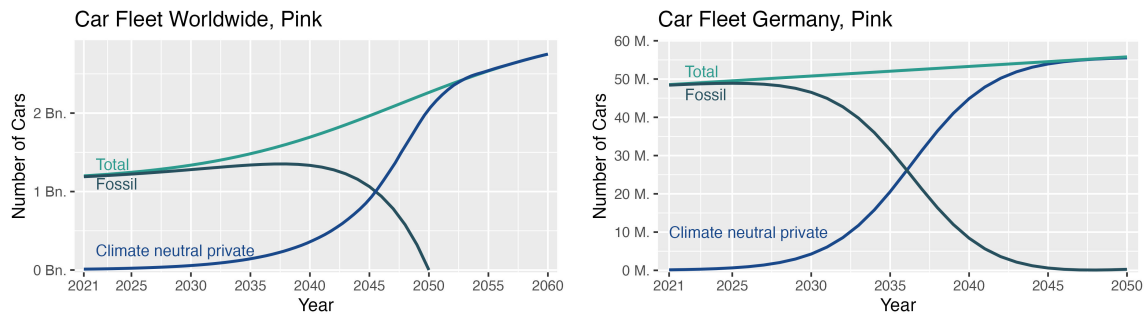


Figure 4: Car Fleet Pink Scenario

For Germany, we draw on the assumption of Ferdinand Dudenhöffer who expects the domestic car stock to increase to 55.8 million in 2050. This would entail a motorisation rate of 660 passenger cars per 1,000 people (Dudenhöffer, 2022). For comparison: In 2015, the motorisation rate in the US was already at 860 registered vehicles per 1,000 people (OICA, 2020). Similar to the global case, to reach the relevant climate goals by mid-century the German car stock needs to consist of carbon neutral cars only. We assume a logistic function for the carbon neutral vehicle stock, a reasonable pattern for the breakthrough of new technologies (Marchetti & Nakicenovic, 1978). At the same time, the stock of fossil fuel-powered vehicles must decline in a mirrored manner corresponding to the development of the total and electric vehicle stocks. In the pink scenario, the goal of the

⁴Optimistic as the pink scenario is from the German car industry’s point of view, there is a serious caveat from the perspective of climate policy. For the shift to electric vehicles to eliminate German greenhouse gas emissions, the electricity needed to drive and most importantly to produce these vehicles has to be fully generated by renewables and possibly nuclear technologies - whether generated domestically or imported from abroad. How fast Germany will reach that benchmark is less obvious than one would like. However, reaching the same benchmark at the global scale will most likely take considerably more time than in Germany.

German Federal Government to have 15 million electric vehicles on the road by 2030 is reached four years later (Bundesregierung, 2022).

To reach climate-neutrality by mid-century, it would be necessary to produce the last fossil-fueled vehicle around the year 2035, since the average durability of a car is assumed to be about 15 years (Held et al., 2021).⁵ For the same reason, all vehicles produced after 2035 must be climate neutral. Therefore, in Germany and globally the production of fossil-fueled cars needs to experience a strong decrease, whereas the production of electric vehicles must grow substantially. Thereby, climate neutral vehicles do not only replace fossil-fueled car production but overtake it by a significant margin in order to increase the overall production necessary to form a growing car stock.

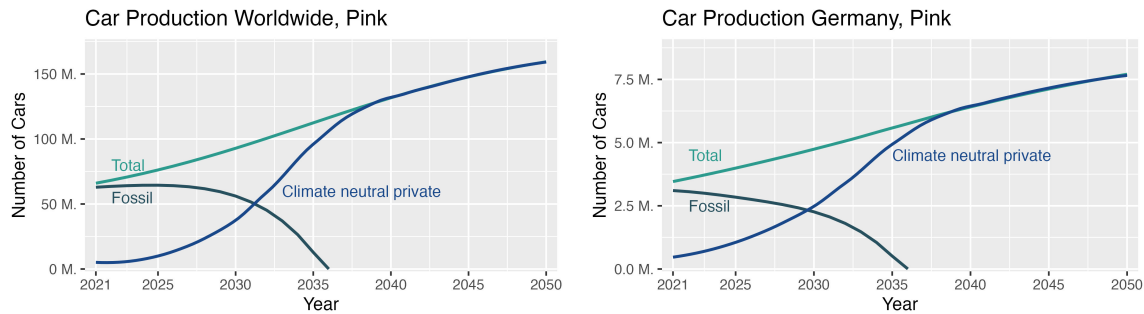


Figure 5: Car Production Pink Scenario

As already mentioned above, Germany is highly dependent on global car markets and their future development. Sustaining its market share on the global market will be very important for the German car industry, due to its high export share. In the pink scenario we assume the global market share of domestically produced cars to remain constant over the projection period, i.e. at 4% (a possible decline in China may be neutralized by increases in other emerging markets). Therefore, car production in Germany will develop analogously to the global one, reaching almost 7.5 million produced cars in Germany alone in 2050. This yields a rather optimistic scenario that constitutes an upper bound for reasonable future scenarios.

⁵The car lifespan can vary from country to country depending inter alia on imports and exports of used cars as explained in Held et al. (2021). We take the estimated lifespan of passenger cars in Germany as our proxy for overall car durability.

2.2 Black Scenario: A shrinking car industry

A "black" scenario projects a future where the global car stock does not increase as strongly as in the pink one. Moreover, the resulting global car stock will be climate-neutral only to a limited degree. Globally, the total car stock increases up to 1.5 billion vehicles in 2050, with an annual growth rate of around 0.8%. An analysis by Wood Mackenzie (2021) foresees the climate neutral (in Wood Mackenzie's paper just electric) vehicle stock to grow to 700 million in 2050 globally.⁶ as shown in figure 6. The black scenario takes into account that displacing a global car fleet based on internal combustion engines by one based on electric vehicles may well take several decades (Smil, 2006).⁷

