Infrastructures as Catalysts for Ecological Transformation

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Abstract: *In a globalized world, infrastructures act as catalysts for cultural progress and economic development as well as essential instruments for fighting climate change. However, it is essential to always take an ambivalent view of the technology used and to continuously question the need for infrastructural expansion. A particular challenge lies in the inherent characteristics of infrastructure projects, which emphasize the need for far-reaching future ethics. Infrastructure decisions typically involve lengthy planning phases, considerable financial expenditure and a wide range of environmental and social interventions, the long-term, unintended consequences of which are often not fully foreseeable. Political decision-makers can be guided by a variety of sustainability approaches in order to assess the resulting conflicts of objectives. However, the plurality of sustainability itself raises the question of how a necessary framework for action can be developed from a political perspective in order to resolve the dilemma of conflicting objectives. This plurality raises a guiding question: How can a policy and infrastructure governance framework for the ecological transformation of heavy goods road transport—exemplified by the eHighway system—reconcile ecological effectiveness, social justice, and economic efficiency under conditions of uncertainty and natural-monopoly characteristics? The following section uses the case study of the ecological transformation of heavy goods transport and the associated infrastructures to show which understandings of sustainability are suitable for promoting an ecological transformation of the transport sector and at the same time enabling inclusive mobility. A particular focus is on analyzing barriers to market entry, user accessibility and the importance of a resilient infrastructure in a networked world in the course of the ecological transformation. This analysis shows the central role of infrastructure as a key component for social, ecological and economic transformation processes and emphasizes the need for a holistic approach that integrates technical, cultural and social dimensions. The introduction of new infrastructures such as the eHighway system is associated with complex challenges that must be addressed*

through targeted measures and transparent communication. To ensure social justice, a fair distribution of costs and benefits as well as targeted support for smaller players and lower-income groups is essential. The development of resilient and sustainable infrastructures requires flexible, adaptive and open-technology approaches that ensure both short-term efficiency and long-term adaptability. In conclusion, it is clear that balanced regulation is necessary to enable innovation and at the same time ensure social and ecological objectives in the transformation process. The case analysis indicates that reconciliation is feasible through a balanced governance architecture that combines transparent communication, targeted distributive instruments to safeguard equity, adaptive regulation of natural-monopoly elements to ensure fair and efficient market development, and modular, technology-open design to enhance resilience.

1. Methodology

The methodology follows an integrated mixed-methods approach that systematically captures the entire technological value chain—from energy generation through transmission and storage to use in road freight transport—and triangulates quantitative governance analyses. Quantitatively, market structure in the subsystems of power generation, transmission and distribution grids, storage infrastructure, and stationary and dynamic charging infrastructure is represented using the Herfindahl-Hirschman Index, with market shares consolidated and interpreted from official and industry-specific secondary sources (e.g., BDEW, Federal Network Agency/Monopolies Commission, operator registries, industry statistics). The socio-economic impact analysis differentiates along a clear impact pathway between energy-affected persons, exposed persons, and disaster victims. It combines heuristic risk parameters from the literature on mortality and morbidity in energy and grid infrastructures, a meta-analytic evaluation of publicly documented BESS incidents (including the EPRI database) to derive normalized indicators per unit of energy or storage capacity, as well as model-based exposure estimates using population densities and near-source emission dispersion radii for typical plant configurations. Primary data come from the ELISA field trial (2018–2025): usage and availability data on dynamic charging and previously published work in the context of doctoral theses and scholarly journals. The statistical evaluation comprises descriptive analyses, correlation analyses, and multivariate procedures to identify perceived barriers to market entry; scales were harmonized and, where necessary, examined via sensitivity analysis.

2. Interdisciplinary understanding of infrastructures

In the course of scientific progress, the understanding of infrastructure has changed significantly and in many ways. Historically, the term was initially reduced to singularly networked technical structures that played a central role in the development of human civilization. The water supply infrastructure is one of the oldest and most essential forms created by early societies (BfG, 2023, 212). At the same time, transportation and energy supply infrastructures emerged, which together laid the foundation for the technology-centric perspective on infrastructure (Thacker et al., 2019, 251–252). For a long time, this technology-induced view shaped the general understanding of the term, which is still closely associated with physical structures such as roads, power grids and bridges. However, these physical infrastructures only represent a subset of the broader concept of infrastructure.

Since the industrial revolution, the technical conditions of physical infrastructures have changed fundamentally. Energy infrastructures, which had their origins in the simple supply of wood to small groups of people, have developed over the course of history into highly complex systems that today supply cities with millions of inhabitants via widely ramified electricity and gas networks (Bridge et al., 2018, 1–7). A comparable transformation process can also be observed in the transportation infrastructure. Paths and roads originally constructed from simple materials, which primarily served regional trade and logistical mobility, now form the basis of global supply chains that span the entire planet (David Daniels and Sonia Yeh, 2022, 1–2). These developments are complemented by modern phenomena such as mass mobility and advancing digitalization, which open up new dimensions of infrastructure and networking.

The availability of mobility services and energy supply is considered a central factor for social development in numerous system theories and guidelines (Wang et al., 2025, 49–51; Sovacool et al., 2021, 218–222). A prominent example of this is the Kardashov scale, which classifies civilizations according to their energy consumption. It postulates that societies with higher energy availability are able to develop more advanced technologies and establish more complex social structures (Nikolai S. Kardashev, 1964, 217–221). This close link between energy, technology and social development is also reflected in the global sustainability goals. For example, the United Nations Sustainable Development Goal (SDG) 8 entitled “Decent Work and Economic Growth” refers to the reciprocal relationship between economic progress and social transformation, whereby sustainable infrastructures are considered an essential basis for both areas from the perspective of the SDG (United Nations General Assembly, 2015). However, technological developments and population growth are leading to increasing consumption of planetary resources.

In addition to physical infrastructures, social infrastructures occupy central areas of human life. System theories such as those of Urry (2012) or Simmel (1997) see infrastructures and mobility in their centrality not as a direct physical connection between two places, but as a complex system in between (Urry, 2012, 47–48; Simmel, 1997, 171; O'Neill et al., 2018, 88–95). Social infrastructures define the space for social interactions and emphasize their multidimensional relevance, from the microcosm to the macrocosm of human life. Social infrastructures are therefore essential components of a functioning society and help to ensure that people can participate in social life regardless of their economic situation or physical location. Modern approaches to the conceptualization of infrastructure question the historically evolved, primarily economic perspective on infrastructure and view it as discursively constructed, i.e. as the result of specific social, political and cultural negotiation processes. In this context, an expanded understanding of mobility and infrastructure is suggested that goes beyond purely economic interests and includes social, ecological and cultural dimensions. The so-called "new mobility paradigm", for example, emphasizes that mobility is not only to be understood as the physical movement of people and goods, but as a complex network of social practices, technologies and infrastructures that reflects and influences social inequalities and power relations (Urry, 2012, 20–32).

Similarly, the Economy for the Common Good (exemplified by Felber (2015)) focuses on infrastructures as central elements of a sustainable and common good-oriented society, in which the provision and use of infrastructures does not primarily follow market logic, but serves the goal of promoting social justice, ecological sustainability and collective well-being (Felber, 2015). Arne Næss (1986), for example, addresses the oldest and at the same time most fundamental form of infrastructure, namely natural, ecological systems, whose inherent value and central importance for human life and social development have long been underestimated or even ignored. In his deep ecology perspective, Næss emphasizes that ecological systems not only serve as a resource base for economic activities, but must be seen as independent, complex networks that enable and sustain life on earth (Næss, 1986, 1–3).

This holistic understanding of infrastructure calls for a shift away from sectoral approaches towards a systemic perspective that focuses on the interactions between ecological, social and economic dimensions. As part of an expanded understanding of infrastructure, it is increasingly recognized that ecological, social and economic infrastructures are closely intertwined and interdependent.