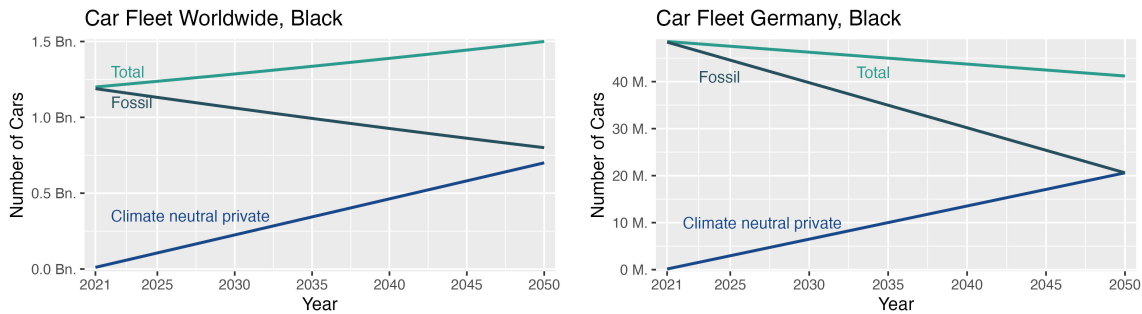


Figure 6: Car Fleet Black Scenario

Following the projection of car stocks globally and in Germany, the total production develops as follows. Unlike in the pink scenario, fossil-fuel based vehicles will still be produced in the first half of the century in the black scenario despite a declining trend. The production of climate neutral vehicles increases linearly and will be responsible for the majority of vehicle production by 2050. The global projections also affect German car production. Fossil-fuel based car production decreases continuously, while production of climate neutral (probably mostly electric) cars grows -

⁶Although the present trend, driven primarily by Tesla, goes in the direction of battery electric vehicles, some producers and authors consider as climate neutral not only battery electric vehicles, but also vehicles driven by efuels via fuel cells or hybrid combinations between batteries and efuels

⁷There are four major factors influencing the relevant time scales. First, the initial inventions and processes need constant refinement and intensifying until they can work reliably at affordable costs. Second, technological breakthroughs come with large-scale infrastructures that take time to design, build and refine. Third, neglected by Smil but documented in Hopkins' (1983) magisterial analysis of electrification in Western societies, mature breakthroughs result from many complex political, economic, and cultural structures that take more than a human generation to evolve. Last not least, from a climate policy point of view, global electrification of car traffic will require a global system of renewable energy generation, transport and storage - a system that will take decades to establish as well.

mainly due to global demand.

However, in contrast to the pink scenario, the market share of cars produced in Germany decreases to 2% in 2050. Thus, in the black scenario domestic manufacturers lose global market shares, which results in less car production by mid-century despite a growing (climate neutral) global car demand.

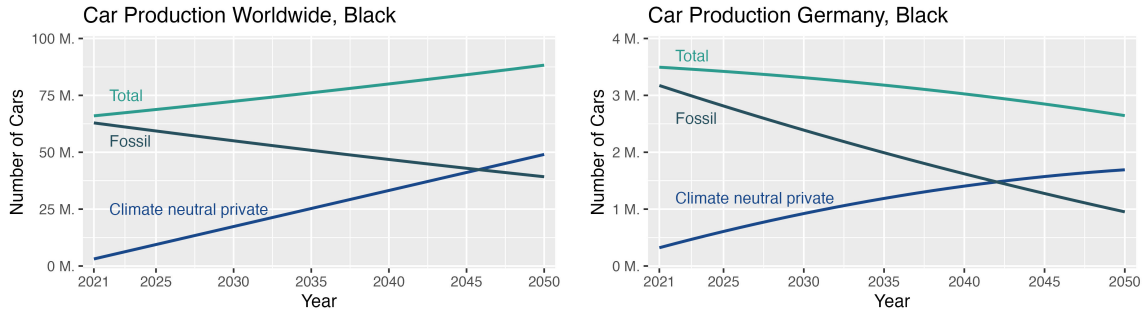


Figure 7: Car Production Black Scenario

2.3 Green Scenario: Reinventing individual mobility

In an important way, the pink and black futures are cut from the same cloth: they replace internal combustion (IC) cars with electric (or other climate neutral) vehicles, but they don't change the way private cars are used, nor the role of public transport. Traffic jams, some of them exasperating, continue to be part of day-to-day urban life; road accidents are normal; over 80% of US car sales continue to be trucks and SUVs; cars continue to massively add weight, especially electric cars with huge batteries; significant portions of public space are blocked by cars.

Against that background, a recent paper about "The Future of Mobility. Winners and Losers and New Options in the Public Space" by [Canzler & Knie \(2023\)](#) describes a remarkably different future: "Electrification of drive technology is one step toward the transition of transportation, but just as important is a drastically more efficient organization of transportation with fewer passenger cars and a significant shift to resource-efficient public transportation" ([Canzler & Knie, 2023](#)). They envisage a future combining technical advances like the possibilities of self-driving cars with the socio-cultural shift from "ownership" to "access".

These ideas lead to a scenario where private and public mobility are no more strictly separated, the former characterized by a big role for robotaxis, the latter by a key role for shuttles on demand,

both connected by markets for intermodal transport. We call it the "green" scenario.

As a result, the number of cars per capita is greatly reduced by innovative forms of shared mobility services, where urban regions, building on the experience of places like Copenhagen, may become climate friendly.

This kind of transition will happen faster in industrialized countries, where tech companies are more affine to the business models implied. In Germany, the commitment to climate policy may accelerate it even further.

Remarkably, "The BMW Group has been working on concepts for the future of urban spaces with selected cities for almost 30 years. These include the flagship cities of Los Angeles, Beijing, Rotterdam and Munich." (BMW, 2023). BMW has also avoided the bandwagon emphasizing only a fast and narrow transition from IC cars to battery electric vehicles (Andrusio, 2023). Presently, all major German car firms are investing in self-driving cars, although with a lag against the two leaders, i.e. Google's Waymo and GM's Cruise.

So far, the biggest challenge for efforts to turn self-driving cars from science fiction-style gadgets into normal vehicles is the problem of liability in case of accidents. Ugly and lengthy legal procedures might become normal, leading to severe public mistrust and opposition against this technology. A reliable way to create and nurture trust would be to request companies producing self-driving vehicles to become members of a specific association. The members of the association would be solidarily liable for accidents unless there is overwhelming evidence that an agent who does not belong to the association is clearly liable. This kind of regulation would drastically reduce accidents involving self-driving cars, because the companies involved will have the know-how needed to monitor each other in ways standard public authorities could not apply effectively.

With such a regulation, the probability of accidents caused by self-driving cars would be drastically smaller than the probability of accidents caused by human drivers. Without such an arrangement, however, a car company producing self-driving vehicles involved in frequent accidents would run into a moral abyss and eventual into bankruptcy. This suggests that trade unions might have a role to play in establishing solidarily liability in a green scenario.⁸

For Germany, the green scenario can be anchored in a study by the German Federal Environ-

⁸Developing and improving regulation for self-driving cars will become a major challenge in the decades to come. We are suggesting a starting point, many additional features will become relevant as well.

mental Agency (Umweltbundesamt, 2017), where the "City of tomorrow" is described as consisting of over 100,000 inhabitants with a motorization rate of 150 passenger vehicles per 1,000 people. For 2050, we stick to that ratio, with vehicles including robotaxis, rented cars, and a rather small fraction of privately owned cars. In the green scenario, in 2050 all these cars are climate neutral.⁹

Today, around 30% of Germany's population is living in big cities with over 100,000 inhabitants (Auswärtiges Amt, 2023). Following the population projection for various areas by the Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR), big cities (>100,000 people) will grow by about 3% until 2040 (BBSR, 2021). Continuing this trend linearly until 2050, around 28 million people are projected to live in big cities in Germany. This translates into a stock of cars in these cities of around 4.2 million in 2050 ("urban access" in figure 9).

However, with a projected total population of almost 84 million people in Germany in 2050¹⁰, around 56 million people will then live in areas with less than 100,000 people. In the countryside, today's public transportation system will be enriched by robotaxis, shuttles on demand and intermodal services (accessible through what will be the successor of today's internet), seamlessly connecting long, medium and short distance mobility. As population density is lower than in big cities, we assume a somewhat higher motorization rate of 200 vehicles per 1,000 people, resulting in 11.2 million climate neutral vehicles - including robotaxis, shuttles on demand, and a smaller set of privately owned cars.

With a domestic car fleet of 15.4 million vehicles and an average lifespan in the order of 15 years per car, domestic car production will fall to a level where the German car industry will either become a match for tech companies engaged in mobility services, or it will have a hard time to survive.

Of course, global demand for German cars may keep the industry going, but the green scenario comes with global challenges of its own.

⁹By carbon neutral here we mean that a car does not generate net greenhouse gas emissions, neither in its production nor in its subsequent use. We leave open whether this happens by using electricity generated by renewables (the most likely approach), by running internal combustion engines with E-fuels, again produced by renewables, by carbon capture and sequestration, or other techniques.

¹⁰This forecast assumes a modest birth rate, a modest increase of life expectancy, and of migration. For further details see Destatis (2021).

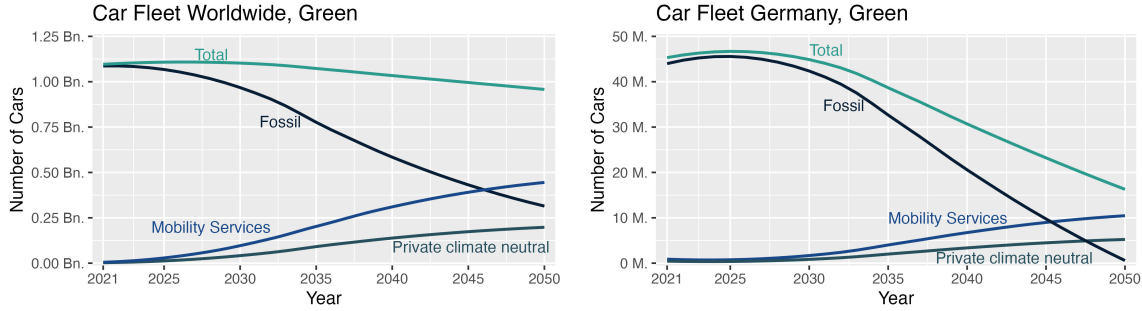


Figure 8: Car Fleet Green Scenario

For 2050, we reckon with a world population of about 10 billion, following the UN (2022) demographic outlook. Presently, the global car fleet counts about 1.2 billion vehicles. Since many decades, the car fleet has grown faster than world population. That growth will continue for at least a decade, after which in the green scenario the global car stock might decrease as a result of politically accelerated reductions of IC cars and of gradual shifts from ownership of private cars to access to shared mobility services.

These two reasons, however, will be more effective in the global North than in the global South. Presently, the US, EU, and Japan together make up about half the global car fleet. By 2050, in the green scenario they will reduce their fleet by half, i.e. by one quarter of today's global fleet. In the green scenario, therefore, the German car industry will be challenged by drastic reductions of demand from the global North for traditional passenger cars. The challenge then is to develop vehicles that will be used as robotaxis and shuttles on demand while implementing business models based on selling multimodal mobility as a service.

In the global South, implementing a comprehensive system of mobility as a service, moreover based on climate neutral cars, will hardly be feasible in the poorest, so-called least developed countries. Overcoming global inequality would help, but should not be taken for granted. Still, the overall population in least developed countries is about 1.1 billion and growing. In the green scenario, a passenger car fleet of 200 million will be there in 2050, with many used cars and only half climate neutral.

The countries labelled by the UN as developing (without "least developed") have an overall population of 5.5 billion (including China with 1.4 billion). According to the green scenario, climate neutral systems of mobility as a service will be established to some extent in urban regions. Still,

it would be unrealistic to reckon with less than 500 million privately owned passenger cars in developing countries. Setting up the charging structures for battery electric cars will take time, and the same holds for systems to generate and store electricity from renewables. As a result, in the green scenario developing countries will host a fleet of 500 million privately owned cars, 300 million of which will be climate neutral, the other 200 million not.

From the perspective of the German car industry, the global South will gain importance as a market for privately owned passenger cars. However, China, India and other countries will find ways to keep the fraction of German cars in their national vehicle fleets at bay. In other developing countries competition from Asia and other parts of the world (including Europe) will be fierce.

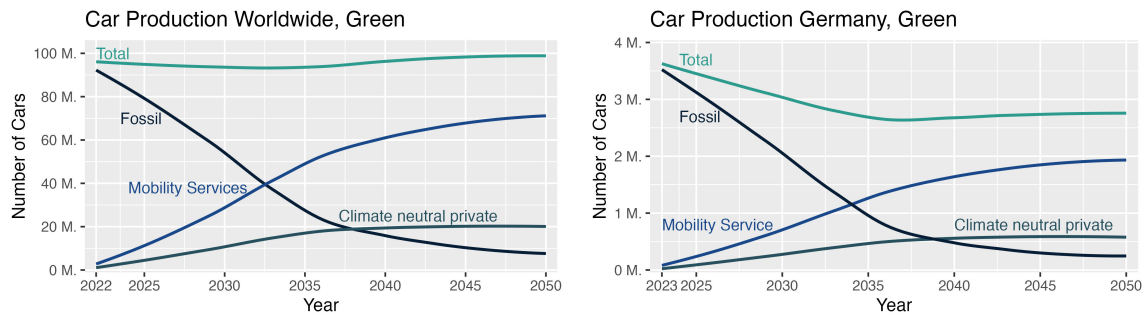


Figure 9: Car Production Green Scenario

The green scenario holds promise of great steps towards climate neutrality and increased quality of urban life, but it also comes with both challenges and opportunities for the German car industry.