3. Objectives and questions of the work

The infrastructures described above have a profound and multi-layered impact on human life. In particular, rapid technological development, coupled with continuous population growth, is leading to more intensive use of physical infrastructures. One result of this is the increasing consumption of natural resources, which in turn has far-reaching and often irreversible effects on global ecosystems (Wang et al., 2022, 1–15). At the same time, access to infrastructure is essential, as it forms the basis not only for social participation, but also for economic development and individual fulfillment (Thacker et al., 2019, 113–119). Against this backdrop, the key question is how infrastructures can be made more sustainable without jeopardizing inclusivity and accessibility for all social groups.

In order to shed light on this issue, a case study from the mobility sector is used below, namely road-based catenary line technology. This example is used to analyze the challenges and ambivalences associated with the introduction of a technological innovation. In particular, the barriers to market entry and consequences for third parties are examined in order to develop a comprehensive understanding of the dynamics that occur when new technologies are implemented in infrastructures. The methodology of this study is based on an integrative and systemic approach. Not only the primary infrastructures, but also downstream and supporting systems are included in the analysis. The first step is a quantitative assessment of the market structure in order to identify the intensity of competition and potential monopoly positions.

A particular focus is on identifying the causal link between specific socio-political instruments—for example liberalization measures such as unbundling, regulated third-party access, and retail competition—and market density and structure. For this purpose, the Herfindahl-Hirschman Index (HHI) is calculated, which serves as an established indicator for measuring market concentration. The analysis covers several key areas: the energy generation infrastructure, the electricity grid infrastructure, the storage infrastructure and the dynamic charging infrastructure. This comprehensive view makes it possible to capture the interactions between the various infrastructure levels and to identify potential social inequalities and initial user accessibility restrictions.

The next step is a detailed evaluation of which groups of people could potentially be disadvantaged by the introduction or transformation of infrastructures. The analysis is carried out along the entire impact chain in order to comprehensively identify the effects. The focus is on two central groups in particular: exposed persons, potential disaster victims and those affected in terms of energy. Exposed persons are those who are exposed to an increased risk due to their professional, social or geographical position, for example due to direct dependence on certain infrastructures or proximity to critical energy facilities. Energetically affected persons, on the other hand, are those whose quality of life, economic situation or social participation is significantly influenced by changes in the infrastructure chain, such as rising energy costs or restricted access to energy. Disaster victims, meaning fatalities and injured persons, who are particularly vulnerable due to extreme events such as technical incidents are also taken into account. The analysis of these groups is differentiated and serves to evaluate the distribution effects and identify possible social inequalities or disadvantages.

Based on this, a detailed analysis of the accessibility and availability of the infrastructure components under consideration is carried out, based on the results previously obtained from the case study. The aim of this evaluation is to systematically examine the possible uses for both market participants and end customers. In particular, it looks at the conditions under which the various facilities and technologies are accessible, what restrictions exist, and what external factors influence their use. The methodology of this study is based on a combination of qualitative and quantitative analysis. First, the infrastructural and regulatory framework conditions that determine access to the systems are identified. In addition, a usage analysis is carried out based on empirical data from the ELISA[1] field trial. This data includes the availability of connection options and the cost structures associated with usage. A particular focus is placed on identifying barriers that could restrict accessibility. These include technical

1 The ELISA project (2018–2025) tests the real-world use of hybrid and electric trucks powered by catenary lines on a pilot section of the German A5 motorway, aiming to demonstrate technical feasibility and gather data for future electrified freight transport concept (Hein, Knezevic et al. 2023, 57).

hurdles, such as compatibility with existing systems, and socio-economic factors, such as the financial resilience of end customers. In addition, the study examines the extent to which external conditions, such as regional energy infrastructure or the availability of resources, influence usage possibilities.

The systematic investigation of these obstacles makes it possible to identify key challenges and develop targeted solutions that can promote use of the technology.

4. Technology portfolio for road-based catenary line technology

In the political and social discourse on sustainable development, there are a variety of solutions and technological alternatives for mitigating the long-term effects of harmful greenhouse gases on the climate. Technological developments in the transport sector are also ambivalent. On the one hand, they cause problems, but on the other hand, without them, it is often impossible to solve problems. Over time, some technological developments have helped to conserve natural resources. Significant sections of politics, business, and research attest to the promising potential of electrifying roads using catenary lines for the sustainable development of the transport sector (Prof. Dr.-Ing. Manfred Boltze et al., 2022, 2–15) (Hein, Petermann et al., 2023). However, this raises the question of which elements of sustainability and which sustainability approaches should be used for evaluation.

The technological basis for the functioning of road-based catenary lines, also known as dynamic charging, is based on adapted pantograph technology, which was originally developed for trams and trolleybuses and is still used by them (Hein and Wauri, 2024, 8–11). The principle of dynamic charging is based on supplying energy to electrically powered trucks via a catenary above the right lane of a highway. The catenary line system to be installed can be integrated into the existing road infrastructure without major intervention (Hein and Wauri, 2024, 14–17). In addition to an electric motor (and combustion engine), the purely electric (or hybrid) vehicles are equipped with an energy storage device and a pantograph (Hein and Wauri, 2024, 8–11). This enables electrical energy to be transferred from the catenary line system to the vehicle's electric drive system. The trucks can connect to and disconnect from the catenary line at any speed, which ensures the usual driving flexibility. Overtaking maneuvers are therefore still possible without any problems (Prof. Dr.-Ing. Manfred Boltze et al., 2022, 2–15).

Figure 1: BEV+PAN during the charging process.

Source: (Own illustration)

As can be seen in Figure 1, dynamic charging uses a pantograph integrated into the driver's cab (marked in blue) to draw power from the catenary line (marked in orange). With the current state of technology, the batteries of catenary line trucks are charged with a voltage of 600 volts (V) to 750 V and an electric current of 1000 amps (A) while traveling along the route This means that both the traction current and the charging current are provided by the catenary line technology within a section of the route.

Due to the size of the battery installed in the "Battery Electric Vehicle + Pantograph" (BEV+PAN), a continuous route network is not necessary. Additionally, the battery can be smaller than if only traction current were available, which in turn saves resources. The battery capacity enables the last few kilometers on the federal highway and cyclical gaps on the highway to be bridged. System sections of 10–15 km in length are recommended (ibid.).

Battery capacities currently vary depending on the vehicle generation. The first vehicles were still plug-in hybrids and had a battery capacity of 90 kWh. The latest purely electric BEV+PAN have a battery capacity of 300 kWh (ibid.).

The SDGs currently serve as a central framework for the development of political strategies, development plans, and legislation to promote sustainable development globally. Taking these goals into account, key aspects of inclusive mobility can already be identified. In particular, free access to highways, in principle, enables all persons with vehicles that have the necessary technical resources to use these infrastructures. This is in line with the goal of reducing inequalities and ensuring access to basic services for all, as formulated in SDG 10 "Reduced Inequalities" (United Nations General Assembly, 2015; LfU, 2020, 10). In this context, the first step is to examine the extent to which free market and user accessibility is guaranteed in the areas of sustainable mobility use in the form of dynamic charging. This includes energy generation, energy transport, catenary line infrastructure, and the use of dynamic charging infrastructure.

5. Economic perspectives on infrastructure-driven progress and change

The HHI is a measure of market concentration and is often used to analyze the intensity of competition in a market. A high HHI value indicates a high degree of market concentration, with a few companies dominating the market, while a low HHI value indicates a highly competitive market with many evenly distributed players (Palan, 2015, 10–14). Low competitive intensity suggests significant barriers to market entry, which should be removed in the context of inclusive use.