Under these conditions, trade unions with roots in that industry are faced with a far-reaching bifurcation. There is a clear and present danger of losing power and relevance against the background of an industry in disarray. But there is also a growing chance of helping shape the economy and ways of life in the future. It is therefore noteworthy that the Canzler & Knie (2023) study was sponsored by the Geneva-based IndustriALL Global Union. The study includes a remarkable design for new roles of trade unions that foster both "good pay" and "quality of work", while creating "fairness of land use in the city", and "safeguarding the quality of urban life in the light of the climate crisis".

3 The coevolution of innovation system and car industry

3.1 How things started in Germany

The goal of decarbonization confronts the German car industry with a unique historical challenge. Ignoring the evolutionary dynamics that have led to the present challenge is a recipe for disaster. To understand the challenge, one needs to consider the development of the German innovation system since the formation of Germany as a nation state (Naudé & Nadler, 2021). In 1871, the Prussian-led North German confederation having won the Franco-Prussian war, it was enlarged so that imperial Germany could be founded as a unified nation in the hall of mirrors of the Palace of Versailles. The new state inherited two kinds of institutions: on the one hand, a whole ecosystem of universities together with a tradition of apprenticeship geared to the concept of vocation, or better "Beruf" - a concept closely related to the role of craftsmen who pass their skills to the next generation;¹¹ and on the other hand a network of industrial businesses supported by a central bank and a legal framework supporting joint-stock corporations.

In German society of the time, the three elements of science and education, the world of business, and the state formed what is known in today's literature on innovation systems as the 'triple helix' model of innovation and development (Galvao, 2019).

The list of radical innovations generated by the triple helix of imperial Germany is impressive - see Naudé & Nagler (2021) for a partial list. These innovations had and still have a huge practical impact on the society, to a large extent due to the connection between academic knowledge and the skills of craftsmen. This connection is evident in the biography of Gottlieb Daimler, born in 1834, who made an apprenticeship as gunsmith, worked in an engineering company, and studied mechanical engineering at Stuttgart Polytechnic Institute. He then worked in different factories, and in one of them became friends with the industrial designer Wilhelm Maybach. In 1883, Daimler and Maybach designed and built their first internal combustion engine and patented its ignition mechanism. In the same year, Carl Benz, a German engineer full of passion for engines and cars, founded the company Benz & Cie. Two years later Benz built his "Benz Patent Motorwagen", often considered as the first practically viable internal combustion automobile (Parissien, 2014). In

¹¹in German, the word "Beruf" is a normal element of everyday conversations, which the often found translation "calling" is not.

1885, Daimler and Maybach built their next internal combustion engine, suitable for motorcycles. Five years later, the two founded the Daimler Motoren Gesellschaft - precursor of the Daimler AG that in 2009 would save Tesla from financial trouble.

In the following decades, a boom of car start-ups set in in Germany. In the decade 1900 - 1910 there were about 100 German car companies. As usual with start-ups in a new domain, most of the pioneering firms disappeared. However, many brands of that period are still used today, e.g. Mercedes and Maybach (both brands being connected with Daimler in the course of time) as well as Porsche.

Ferdinand Porsche was a tremendously gifted Austrian engineer who never completed his studies, but later on got the title "Doktor Ingenieur Honoris Causa" from Vienna University of Technology. In 1901, at age 26 and working with the coach-producing Lohner company in Vienna, Porsche introduced the first hybrid car, combining an internal combustion engine with an electric one. Ferdinand Porsche wasn't the only one to see internal combustion engines as one alternative among others. Around 1900, in the US there were four competing modes of transportation on the roads (see table 1). Of these four modes the share of IC cars, 20%, ranked only third place behind steam cars and even further behind electric cars, only before horse driven vehicles.

Mode	Share
Steam	40%
Electric	30%
Combustion	20%
Horse	10%

Table 1: Modes of transportation on US roads around 1900 (Richardson, 2018).

3.2 Fordism and the triumph of the internal combustion engine

At the end of the 19th century, start ups producing cars mushroomed in many countries, but only a few survived (Renault in France and Fiat in Italy are amongst them). In the US there were many more than in Germany, and while most of them were wiped out, the Ford Motor Company, founded

in 1903 by Henry Ford, would not only survive, but change the world.

Ford started production with the so-called letter cars: model A (1903-1904), B (1904-1905), and so on with letters all the way up to S (1907-1908). The letter cars were produced and sold in small quantities only; of model A, barely 1750 units were produced. But by 1908, when the letter T was ready for the next model, Ford had understood that the car market would be enormous if a car was desirable and affordable for large parts of the US population.

To make it desirable, model T was designed carefully by a team of skilled engineers. To make it affordable, individual parts as well as workflows were standardised to the max in order to cut production costs. In 1913, this enabled Ford to drastically increase productivity by introducing the assembly line (an approach already used in the meat processing industry). Sales were roaring, and on January 1, 1914, Ford introduced the 5 Dollar day, doubling up on workers' salaries with a profit sharing plan. This intensified the extrinsic motivation of the workers who had to mechanically fulfill a stressful workflow dictated by the machinery of the assembly line. Moreover, model T became affordable for workers and the idea that increasing wages could lead to greater effective demand expanded from Keynes' theory to practical experience.

Eventually, model T sold 15 million units by 1927: the first mass-affordable automobile had been born. Mass production and mass consumption developed hand in hand. This was only possible with a growing infrastructure of roads, supported by government, and an expanding network of gas stations, dependent on the huge US oil industry.

The combination of mass production, mass consumption and infrastructure sustained by government is characteristic of a stage of capitalism known as Fordism. It came about in the US, but it would shape to a large extent the global industrial fabric - including Nazi Germany and Soviet Russia (Link, 2020).

With the emergence of Fordism, the internal combustion engine became the uncontested drive of passenger cars, and fossil fuels the default energy carrier for trucks, ships, and planes¹². In 1900 there were only 8.000 cars on US roads, but from 1910 on the US car fleet grew faster than the population for more than a century (see figure 10).

¹²So far, aviation fuels are fossil fuel based, be it for piston-engines or for jet engines

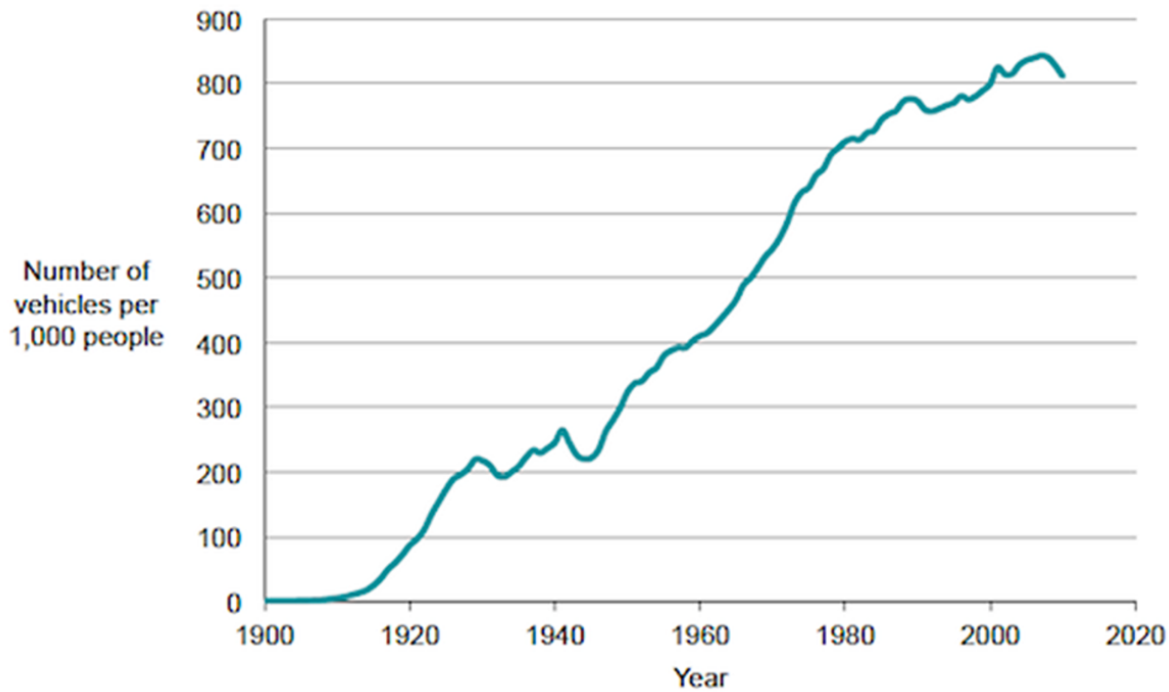


Figure 10: US cars per capita 1900-2010 (Davis et al., 2012).

3.2.1 The German car industry after Ford T

Things evolved very differently in Germany. At the beginning of the 20th century no mass-affordable car like Ford’s Model T triggered an explosive growth of the national car fleet; even less during World War I, when the German car fleet languished close to zero (see figure 11).

After World War I the economic situation for German car producers became increasingly difficult. Reacting to the challenge, Benz & Cie and Daimler Motoren Gesellschaft merged, becoming Daimler-Benz, two years later renamed Mercedes-Benz. In 1928, with BMW the next big player entered the German car market.¹³

One year later, Henry Ford established a car factory in Cologne, encouraged by Konrad Adenauer, then mayor of Cologne and a staunch opponent of the rising Nazis. In 1925, Hitler had published ”Mein Kampf”, where he approvingly mentioned Ford’s book ”The International Jew” of 1920. In 1934, Hitler decided to follow Ford’s Model T example and create the basis of a German

¹³Before that BMW was an aircraft producer with a side-business in farm equipment, household items and more.

"People's Car" (i.e. "Volkswagen"). Ferdinand Porsche was designed as the leader of the project. He went to Detroit to learn from Fordist America, developed the VW "Beetle" with a novel rear-engine design, and kept in mind that it should be at home in the German highway system, that was established two decades earlier than the American one. In 1937, Volkswagen was founded as a state owned company. World War II, however, blocked the sale and production of the new car. But after the war the VW Beetle became a legendary success in Germany and later on in the US, too.

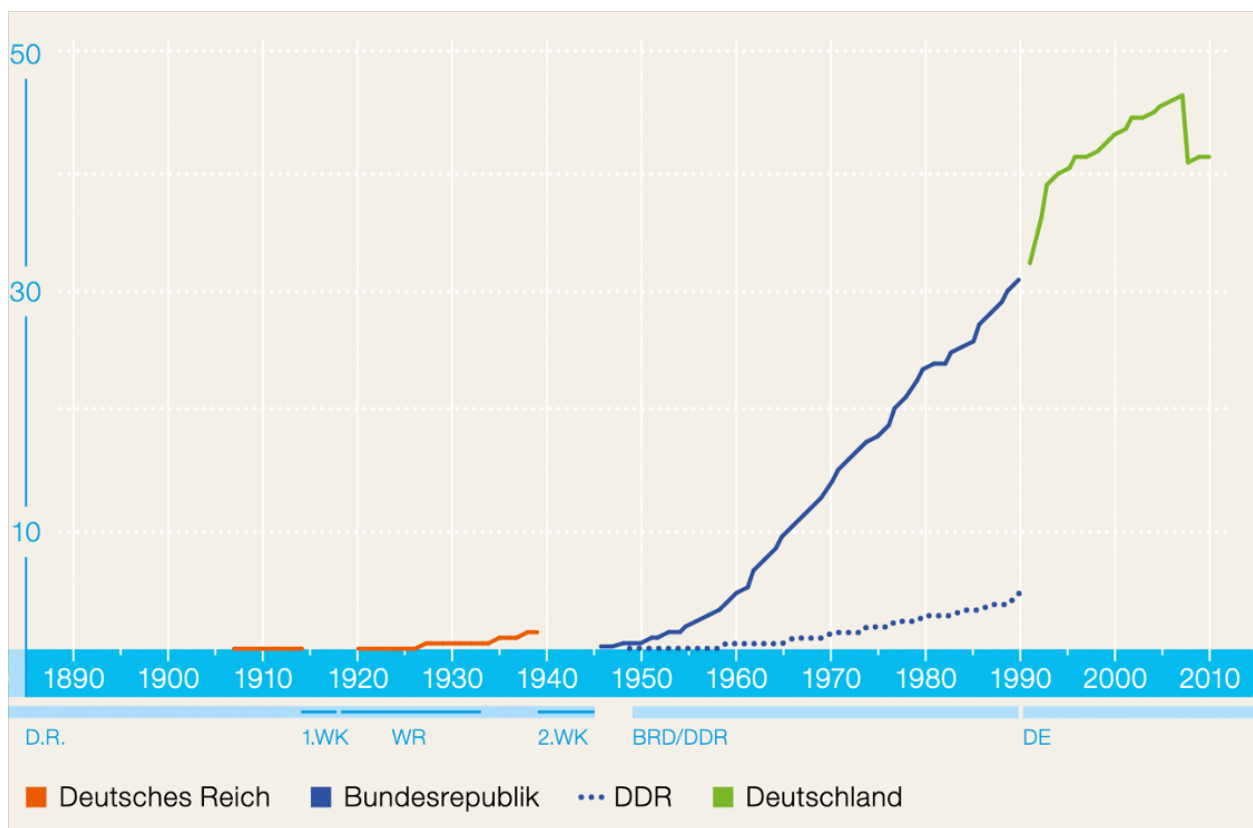


Figure 11: German car fleet 1900 - 2010 (Rahlf, 2015).