On the one hand, the centralization of market conditions among a few participants enables economic focus, as exemplified by the railway sector in the 1990s (Esposito et al., 2017). By focusing on increasing efficiency and optimizing costs, companies can increase their economic performance and strengthen their market position. On the other hand, however, this development often leads to social injustices, such as the introduction of a three-class system that treats different customer groups unequally and makes access to mobility more difficult for lower-income groups (Urry, 2012, 90–112). Such inequalities undermine the goal of an inclusive infrastructure that should be accessible to all people, regardless of their social or financial situation. Furthermore, such measures can jeopardize the long-term social acceptance of centralized infrastructures and contradict a sustainable and fair infrastructure solution that takes equal account of ecological, social, and economic aspects. Infrastructure should not be evaluated solely from an economic perspective and labeled a "natural monopoly," but should also take into account environmental impacts and social relevance.

In the context of sustainable energy production, for example through wind and photovoltaic systems, the HHI can help to evaluate the market structure and identify possible monopoly or oligopoly positions. In order to calculate the HHI, the market shares of the individual companies or players in energy production are required. The HHI is calculated by squaring the market shares (s) of all players (N) and then summing them.

The formula is as follows:

Equation 1: Calculation of HHI (Herfindahl 1950; Hirschman 1945)

$$HHI = \sum_{i=1}^{N} s_i^2$$

There are currently 1,331 electricity suppliers in Germany, with four large companies accounting for 50% of the market share. For the purposes of the calculation, it is assumed that the remaining 50% of the market is distributed evenly among the other 1,327 suppliers. As shown in Equation 2, the HHI for energy supply for the year 2024 (HHI_{EV2024}) is 626.87 (BDEW 2024). This value indicates low market concentration, as it is well below the threshold of 1,500, which is generally used as an indicator of moderate concentration.

Equation 2: Calculation of HHI for energy suppliers 2024 (own calculation, data from (BDEW 2024))

$$HHI_{EV2024} = 4 \cdot (12.5)^2 + 1{,}331 \cdot (0.0378)^2 \approx 626.87$$

A low HHI indicates that the market is highly competitive and that no single player has excessive dominance (Brezina et al., 2016, 49–72). Despite the strong position of the four major suppliers, which together control half of the market, the large number of smaller players ensures market diversification and maintains competition. This suggests that although the German electricity market is dominated by a few large companies, there is still room for smaller suppliers, whose market presence increases the intensity of competition. This suggests moderate barriers to competition, which do not completely prevent new providers from entering the market, but nevertheless pose certain challenges. Currently, the high complexity of energy industry processes and the highly dynamic purchasing market are worth mentioning here.

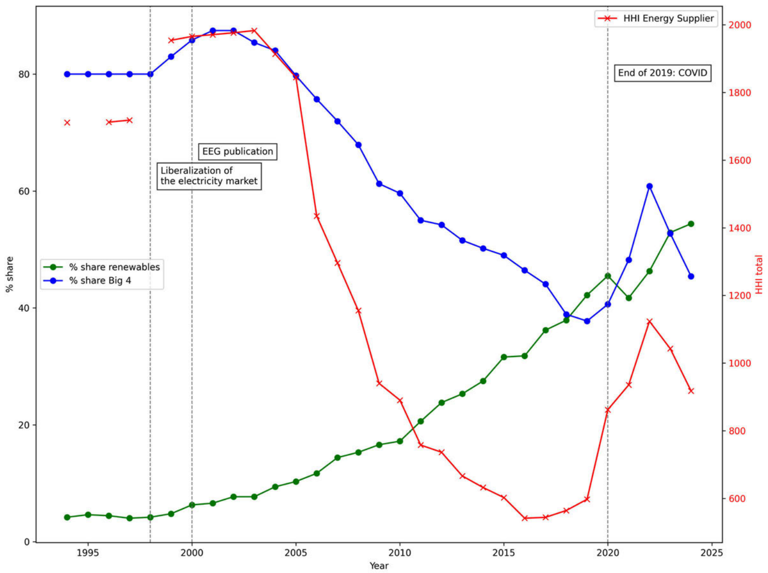
As shown in Figure 2, two key factors can be identified that explain the declining HHI and the associated increase in competitive intensity in the energy market. The opening of the electricity market in Germany, which began in the 1990s, was intended to lead to fairer competition. However, the market effect was the opposite. Deregulation significantly lowered the barriers to market entry for new providers, enabling small and medium-sized enterprises to enter the market. The economic dominance of the four major providers initially led to an increase in market density, as can be seen in Figure 2. It was only in the following years that the number of market participants and their associated market share increased. The diversity of supply and the pace of innovation in the energy sector were strengthened, and consumers benefited from a wider choice of electricity tariffs, while competition forced providers to operate more efficiently and in a more customer-oriented manner.

The structure of the energy market has undergone fundamental change due to the increasing relevance of decentralized energy supply. Technological advances, particularly in the field of renewable energies such as photovoltaics and wind power, now make it possible to generate electricity locally and individually. This has significantly reduced traditional economic barriers to market entry, such as the high capital requirements for the construction of large coal or gas-fired power plants. This development has paved the way for smaller providers and even private individuals to actively participate in the energy market, for example by operating solar panels or small wind turbines. At the same time, decentralized energy supply enables greater regional value creation and contributes to the resilience of the energy system.

The HHI for energy production currently stands at 626.87, a significant reduction compared to the 1990s, when it was still above 1,000. This development is primarily attributable to the expansion of renewable energies and the gradual liberalization of the energy market. In particular, the decentralization of energy production has led to a noticeable reduction in market concentration. This transformation has not only increased the intensity of competition, but has also brought ecological and social benefits by promoting sustainable energy sources, strengthening the diversity of market players, and facilitating access to energy for various social groups.

In addition to energy generation, market concentration and the resulting barriers to market entry for energy infrastructure must be examined. A distinction is made here between transmission system operators and distribution system operators.

Figure 2: HHI vs. market share of the big 4 and renewables. (Own representation)



Source: see Appendix 1 for data sources

A transmission system operator (TSO) is responsible for the operation, maintenance, and expansion of interregional and transnational high-voltage and extra-high-voltage grids. These grids transport electrical energy over long distances and connect large generation facilities, such as power plants or offshore wind farms, to regional distribution grids. There are four transmission system operators in Germany: 50Hertz, Amprion, TenneT, and TransnetBW (Tripathi and Mackensen, 2017). They play a central role in ensuring grid stability and the integration of renewable energies.

A distribution system operator (DSO), on the other hand, operates the regional and local power grids that transmit energy from the transmission grid to end consumers, such as households, businesses, and public institutions. These grids operate at medium and low voltage levels and are responsible for the granular distribution of energy. Distribution system operators are often municipal companies or public utilities and ensure that electricity reaches consumers reliably and in the quantities required. There are currently 866 distribution system operators (Bundesnetzagentur 2025).

Equation 3: Calculation of HHI for TSOs (own calculation, data from (Statista GmbH)

$$HHI_{TSO2024} = (0{,}3636)^2 + (0{,}2740)^2 + (0{,}2118)^2 + (0{,}1507)^2 \approx 2{,}749.05$$

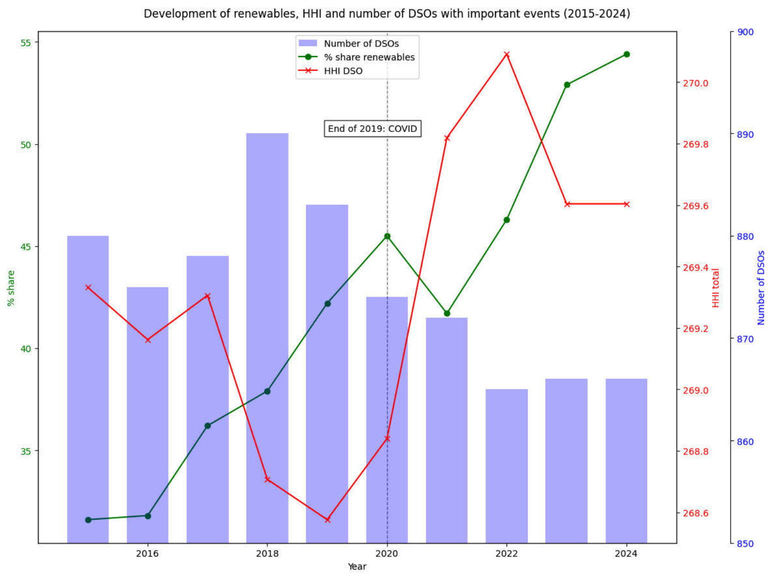
The current market shares of the transmission system operators, based on revenue, are as follows: Amprion: 36.36%, TenneT: 27.40%, 50Hertz: 21.18%, and TransnetBW: 15.07%. This gives a HHI of 2.749,05 (Statista GmbH). A HHI of 2,749.05indicates a high degree of market concentration. This is not surprising, as the market for transmission grids in Germany is dominated by just four major players, with TenneT holding the largest share at over 50%. The high concentration is typical for natural monopolies such as transmission grids, as the operation of such infrastructure is severely limited due to significant investment costs and regulatory requirements. Projects such as the north-south routes preserve the existing market density, as their technical and logistical complexity and the financial and regulatory hurdles maintain barriers to market entry. These secure the dominance of the established transmission system operators and underscore the market's characteristic as a natural monopoly with structurally limited competition.

In contrast, the distribution network market, with an HHI of 269.6 indicates lower market concentration in 2024. This underscores the highly fragmented structure of the German distribution network market, which is characterized by a large number of players, including numerous municipal and regional network operators. Although some larger distribution network operators such as Westnetz (13,6%), Bayernwerk (12,1%), Netze BW (7,6%), Avacon (6,6 %), E.DIS (6,2%), Mitnetz Strom (3,3%), Stromnetz Berlin (2,8%), LEW-Verteilnetz (2,7%), Hamburg Netz (2,3%) and Süwag Netz (2,3%) have significant market shares, the market as a whole remains highly fragmented, as many smaller operators (e.g., municipal utilities) also play an important role (Westnetz GmbH, 2025) (Netze BW GmbH, 2025) (E.DIS Netz GmbH, 2025) (Bayernwerk Netz GmbH, 2025) (Avacon Netz GmbH, 2025) (Süwag Energie AG, 2025) (Stromnetz Berlin GmbH, 2025) (Hamburger Energienetze GmbH, 2025) (LEW Verteilnetz GmbH, 2025) (Mitteldeutsche Netzgesellschaft Strom GmbH, 2025) (Bundesnetzargentur | Bundeskartellamt, 28.02.2025, 109). In contrast to the infrastructure level of energy generation, the increasing costs associated with the expansion of renewable energies at the distribution network level are leading to increasing market concentration, as can be seen in Figure 3.

The energy transition is primarily taking place at the low-voltage level, as this is where photovoltaic systems and new consumers such as heat pumps and electric vehicles are connected (Hein, C. R., Lerchl-Mitsch, K., Petermann, D., Simon, L. et al., 2024, 51). The high investment costs for the necessary digitization of the grids and compliance with environmental requirements pose considerable economic challenges, particularly for smaller distribution system operators, which often leads to their takeover by larger market players (Hein, C. R., Lerchl-Mitsch, K., Petermann, D., Simon, L. et al., 2024, 51). The HHI is 2,749 at the TSO network level, while it is 269.6 for DSOs. The increasing expansion of controllable consumers and generators, such as wall boxes, heat pumps, and photovoltaic systems, poses considerable technical and organizational challenges for distribution system operators. However, an unintended consequence of this development is increasing market concentration at the distribution grid level, as the complexity of grid control and infrastructure requirements increasingly disadvantage smaller players.

The increased use of renewable energies and the transformation in the mobility sector are giving rise to supporting sub-infrastructures. The storage infrastructure and charging infrastructure must be considered central here. Energy storage systems form the essential core for effectively compensating for and stabilizing the volatility of electricity generation from renewable energy sources such as wind and solar energy (e-netz Südhessen AG, 2024, 110). Due to the close link with energy generation, it can be assumed that market concentration in the battery storage sector is similar. Battery storage can basically be divided into three categories: large-scale storage with a capacity of over 1,000 kWh, commercial storage with a capacity between 30 and 1,000 kWh, and home storage with a capacity of up to 30 kWh (Pawlik 23.06.2025). In Germany, a total of 270 large-scale storage systems, 10,936 commercial storage systems, and 1,651,520 home storage systems were installed as of December 18, 2024 (Pawlik 23.06.2025). Market concentration in this sector is described by an HHI of 626.87.

Figure 3: HHI for DSOs vs. renewable energy market share. (Own representation)



Source: see Appendix 2 for data sources

The transformation of energy and mobility systems is leading to the emergence of a new market for energy storage. Due to its close links with energy generation, this market exhibits a comparable level of market concentration, as described by an HHI of 626.87.

Finally, the market concentration of charging systems is examined. For comparison purposes, stationary and dynamic charging are considered. There are currently 161,700 charging stations and 2,487 charging station operators in Germany, of which 9,086 stations are operated by EnBW mobility+ AG und Co. KG, 4,396 by E.ON Drive GmbH, 3,194 by Tesla Germany GmbH, 2,670 by EWE Go GmbH, and 2,603 by Mercedes-Benz AG (Impey 23.06.2025).

Equation 4: Calculation of HHI for Charging Stations (own calculation, data from (Impey 23.06.2025))

$$HHI_{LS} = (0.0562)^2 + (0.0272)^2 + (0.0198)^2 + (0.0165)^2 + (0.0161)^2 + 2482 \cdot (0.000348)^2 \approx 51.2$$

The HHI for the stationary charging market in Germany is 51.2. This indicates very low market concentration, which is typical of a highly competitive market. The stationary electric mobility market is subject to increased monitoring by the Monopoly Commission. The competition model underlying this market currently comprises the provision of locations for charging points, the market stage of operating publicly accessible charging stations by so-called charge point operators (CPOs), and the market stage of electric mobility providers (EMPs) and roaming platforms (Hein, Knezevic et al., 2023, 20–22). The upstream market stage of electricity production follows an independent competition model and is not directly integrated into the charging point infrastructure. As competition can develop in the charging point infrastructure sector, this economic sector is not considered a classic network sector based on a natural monopoly. The competition parameters at the infrastructure level of electric mobility are complex and include aspects such as charging time, charging capacity, location availability, transparency, and accessibility of charging points. In regions where CPOs have a dominant market position, end customers may not have a choice between different providers or charging points, which can significantly restrict competition (Hein, Knezevic et al., 2023, 14–48).

The HHI for stationary charging is 51.2. The strong focus on a socially acceptable and economically oriented market means that efforts to transform the transport sector in an environmentally friendly way are being significantly hampered.

As described above, there are currently three catenary lines in pilot operation with a single catenary line operator for dynamic charging. The HHI for the dynamic charging market with a single catenary line operator is 10,000, which indicates a complete monopoly. From a competitive economics perspective, the catenary line infrastructure also represents a natural monopoly in the long term, as the parallel construction of several catenary line networks would not be efficient from either an economic or a resource-related point of view. However, this is not solely due to economic market barriers (Hein, Knezevic et al., 2023, 14–48). Regulatory measures are necessary to ensure fair competition in network sectors. Regulatory law serves as the legal implementation of the findings of network economics, whose principles are primarily based on the logic of networks and not on the logic of the goods transported within these networks (Hein, Knezevic et al., 2023, 14–48). Specific regulatory requirements apply to energy supply networks, defined as electricity and gas supply networks according to Section 3 No. 16 EnWG, such as unbundling, access regulation, and tendering. However, these requirements cannot be readily transferred in their current form to the new network sector of "catenary lines on highways" (Malmendier and Schendel, 2006, 362–383). Instead, an independent market for traction current should be created with specific regulatory mechanisms that can be flexibly adapted to the respective market situation.