It seems plausible that the German innovation system lost its amazing capabilities because the Nazi police state destroyed academic freedom (Mroczkowski, 2014). However, one should not forget that in Nazi Germany Ferdinand Porsche developed the path-breaking Volkswagen Beetle, Konrad Zuse built the first programmable (and Turing complete) computer, Wernher von Braun developed the first long-range guided ballistic missile, Heisenberg identified the amount of U-235 necessary

to build an atomic bomb, C.F. von Weizsäcker submitted patents for plutonium bombs, Hans von Ohain developed the first turbojet aircraft, Manfred von Ardenne, who got hundreds of patented inventions, presented the first TV broadcast device in 1931, making it to the New York Times front page. It goes without saying that this list can easily be continued.

3.2.2 After WW II: specialising on incremental innovations

What really undermined the German innovation system was not the third Reich as such, but the defeat of Germany in World War II. This was the event that led to the "fall of Germany as a science and innovation leader of the early part of the twentieth century and its transformation from a breakthrough to an incremental innovator after 1945" (Mroczkowski, 2014). After the war, many of the best scientists of the world were no more in Germany; either because they had emigrated to the US or elsewhere, or because they had been murdered in the third Reich. Members of the scientific community who had survived and stayed in Germany now had a poor reputation - usually for good reasons - and thereby undermined that community. The link between academia and government was weakened, as was the one with business: the triple helix lost its effectiveness. It took a long time to rebuild a strong scientific community, and where this succeeded the social and cultural distance between academia and the system of vocational education increased drastically. This split in the education system destroyed the inventiveness and competence that earlier on characterised people like Gottlieb Daimler, Carl Benz, Ferdinand Porsche, Werner von Siemens and many others.

In the car industry, an exemplary case of incremental innovation after World War II was the re-activation of the Volkswagen Beetle that Ferdinand Porsche had audaciously developed in the 1930ies.¹⁴ After the war, the Volkswagen company was reconstructed, and in 1946 production and sales of slightly changed versions of the original beetle started. It lasted until 2003, and at that time was the best selling car in the world, with over 21 million units sold.

After the war Germany experienced what was called its economic miracle. Surprisingly, no German-made radical innovations were needed for this; the "miracle" happened on the basis of an innovation system narrowed down to incremental innovations. This led to a period with an exponential trend in car production and sales.¹⁵

¹⁴During the war, he designed and developed tanks and more for the Wehrmacht as well.

¹⁵The trend was blurred by fluctuations and shocks, in particular, a relatively slow growth period happened from 1960 to 1990, and was speeded up again in 1990 after the reunification of Germany.

From 1950 to the present, the German car industry as a whole was able to develop a first-class reputation worldwide, based primarily on the quality of its products together with the capability to improve them through continuous incremental innovations. These were fruits of the vocational skills and intrinsic motivation nurtured by the tradition of vocational education that Germany could build on since 1871. In the meantime, this tradition has been modified in many ways - not always for the better -, but from the end of World War II until today the vocational tradition is one of the most important pillars for the success of the German car industry as well as other industries, whether they concern chemistry, pharmaceuticals, machinery and plant production, domestic appliances, and more.

The lack of radical innovations combined with the strength of on-going incremental innovations can be illustrated with three historically significant examples:

- *High speed trains:* In 1964, with the opening of the Shinkansen line connecting Tokyo, Nagoya, and Osaka, Japan surprised the world with the first breakthrough innovation in high speed rail. The French government reacted quickly with plans for the TGV system, and in 1981 the TGV was running. The German government reacted to the Shinkansen within 27 years, too. Taking advantage and motivation from the Japanese and French experiences, Siemens AG (who had experimented with high speed trailcars in 1903) managed to develop and build world-class high-speed trains. In 1991, the German high-speed rail system was opened with the first regular scheduled InterCity Express (ICE).
- *Jet airliners:* In this domain, the key breakthrough innovation happened during and after World War II in the US, leading to the overwhelming dominance of Boeing, with models ranging from the 707 in 1954 to the 737 in 1967. In the latter year the governments of France, Germany, and the UK decided to change this situation by joining forces to develop what would become Airbus, leading to a global duopoly with Boeing. Remarkably, no comparable German aircraft manufacturer has developed. However, Lufthansa (whose precursor was terminated after the defeat of Germany in World War II) became a major player in global air traffic and a hub of the Star Alliance, the largest global airline alliance.
- *Microchips:* Around 1960, in the US different researchers and technicians with backgrounds in electrical engineering, physics, and mathematics found out how to use semiconductor ma-

terials to process digital information with the help of so-called microchips. Some of these inventors founded Intel, and a decade later a whole range of companies started industrial production of microchips. There is no doubt that this has changed the world we live in, and further developments are continuing to change it. In 1976 Siemens managed to establish a cooperation agreement with Intel, and since then incremental innovations in chip design and production became more and more an important need and capability of German industry. At the time of writing, the Federal Government is investing billions of Euros to lure Intel and others to start chip production in Germany, too.

3.3 The transformation of the German car industry: multi-activity dynamics

By 2005, the long-term growth trajectory of the German car industry had made it to one of the three key players among OECD countries on the global car market, along with Japan and the US. At that time, India was catching up with Japan while China had dwarfed all other national car industries on the planet after a catch-up race started in the 1980s.

From 2007 to 2009, however, the German car industry was hit by the global financial crisis. Increasing German VAT in 2007 didn't help the industry, nor did the proposal of a new low-carbon fuel standard by the European Commission. The climate debate became a huge challenge for the German car industry, as the idea of banning sales of combustion engine cars after 2035 gained increasing support (European Parliament, 2021). Although a related law was put on hold through German intervention, the question of the carbon emissions of the car sector remains an important issue in the public debate about decarbonisation.

The climate debate was soon connected with the digitalisation megatrend because of Tesla's amazing success both in terms of sales and of market capitalisation. The German car industry simply couldn't keep up. In the meantime, Chinese competitors - especially, but not only, BYD - became an additional threat.