In this context, it must be ensured that the regulatory requirements of the EnWG do not apply to the Electrified Road System (ERS) and its operators. Simply classifying the catenary line infrastructure as a highway or energy facility does not create sufficient legal certainty. In addition, either the ERS operator should be classified as a final consumer (as in the basic and ELISA models[2]) or the catenary line infrastructure should be classified as a special type of energy facility (as in the AMELIE 2 model) (Hein, Knezevic et al., 2023, 49–60). A four-stage market ramp-up plan is recommended, which provides for the gradual introduction of market players and regulatory mechanisms. The individual stages should be designed depending on the degree of expansion of the catenary line network. In each phase of the market ramp-up, the billing option that best balances ease of market entry (through low regulatory and technical requirements) and acceptance (through user-friendliness and fairness of consumption) should be selected.

The value creation level of traction power supply is particularly important, as there is no location competition in the ERS, as is the case with charging points, for example. The basic and ELISA models provide for a lower degree of regulation than the AMELIE 2 model and are therefore more suitable for the initial phase of the market ramp-up (Hein, Knezevic et al., 2023, 88–89).

2 Further information on the basic, ELISA and AMELIE models are to be found in Hein, Knezevic et al. (2023).

Specific studies are therefore necessary for the ERS in order to identify the appropriate market regulation approaches for the different market phases. Even with new technologies and natural monopolies, a complete monopoly does not usually exist. This applies in particular to catenary line infrastructure, which is considered part of the highway system. Under German law, in particular Article 90 of the Basic Law (Grundgesetz, GG) and the provisions of the Federal Trunk Road Act (Bundesfernstraßengesetz, FStrG), trunk roads are owned by the state. Since catenary lines can be regarded as an integral part of the trunk road infrastructure, they are also reserved for state ownership.

Equation 5: Calculation of HHI for dynamic charging (own calculation, data from ELISA)

$$HHI = (s_1)^2$$

$$= (1)^2 = 1$$

This legal basis prevents private actors from gaining a complete monopoly over the catenary line infrastructure, as the state, as the owner of the highways, retains control over the use and expansion of catenary lines. Instead, private companies can only operate as operators or service providers under concessions or public-private partnerships (PPPs). This ensures that the use of the catenary line infrastructure is in line with the principles of public service and fair competition, while at the same time preserving state sovereignty over the highways.

The HHI for dynamic charging is 1. This market constellation is based, among other things, on the regulatory basis of Article 90 of the GG, which assigns sovereignty over highways to the state and thus ensures central control and planning. The state's focus on social interests and its independence from individual regional interests enables more objective and overarching planning and implementation, but at the same time, this orientation means that the ecological and economic potential of dynamic charging is not fully exploited. Prioritizing social and administrative aspects can thus significantly slow down the pace of innovation and the expansion of this forward-looking technology.

Infrastructure not only shapes social coexistence, but also reflects fundamental values such as justice, inclusion, and sustainability. The HHI analysis shows that infrastructure is often associated with natural monopolies, whereby market concentration is not necessarily motivated by economic factors alone. However, sustainable infrastructure development requires a balance between social justice, environmental goals, and economic efficiency.

The German electricity market, which has a medium level of market concentration with an HHI of 626.87, illustrates how deregulation and decentralization in the 1990s successfully lowered barriers to market entry, increased the number of market participants, and strengthened the pace of innovation. It is particularly noteworthy that the originally socially motivated intervention paradoxically led to an intensification of monopoly formation in the energy market. Only through the introduction of innovative technologies such as photovoltaics and wind power, which also promote ecological objectives, was it possible to achieve a real reduction in market concentration.

Comparable challenges can be seen in the area of charging infrastructure for electric mobility. The current market design is geared toward enabling intense competition, which is intended to ensure socially acceptable access to charging infrastructure. This applies to both stationary and dynamic charging systems. However, from an economic perspective, this competitive structure in both technological approaches is delaying the market ramp-up, which means that the ecological potential of electric mobility cannot yet be fully exploited. While the market for stationary charging has a very low market concentration and is therefore competitive, with an HHI of 51.2, the market for dynamic charging, for example via catenary lines, is a complete monopoly with an HHI of 10,000. This monopoly position, which is based on state control in accordance with Article 90 of the Basic Law, secures social interests and overarching planning, but can hamper the pace of innovation and ecological progress. Flexible regulatory approaches are therefore needed to exploit the potential of such technologies while promoting social and ecological goals. The transformation of energy and mobility systems requires supporting sub-infrastructures such as energy storage and charging points, which are essential for the integration of renewable energies and the stabilization of the energy system. Despite moderate market concentration in the energy storage sector (HHI: 626.87), promoting smaller players remains a key challenge. Sustainable infrastructure development must therefore not only drive technological innovation and environmental goals, but also ensure social justice and fair competition in order to enable long-term progress and change. From an economic perspective, low market penetration can lead to economies of scale, resulting in significant cost reductions. This also has social relevance, as it makes products and services more affordable for low-income households. Improved quality of life can be achieved, for example, through lower energy prices or access to innovative technologies. These effects result from the standardization of processes and more efficient planning of production volumes. However, achieving such effects is challenging, especially in transformation phases, such as the transition to a sustainable energy and mobility infrastructure. In these phases, fundamental processes must first be established, while products are often associated with high engineering, research, and development costs. This leads to the opposite social effect. Sustainable technologies often remain unaffordable for low-income households, which can exacerbate social inequalities. High market penetration also carries risks. It can lead to the formation of monopolies that limit consumer choice and exacerbate social disparities. In addition, ecological consequences can arise, as high market penetration is often accompanied by increased resource consumption, especially if the products are not designed sustainably. To meet these challenges, regulatory intervention is needed to provide sustainable products with a protected market space before they have to compete with established, unsustainable alternatives. The energy industry is a prime example of how the expansion of renewable energies can deliver both ecological and economic benefits. Companies with a small market share also have the opportunity to specialize in environmentally friendly niche markets and offer sustainable solutions there. Lower market penetration can also strengthen social resilience, as society is less dependent on individual suppliers. Table 1 shows a summary of the latest HHI figures.

Table 1: HHI overview

Market segment	**HHI (0–10,000)**	**Concentration interpretation**	**Reference year**
Electricity suppliers (retail)	626.87	Low	2024
Transmission system operators (TSO)	2,749.05	High	2024
Distribution system operators (DSO)	269.6	Very low	2023/2024

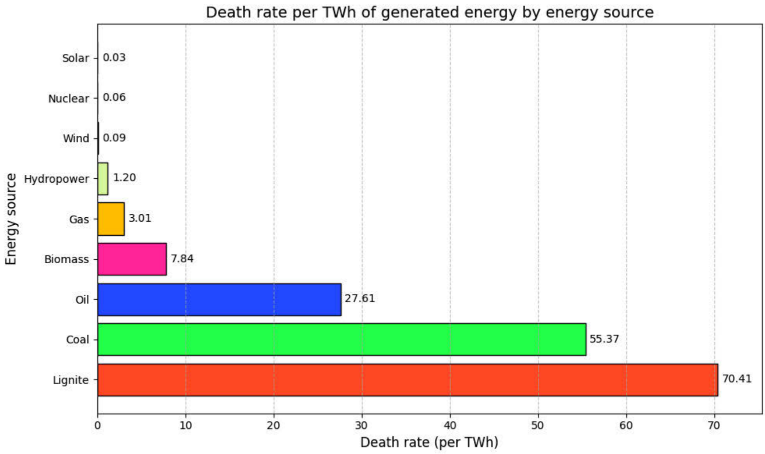
Market segment	HHI (0–10,000)	Concentration interpretation	Reference year
Charging infrastructure (stationary, CPO shares)	51.2	Very low	2025
Dynamic charging (overhead line, pilot stage)	10,000	Monopoly	2025

Source: Data according to the sources cited in the chapter

6. Social ambivalence of technological developments

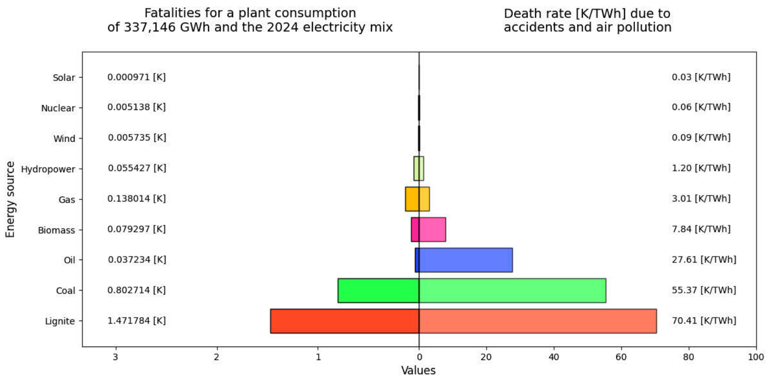
As previously outlined, the introduction of renewable energies and the liberalization of the energy industry have both beneficial and challenging effects on market penetration and the various dimensions of sustainability. A key aspect in this context is the importance of the current transformation process toward an ecologically oriented infrastructure chain. In the economic and social context in particular, this change first requires the comprehensive implementation of new structures before the desired positive effects can be realized. Technological developments play an ambivalent role here. On the one hand, they contribute to existing problems; on the other hand, they are essential for enabling sustainable solutions and overcoming long-term challenges. In the following, we will examine who is negatively or positively affected by new ecological technologies from a purely social perspective, based on their social consequences. We will start again with energy production. Figure 4 shows the number of global deaths caused by different energy sources (Markandya and Wilkinson, 15.09.2007; Sovacool et al., 20.01.2016; UNSCEAR, 2008, 2018). Death rates are measured based on direct deaths, such as accidents, or indirect deaths, such as air pollution per terawatt hour of electricity. It is positive to note that renewable energies in particular are responsible for only a low death rate.

Figure 4: Death rate per TWh of generated energy by energy source. (Own representation)



Source: see Appendix 3 for data sources

Figure 5: Death rate based on the case study. (Own representation)



Source: see Appendix 3 for data sources

In the short term, the current electricity mix must be taken into account when introducing a new technology. Taking into account the evaluation results shown in Figure 4 and an assumed prospective utilization of dynamic charging of 100%, the statistical forecast is that, with the current electricity mix, two people would die each year as a result of the introduction of this mobility solution, based on a single section of road alone. Looking at a future scenario in which the predicted system consumption of 337.146 GWh per year is covered exclusively by renewable energies, the number of disaster victims could be reduced to 0.020229 per year. Currently, the global annual number of fatalities amounts to 2.596314.

In addition to the devastating consequences in the form of disaster victims caused by the use of energy sources, there are two other key figures that must be considered in the context of social consequences. These are, on the one hand, those affected by energy and, on the other hand, those exposed to energy. Those affected by energy are individuals or population groups who are directly or indirectly affected by the effects of energy production. This includes people who are economically or socially affected by energy prices, increased local grid fees, increased local and temporary supply interruptions due to the fluctuating nature of renewable energies, or political measures (e.g., CO_2 pricing). Examples include households suffering from energy poverty or companies affected by rising energy costs.

To illustrate the burden of casualties in the electrical grid infrastructure, the systematic review by (Shih et al., 2018) was used, which comprises 41 publications with a total of 5,485 adult patients (18.0% low voltage, 38.3% high voltage, 43.7% voltage not specified) and documented higher morbidity and mortality in the clinical collective at high voltage (hospital mortality: 2.6% at low voltage, 5.2% at high voltage, 3.7% not specified). Aggregated across all voltage levels, normalizing to an assumed global electricity consumption of 26,000 TWh results in a nominal mortality rate of approximately 0.0072 deaths per TWh. Applying this heuristically to an energy consumption of 0.337 TWh, the expected number of victims is

$$0.0072 \frac{K}{TWh} \bullet 0.337\, TWh \approx 0.00243\, K$$

based on this exact amount of energy.

This figure should be understood as a global approximation and primarily reflects individual events; large-scale, simultaneous damage events caused by grid infrastructure are extremely rare. The high level of safety of power grids in public spaces is the result of extensive technical and organizational protective measures, meaning that relevant residual risks exist primarily in professional activities with direct access to the equipment. In countries with high safety standards and a low proportion of overhead lines, even lower values can be assumed, although no country-specific disaggregated meta-analyses are available for this to date.

Exposed persons are people who are exposed to a specific burden or risk arising from energy infrastructure or projects. The term "exposed" refers to physical, health, or social hazards caused by certain influences, i.e., people who live near energy facilities and are potentially exposed to hazards such as electromagnetic fields (from high-voltage power lines), noise emissions (from wind turbines or storage facilities), or accident risks. Also affected are people whose health may be impaired by pollutants, noise, or other environmental impacts, such as residents living near coal-fired power plants who are exposed to health risks from particulate matter or sulfur dioxide. People who experience social disadvantages as a result of the construction or operation of energy projects, such as resettlement, loss of property, or restrictions on their quality of life, are also exposed persons.

The analysis of exposed and energy-affected persons requires a differentiated approach. Focusing on the locally affected population in Germany, there is an increase in the number of people affected, as a larger proportion of energy is generated by locally installed plants, such as wind turbines. However, if these figures are put into relation to the population already affected by the use of oil, lignite, or other fossil fuels, there is an overall reduction in the number of exposed persons.

Wind power and photovoltaic systems expose affected individuals to different types of impact. In the case of wind turbines, the main issues are noise emissions, infrasound, and shadow flicker, which can impair the quality of life of local residents. In addition, visual impairments and potential hazards such as ice throw are often perceived as a nuisance. Photovoltaic systems, on the other hand, mainly cause conflicts due to glare, the reflection of sunlight, and the use of large areas. The measurable effect, i.e., how many exposed persons are affected, depends heavily on the location, the technical generation used, and the population density. The majority of wind and ground-mounted PV systems in Germany are located in suburban, predominantly hilly areas and should serve as an example here.

To calculate the number of people exposed per megawatt (MW), the total number of people affected within the sound and noise radius of the plant is divided by the installed capacity of the plant. For a 3-megawatt wind turbine, a noise radius of 1 kilometer is typically assumed, which corresponds to an area of approximately 3.14 square kilometers (Lewis et al., 2002, 82–83). Renewable energies, especially wind turbines, are primarily installed in rural areas (Bovet et al., 2019). In this area, the population density in the Rhine-Main region is 400 people per square kilometer, which results in the following total number of people affected (Regionalverband FrankfurtRheinMain, 2022):

Equation 6: Calculation of exposed persons in energy supply incidents. (own calculation)

$$\textit{Number of exposed persons} = \textit{Population density} \cdot \textit{Visibility and noise radius}$$

$$\textit{Number of exposed persons } EV = 400\frac{\textit{People}}{km^2} \cdot 3{,}14km^2$$

$$\approx 1.256 \textit{ Exposed persons}$$

As can be seen from Equation 6, around 418.67 people per MW are exposed here. This figure can be used as an indicator of the social and spatial compatibility of wind and PV projects in suburban areas.