Against that background, the idea that in 2050 there will still be a German car industry producing mostly internal combustion cars driven by gasoline and improved one way or other every few years via some incremental innovation seems like a fantasy. More realistic scenarios have been presented in section 2, "Three futures for the German car industry": the production activities that nowadays produce gasoline driven internal combustion cars will be scaled down. At what speed

this will happen will differ between the different scenarios, but cutting these production activities down to zero in ten or fifteen years might risk excluding the German car industry from significant markets in developing countries. However, in each scenario production activities that produce battery electric cars will be scaled up. At what speed this will happen will depend on other activities, ranging from battery production to renewable energy generation and to activities yielding storage capacities and energy transfer networks.

Last not least, activities producing different kinds of fixed capital are crucial, too. Nowhere is this more evident as in the different kinds of fixed capital used in the semiconductor industry and supplied by the companies of ASML and AMAT. On top of the difference between one equipment and another, the difference of equipment of a certain vintage matters as well.

Against this background, the beginning transformation of the German car industry must be analysed as multi-activity dynamics, where different activities will produce one or several products, including used equipment, and where different activities will be performed with different intensities (i.e. at different scales).

The canonical approach to model and analyse this kind of multi-activity dynamics goes back to John von Neumann, the mathematician known, among other things, as the father of modern game theory. Analysing and modeling the transformation of the German car industry as well as European and global industries needs the von Neumann approach to avoid misleading simplifications.

At the same time, using the von Neumann approach to monitor and foster the socio-ecological transformation of today's economies will lead to further developments of the approach, including extensions and modifications. Therefore, the next section offers an introduction to how the von Neumann's approach offers a model of general economic equilibrium and economic growth.

4 Prices, quantities, and changing production activities

4.1 The von Neumann revolution

In 1937, John von Neumann published "A Model of general Economic Equilibrium"¹⁶ in German language in "Results of mathematical colloquium" with the Viennese mathematician Karl Menger, son of the famous economist Carl Menger, and later in 1945 in an English translation as an article

¹⁶Translated english title

in the acclaimed Journal "The Review of Economic Studies" (Neumann, 1945). The article was the result of long ongoing research and inspiring interactions with other world class economists and mathematicians that von Neumann could meet during his travels around the world (Carvajalino, 2019). The model mentioned in the title, later also known as "Von Neumann Growth Model", should leave lasting impact on the economic profession and shape the way economists build their models to an extent that other economists like Morishima later described as "revolutionary" (Morishima, 1969). In contrast to the older approaches, Von Neumann's model proposed a way of extending economy modelling with a rigorous, but pragmatic axiomatisation, inspired by the challenge for Hilbert's formalist program that follows from the work of the mathematician Kurt Gödel (Gloria-Palermo, 2010).

The Von Neumann framework is built on the idea of defining a economy through the relationship between Inputs and Outputs. These are associated with different processes that are executed with a certain intensity and produce certain goods, which are sold at specific prices. It is important to emphasize that these sets of processes contain some processes that are currently used in production (having an intensity greater than 0) and also processes which would be possible theoretically but are no longer or not yet used at a certain point in time. Let n be the number of different possible processes that could be used in production and m the number of goods (including services) that can be produced using these processes, then the element $a_{i,j}$ of an Input Matrix A is the quantity of the j -th good that the process i utilises if operated with an intensity of 1.

Input Matrix:

$$A = \begin{pmatrix} a_{1,1} & \cdots & a_{1,m} \\ \vdots & a_{i,j} & \vdots \\ a_{n,1} & \cdots & a_{n,m} \end{pmatrix} \quad (1)$$

Every process utilises at least one of the goods in its production process, hence $a_{i,\cdot} > \vec{0}, \forall j = 1, 2, \dots, m$. Analogously an element $b_{i,j}$ of an Output Matrix B is the quantity of the j -th good that the process i produces if operated with an intensity of 1, with the assumption that each good is produced by at least one process, or $b_{\cdot,j} > \vec{0}, \forall i = 1, 2, \dots, n$.

Output Matrix:

$$B = \begin{pmatrix} b_{1,1} & \cdots & b_{1,m} \\ \vdots & b_{i,j} & \vdots \\ b_{n,1} & \cdots & b_{n,m} \end{pmatrix} \quad (2)$$

The Von Neumann approach makes it possible to analyse both the intensity vector x with the intensities of each process (the level at which a process is operated) and the price vector p with an individual price for each good p , separately from the Input and Output coefficients of the different possible processes.

Intensities x and prices p :

$$x = \begin{pmatrix} x_1 \\ \vdots \\ x_i \\ \vdots \\ x_n \end{pmatrix} \quad p = \begin{pmatrix} p_1 \\ \vdots \\ p_j \\ \vdots \\ p_m \end{pmatrix} \quad (3)$$

With this nomenclature we can describe the total usage of goods with $x'A$, the total production of goods as $x'B$ and the total cost of production as $x'Ap$.

Let at this point time be introduced as $t = 1, \dots, T$ so that e.g. x_t is the state of the intensity vector x with time index t . For a stable (or sustainable) growth path it is necessary that each product's total output of one time step is as least as large as the total input required in the following step, hence the equation $x'_t B \geq x'_{t+1} A$ has to be fulfilled. Von Neumann identified and studied a so called balanced growth in which all intensities grow with a constant factor $\alpha > 1$ at each time step, and was able to prove that for a given pair of Input and Output Matrices a solution for x and α exists under the given assumptions and with $x_{t+1} = x_t * \alpha$.¹⁷ The same applies to the dual problem of finding the balanced growth parameters hence the minimal uniform rate of profit β and the corresponding non-negative Eigenvector of prices p . Algorithms for finding the solutions (basically a series of generalized Eigenvalue problems) and the optimal values were later provided by Hamburger et al. (1967) and Bose & Bose (1972).

¹⁷Since von Neumann's discovery his assumptions have been extended and modified in important ways. We will touch this topic in the next section

Equation (4) represents the maximization of the technological rate of growth:

$$\begin{aligned} & \underset{\alpha}{\text{maximize}} && \alpha \\ & \text{subject to} && x'_t B \geq \alpha x'_t A \end{aligned} \tag{4}$$

The maximization of the rate of profit is depicted by equation (5):

$$\begin{aligned} & \underset{\beta}{\text{minimize}} && \beta \\ & \text{subject to} && Bp_t \geq \beta Ap_t \end{aligned} \tag{5}$$

If new processes are introduced or technological changes occur, reflected by a change of the input or output coefficients of the corresponding process, different optimal and balanced paths can result for the whole (new) system. This can lead to formerly used processes being no longer used and dormant processes being active.