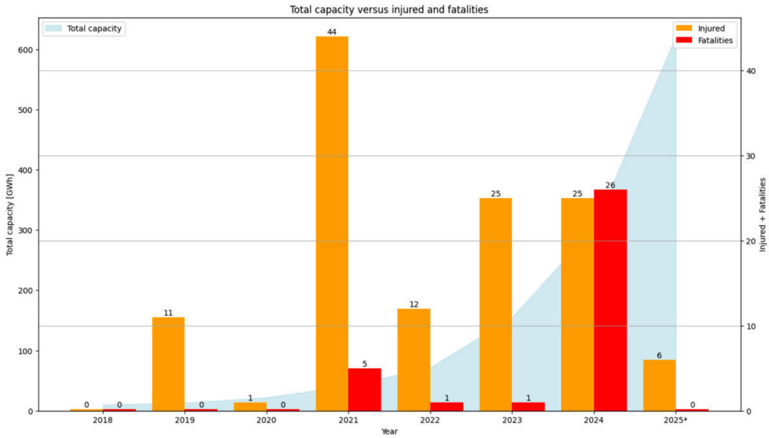
In addition to the exposed persons, approximately 1,000,000 persons would be affected in terms of energy in the scenario under consideration, as all persons living in the adjacent grid area would be directly affected by the effects of a decentralized energy supply (e-netz Südhessen AG, 2025). Persons affected in terms of energy are all those who are directly dependent on the energy supply because they cover their electricity needs from the corresponding distribution grid section. This figure includes private households, commercial enterprises, and industrial consumers who depend on a reliable and stable energy supply. In addition, the energy supply also has financial implications for all those affected by energy, particularly through grid fees. These may increase as a result of the expansion of the grid infrastructure required for the integration of new technologies such as wind turbines and dynamic charging infrastructure. Such cost increases affect not only those directly exposed in the vicinity of the facilities, but also the entire population in the grid area. In this case study, the figure of 1,000,000 people affected by energy highlights the far-reaching significance and potential social and economic impacts of energy infrastructure on the region.

Fluctuating generators add another level of consideration. The need for storage capacity and the people exposed to it and affected by energy, as well as potential disaster victims, must also be taken into account. To this end, a meta-analysis of all disaster cases was first carried out. The present study is based on a comprehensive data collection using the BESS Failure Incident Database. According to the definition of the Federal Emergency Management Agency (FEMA), an "incident" is a natural or man-made event that requires an emergency response to protect life or property in direct connection with large-scale electricity storage facilities (≥0.5 MW). The collected data was used for a meta-analysis to gain systematic insights into the effects of incidents related to large-scale electricity storage systems.

In contrast to the analysis of the global BESS database, which focuses primarily on technical causes and their analysis, this study took an alternative approach. The focus was on reports in the local and trade press, which were evaluated not in terms of technical details, but rather in terms of the health consequences and impacts on the local population. Despite the significant global expansion of large-scale electricity storage capacity from 10.3 GWh in 2018 to 304 GWh in 2024, a well-founded assessment in this context remains lacking (Kurtz and Haegel, 2025, 206–214). To better categorize the consequences, the reports were first divided into two main groups, namely injuries and fatalities. In the further course of the analysis, these categories were merged to enable a uniform consideration of those affected as "disaster victims." This approach allows the social and health consequences of battery storage to be viewed in a differentiated manner and placed in the context of emergency management and prevention. The entire value chain was evaluated, from manufacturing to the final use of storage capacities. Due to insufficient data, the extraction of raw materials could not be taken into account, but should be identified as a relevant research gap. Nevertheless, the present analysis can be used as an initial indicator.

As can be seen in Figure 6, the global number of people injured and killed rose significantly, particularly in the ramp-up years 2023 and 2024. While the storage capacity increased by 113.87% in 2023 (25 injured and 1 fatality) in 2023 and by 104.6% (25 injured and 26 fatalities) in 2024 compared to the previous year, the number of disaster victims also increased dramatically during the same period. In 2023, the number of victims doubled compared to 2022, representing an increase of 100%. In 2024, the number of victims rose again by 96.15%, which represents a further doubling compared to the previous year. In the first quarter of 2025, 11.25% of the previous year's victim numbers were already recorded, indicating a continuation of this trend.

Figure 6: Injuries and fatalities vs. installed energy storage capacity. (Own representation)[3]



Source: Own representation, see Appendix 4 for data sources

The current boom in renewable energies and the associated increase in demand for flexibility in the energy market require a parallel expansion of storage technologies. These are essential, for example, to support electromobility and, in particular, dynamic charging (Hein, C. R., Lerchl-Mitsch, K., Petermann, D., Büchau, N. et al., 2024). Despite the ecological and economic potential associated with the introduction of these technologies, the social impacts must not be ignored. The increase in disaster victims highlights the need to systematically analyze the social consequences of technological transformation and to incorporate them into decision-making processes. Only through a holistic

3 The data for 2025 covers only January to May.

approach can risks be minimized and long-term acceptance by society be ensured.

At this point in the analysis, the unintended consequences of an integrative view of the value chain of mobility solutions, especially dynamic charging, are already becoming apparent. An isolated view of the technology and its effects is no longer appropriate in the context of technology assessment and should not have been taken historically either. It should also be noted that a purely sector-coupling perspective is not sufficient, as central aspects remain unaddressed in the transition areas between sectors. Rather, it is necessary to analyze socially relevant issues along the entire technological value chain—from energy generation to energy transport and intermediate storage to mobility use. The causes of many of the negative effects were and often remain outside the immediate perception of mobility users. Those who are particularly affected are often those who have no direct connection to the mobility solution used, but suffer disproportionately from its consequences.

The problem is further exacerbated when the case study is revisited. To ensure full supply in the case study and to compensate for the fluctuating behavior of renewable energies, a storage facility with a capacity of 25 MWh and an output of 25 MW (type C1) is required. Looking at the ratio of disaster victims (K) to globally available storage capacities, the figure is 0.000302835 K/MWh. This corresponds to 0.007570876 K per plant for dynamic charging. While these figures appear uncritical at first glance, a consideration of the social consequences, as shown in Figure 6, reveals a significant problem in absolute terms.

In addition to those directly affected by the energy supply, there are also exposed persons who are adversely affected by the side effects of storage technologies. Similar to renewable energies, storage facilities cause noise, which is primarily attributable to ventilation systems, as well as waste heat, which can be perceived locally. The integration of large storage parks also often requires an expansion of the local grid infrastructure, which is reflected in increased grid fees that may also affect uninvolved third parties. In the case study, approximately 1,000,000 people are affected in terms of energy, as the entire grid area is integrated into the supply system. The number of people exposed depends heavily on the population density in the respective region and the location of the storage facility. A storage facility can cause noise emissions of up to 70 dB in the short term, which can already be perceived as disturbing. Taking into account sound propagation and population density in the Rhine-Main area, which is around 2,000 people per square kilometer in urban areas, this results in a figure of 6,276 people who are directly affected by noise emissions (TROX TLT GmbH, 2013; Regionalverband FrankfurtRheinMain, 2022). This figure illustrates that even with moderate emissions and a limited number of plants, social and health impacts can occur that must be taken into account in the planning and implementation of such projects. In summary, it is also evident at this level that the introduction and operation of storage technologies pose not only technical and economic challenges, but also social ones. It is therefore essential to take into account social consequences such as noise pollution, waste heat, and the impact on grid fees.

The mobility transition strengthens the polluter pays principle by shifting responsibility for providing the necessary infrastructure and energy supply more toward national circumstances. While oil production and diesel refining have historically taken place predominantly outside Germany, electricity generation from renewable energies, the expansion of transmission infrastructure, such as in the case of the SüdLink project, and the implementation of storage technologies for supplying electric mobility are increasingly taking place within Germany. However, these developments are increasingly causing discontent among the population, as the associated impacts on the environment and quality of life are directly felt at the local level.

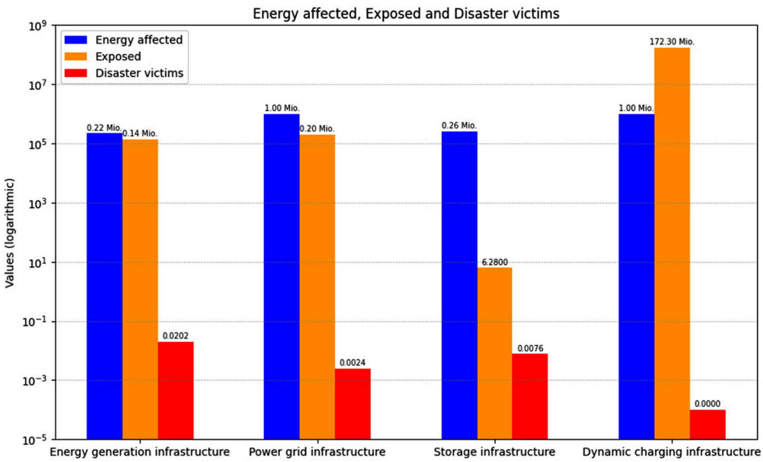
In order to complete the evaluation of the social impacts of dynamic charging, it is necessary to assess the consequences for various exposed persons, those affected by energy issues, and potential disaster victims in the context of mobility provision.

In this context, those affected by energy are primarily those who live within the network area of a specific network section. The planned ramp-up of dynamic charging will be limited to central corridors along highways. As already explained, this requires the expansion of the local electricity infrastructure. The associated costs will be passed on to the grid fees, which will lead to a local financial burden for individual energy-affected persons. Based on the size of the affected grid area in the case study, the number of energy-affected persons can be estimated at around 1,000,000.

The negative impacts and the resulting number of people exposed can be derived from the following aspects. The construction phase will lead to restrictions in the road infrastructure, such as traffic jams and traffic restrictions, which may cause increased stress for those affected. With catenary line technology, maintenance work can usually be carried out during operation, reducing the number of people exposed and the severity of the disruption to everyday life. During normal operation, the restrictions are considered less severe and are primarily limited to visual impairments caused by the catenary line. Nevertheless, the number of people directly or indirectly affected is considerable due to the high traffic density on the highways. In 2024, an estimated 172.3 million people were affected by visual impairments along the highway. However, studies conducted as part of the field trial show that after multiple trips on the route, no significant changes in driving behavior or visual stress on road users could be detected.

During the six-year field trial, there were no injuries or fatal accidents that could be directly attributed to the catenary line system. The sophisticated safety concept, which consists of a restraint system that allows vehicles to bounce off in a controlled manner and an automated contact wire shutdown in the event of damage, means that the technology can be classified as very safe (Gurske et al., 2023). The complete figures from the analysis can be found in Figure 7.

Figure 7: Affected, exposed and injured/fatalities for different infrastructures.[4]



Source: (Own representation)

4 Please note that the "Disaster victims" value for dynamic charging infrastructure is actually 0, however this can not be displayed accurately on a logarithmic scale.

7. Discussion and recommendations for action

This discussion revisits the guiding question of how a policy and infrastructure governance framework for the ecological transformation of heavy goods road transport—exemplified by the eHighway system—can reconcile ecological effectiveness, social justice, and economic efficiency under conditions of uncertainty and natural-monopoly characteristics. This analysis underscores the central importance of infrastructure as a driving force for social, ecological, and economic transformation. At the same time, it becomes clear that the introduction of new infrastructure, such as the eHighway system, is associated with a multitude of challenges that encompass technical, social, cultural, and economic dimensions. To meet these challenges, targeted recommendations for action and approaches to discussion are needed to enable a sustainable and equitable transformation.

First, a holistic assessment of infrastructure is essential. Infrastructure is not just a technical system, but is deeply embedded in cultural and social practices. Decisions about its expansion or transformation must therefore be made systematically and take into account the interactions between ecological, social, and economic dimensions. A striking example of this is the liberalization of the energy industry, which was originally aimed at promoting social justice and strengthening competition by opening up the market. However, high barriers to market entry and existing market concentration initially had the opposite effect, as they consolidated the dominance of a few large players. It was only with the rise of renewable energies that a decisive decentralization of energy supply was achieved, which not only increased competition but also made a significant contribution to strengthening social justice.

An integrative perspective is necessary to take into account both long-term climate goals and the social acceptance and cultural significance of existing structures. In this context, the question arises as to how assessment frameworks can be developed that adequately reflect both the ecological advantages of new technologies and the social and cultural costs of their introduction. Another key aspect is promoting acceptance through transparent communication. The analysis shows that acceptance of new infrastructure depends heavily on the perception of its benefits and risks. Although scientific studies classify most concerns as unfounded, the survey results indicate that both the general public and affected populations express reservations regarding the visual impact of the catenary line infrastructure. To promote acceptance, broad-based information campaigns are needed to explain the functioning and advantages of the eHighway system in an understandable way. In addition, the population should be involved in planning processes at an early stage in order to identify and address such reservations.

However, the transformation of infrastructure must not lead to an exacerbation of social inequalities. The analysis shows that smaller players and lower-income population groups in particular could be disadvantaged by high investment costs or local burdens. At the same time, the decentralization of energy and mobility systems offers opportunities for greater regional value creation. Support programs that specifically target smaller players and low-income households, as well as a fair distribution of the costs and benefits of new infrastructure, for example through socially acceptable and decentralized network charges, are therefore of central importance. This raises the question of how social justice and economic efficiency can be reconciled in infrastructure planning.

In addition, the long-term planning and high investment costs of infrastructure projects require a forward-looking and flexible design that can respond to unforeseen developments. Resilient infrastructures must not only meet current requirements, but also anticipate future technological and societal changes. Modular and adaptive infrastructure solutions that enable gradual expansion and adaptation, as well as the integration of scenario analyses into planning processes, are crucial in this regard. It remains to be discussed how infrastructure projects can be designed to ensure both short-term efficiency and long-term resilience.

Another key aspect concerns the regulation and design of market mechanisms. The HHI analysis shows that natural monopolies—such as in the case of catenary line infrastructure—require targeted regulatory intervention. This is necessary to ensure fair competition and social justice on the one hand, and to guarantee both ecological transformation and economic sustainability in the long term on the other. At the same time, regulation must not hinder the pace of innovation and market ramp-up. Specific regulatory mechanisms are needed for new infrastructure sectors, such as dynamic charging, which can be flexibly adapted to the respective market situation. A balanced market ramp-up that takes into account both economies of scale and social and ecological goals is essential. It is important to examine which regulatory approaches are suitable for exploiting the potential of natural monopolies without jeopardizing social and ecological goals.

Technological openness and diversification are also decisive factors. A one-sided focus on a single technology carries the risk of increasing social resistance and neglecting alternative solutions. A technology-neutral approach that develops and evaluates different solutions in parallel, as well as support for pilot projects and field trials to test the practical suitability are therefore of great importance. The central question is how to design a technology-neutral strategy that, on the one hand, taps into innovation potential, while at the same time ensuring the urgently needed transformation toward an ecologically sustainable future.

In summary, the transformation of infrastructure in the context of climate protection requires a careful balance between ecological, social, and economic goals. The eHighway system offers promising potential for making road freight transport more sustainable, but faces challenges in terms social justice and regulatory framework conditions. Successful implementation therefore requires an integrative approach that reconciles technological innovations with societal needs and cultural practices.

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Appendix

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