4.2 Extensions and challenges for a model of shifting economies

The characteristics of the Von Neumann Model described in 4.1 are very suitable to model a technological shift, where once non existing or non competitive production processes replace existing ones that have been used in production up to this point. One can think here of historical changes like the replacement of typewriters with personal computers, or of the recent example that has been discussed in section 1, the shift from the combustion engine to an electrical one in the car sector.

Empirical data for a model of this type is challenging to get, as the most used publicly available data is regularly the Input-Output coefficients of a Leontief model, which convey monetary values, but no units or quantities used or produced on the one hand, and prices on the other hand, as handled in the von Neumann approach (Weil, 1967).

Furthermore there is a need for data on the individual prices of each good (or at least good basket) which are documented, if at all, very rarely and only for a small fraction of goods and will require some creative solutions.

Despite the hugely useful and integral characteristics of that structure for designing a model of technological innovations and shifts, the original unaltered structure lacks some integral parts. One

can think of the absence of demand (both public and private), labor, taxes, capital, money, credit, and trade. The integration of most of these augmentations has been discussed by researchers in the time after the publication of the original model. The challenge lies in developing extended models for specific problems.

Since it is one of the most natural augmentations as it stays the closest to the original Von Neumann structure, we introduce the capital of different age classes in the next section.

4.2.1 Example: Fixed capital

The Von Neumann growth model offers the possibility for a simple inclusion of capital goods with distinct age classes and their production processes. New capital goods can be produced by different processes. They differ in the technologies they are utilizing reflected by the input of capital goods from different age classes. Let C_{new} , C_1 and C_2 be capital goods of different age classes, where new indicates a recently produced capital good and 1 and 2 stand for goods with an age of one and two years respectively. Next, we introduce three processes that produce new, unused capital goods using (amongst other inputs) one of the three capital age classes as input. These do not necessarily represent different industries but can also reflect the different levels of productivity of the capital goods and the production process associated with these. Building on the basic von Neumann structure in section 4.1 we get a new Input Matrix A :

$$A = \begin{pmatrix} a_{goods,goods} & a_{goods,C_{new}} & a_{goods,C_1} & a_{goods,C_2} \\ a_{C_{new},goods} & a_{C_{new},C_{new}} & a_{C_{new},C_1} & a_{C_{new},C_2} \\ a_{C_1,goods} & a_{C_1,C_{new}} & a_{C_1,C_1} & a_{C_1,C_2} \\ a_{C_2,goods} & a_{C_2,C_{new}} & a_{C_2,C_1} & a_{C_2,C_2} \end{pmatrix} \quad (6)$$

Because of the inter-temporal definition of A and B (see section 4.1) any amount of new capital used as input for a process creates fixed capital that is one year older, as an output of the same amount. This has implications for the coefficients in the Output Matrix B . The input of a capital good $a_{.,C_t}$ has to be equal to the output of the capital good with an age index of $t + 1$, hence $a_{.,C_{t+1}}$ for all processes.

$$B = \begin{pmatrix} b_{goods,goods} & 0 & a_{goods,C_new} & a_{goods,C_1} \\ 0 & b_{C_new,C_new} & a_{C_new,C_new} & 0 \\ 0 & b_{C_1,C_new} & 0 & a_{C_1,C_1} \\ 0 & b_{C_2,C_new} & 0 & 0 \end{pmatrix} \quad (7)$$

This Input-Output pair already forms the base of a promising model architecture for a technological shift like the one taking place in the car industry.

Depending on the problem some augmentations may still be necessary (see section 4.2). Its feasible to include more different forms of fixed capital and hence make it possible to model the redistribution of the current capital stock structure, a process that is crucial to achieve a carbon neutral economy in the future and an important part of the recent deindustrialisation debate.

5 Silver bullet or robust action

There is a temptation to solve economic problems unfolding over time - like climate change or worrying demographic trends - by identifying the one and only optimal trajectory to reach the desired solution state, together with the policy measures that will get the economy on that trajectory. But this silver bullet approach rarely works. The economy we live in is a multi-stable system, that can be pushed or pulled from one trajectory to another by unforeseen and often unforeseeable events - like the invention of microchips around 1960, the 2007 financial crisis, the 2019 Covid pandemic, the Russia-Ukraine war, and more.

What is needed is not an illusory silver bullet but a strategy of robust action, that keeps enough degrees of freedom to be able to deal with surprising actions by other players, including nature.

Robust action doesn't mean "anything goes". With regard to climate change, increasing the intensity of activities producing carbon neutral cars will be needed to reduce the complex climate risks that are exacerbated by the global fleet of fossil fuel based internal combustion cars. This requires new machinery, new equipment, often new buildings, and more. Therefore, the intensities of other activities will increase, generating additional investment needs. These investments, however, must be identified in two ways: on the one hand as a basket of capital goods like robots, buildings, equipment, databases etc; on the other hand the monetary value of such a basket of capital goods.

Assessing the range of investment needs that may arise in the coming years and up to 2050 or even 2045 requires estimating the intensities of activities producing different kinds of fixed capital along with the prices of these items. This is best done by estimating the two matrices and vectors defined by the von Neumann approach. If investment needs are assessed poorly in the face of on-going climate policy, the German car industry will most likely shrink its overall production facilities and displace an increasing part of it out of Germany. Eventually it may well be faced with the black scenario introduced in section 2.

What is needed in Germany is a serious investment plan for the car sector and related activities, a plan not defined and imposed by the government but developed through a complex coevolution process involving the government, companies, trade unions, academia, and the financial sector.

If the resulting large-scale investments will be pursued on a German stand-alone basis, they will end up being too small and will be faced with massive political obstacles at the European level. To overcome these obstacles it may be useful and probably indispensable to follow the proposal by Draghi (2023), bringing about a fiscal union in the Eurozone, knowing that this will require a revision of EU treaties.

Along these lines, one could replicate for ground transportation the great European success of the Airbus. There, joining forces across key member states led to an extremely successful multinational aerospace corporation.

However things will unfold at the EU and Eurozone levels, in order to transform the German car industry into a leader of climate friendly ground transport, Germany will need to renew its innovation system so that it will again be able to generate both incremental and path-breaking innovations hand in hand.

Among the weaknesses of the German innovation system Naudé & Nagler (2021) list weaknesses in the education system. This may well be the most important task in order to achieve a sustainable future. On the one hand, it will require a creative overhaul of the present system of vocational education and a new continuity between vocational and academic education. Again, renewing the German education system cannot be successful as a government-led operation. Trade unions, employer associations, and different German "Länder" will have key roles to play. On the other hand, academia itself needs to rethink its role and responsibility in the Anthropocene (Renn, 2020). Transforming the German car industry is more than an effort to avoid deindustrialisation, it is a

vital contribution to a good life in the future for Germany and the world.

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