Hasse *et al. European Journal of Futures Research* (2026) 14:7
https://doi.org/10.1186/s40309-026-00267-x

European Journal of Futures Research

RESEARCH ARTICLE Open Access

Transition of the transport sector in a mining region: a cross-impact-balance analysis

Jasmina Hasse[1,2], Stefan Vögele[1,2*], Dirk Rübbelke[2] and Jochen Linssen[1]

Abstract
Cross-Impact Balance (CIB) analysis has proven to be a valuable approach for modeling complex socio-technological-economic systems. Traditionally, it has been applied to well-defined systems characterized by a high level of aggregation. The main objective of our study is to extend the scope of the CIB method to less aggregated contexts that incorporate greater detail. Specifically, we demonstrate its expanded applicability through the example of transport system development and restructuring in a region composed of multiple subregions. The focus lies on identifying possible development pathways that account for interactions between measures implemented within individual subregions. Our findings highlight both the value and the necessity of tools for soft-linking and drill-down analysis.

Keywords Cross-Impact Balance, Structural change, Economic transformation, Transport sector, Rhenish mining area

Introduction

The world is undergoing a continuous transformation that is rather diverse in different regions on the planet. Challenges for regions (like Bilbao or Manchester) that had to cope with a declining heavy industry tend to be rather distinct from those faced by rural areas (like in Castilla-La Mancha, Spain) that severely suffer from depopulation, for example. Yet, what the developments in these and other transforming regions largely have in common is an element of uncertainty. We will illustrate this in the context of the Rhenish mining area in Germany which is undergoing also a great transformation that is mainly driven by the decline of its mining sector. Lignite is still mined there in an area of 5,000 km^2 populated with 2.4 million inhabitants, but the exit of coal extraction is already scheduled. Although the region is broadly branded as a climate neutral model region for Germany and Europe [1], it remains largely uncertain how and in which direction this region will develop after the termination of coal extraction. Hence, depending on the development of the socio-techno-economic framework conditions policy measures can result in different outcomes.

Our study focuses on the assessment of effectiveness of measures in different (regional) contexts and different futures. The research aims to provide an approach that can deal with 1) complex socio-techno-economic contexts ensuring consistency between the different factors, 2) openness of the future showing that different outcomes are possible and hence, provide information on interactions between changes in contexts and policy measures and 3) enables to draw conclusions on subregion level.

Accordantly, we develop an approach for the identification and assessment of possible future paths for the region which could serve as a template also for other transforming regions. This novel approach is a combination of a Cross-Impact Balance (CIB) analysis with an

*Correspondence:
Stefan Vögele
s.voegele@fz-juelich.de
[1]Forschungszentrum Jülich, Institute of Climate and Energy Systems - Jülich Systems Analysis, Jülich 52425, Germany
[2]TU Bergakademie Freiberg, Schloßplatz 1, Freiberg 09599, Germany

explorative network analysis and drill-down feature for taking a closer look at developments on subregion level.

We apply this approach to the analysis of the transformation of a complex socio-technological-economic system focusing on infrastructures and their use. In doing so we focus on policies (e.g., climate policy in general, implementation of mobility concepts) and socio-economic factors (e.g. public transport ticket price) framing mobility patterns as well as intermediately the transition of transport infrastructure.

A climate neutral model region like the Rhenish mining area may require the expansion of the electricity grid in the future in order to make extensive use of e-mobility replacing CO_2-emitting vehicles powered by gasoline or diesel capable, for example. As a result, scenarios are presented showing potential mobility development paths of the region being impacted by socio-techno-economic factors. Based on these scenarios we draw conclusions on needs for infrastructure and policy measures aiming to support transition of the mobility sector. The study shows how transformation paths can be modelled taking aspect on regional and subregional level into consideration.

Structural change and the mobility transition are inextricably linked in the Rhenish mining area. Mobility is seen as an important impetus for developing new paths that represent an alternative to fossil-fueled structures [2]. It can be seen as a transformational driver by creating accessible and multimodal mobility, new technologies and an improved quality of life through the restructuring of regional infrastructure [3]. The mobility transition is included in the strategic plans for structural change, such as the economic and restructuring program ("Wirtschafts- und Strukturprogramm") and the spatial strategy 2038 + ("Raumstrategie 2038 + ") [4]. Goals include decreasing private car use, promoting car and bike sharing, developing community-friendly freight transport, and improving cycling infrastructure [5]. Resultingly, structural change creates framework conditions for a successful mobility transition.

Although the transformation is characterized by uncertainty and challenges, it harbors the opportunity to shape the area into a model region for climate neutrality and innovation. The expansion of renewable energies—especially wind and solar energy—enables climate-neutral energy generation, which is essential for the transformation and redesign of mobility [6]. To contribute to decarbonization, the promotion of sustainable mobility services such as public transport is necessary. Concurrently, it is important to consider the current attractiveness of motorized individual traffic (MIT) and to evaluate expert opinions on the development of both public transport and MIT. Industries such as the transport sector and its numerous services are a central component of structural change. Mobility, on the other hand, is a defined and strategically important future field of regional upheaval [7]. All in all, a successful transformation requires a deep understanding of technological, infrastructural, economic, social and behavioral factors.

As a rule, regions differ in terms of their existing socio-economic structures and their development potential. Findings obtained at the national level must therefore be reviewed and adapted to ensure their applicability to regions. The same applies to the consideration of subregions. Here, findings obtained at the more aggregated level can also only be partially transferred and must be adapted. Approaches are therefore needed that can deal with a wide range of influencing factors and also offer opportunities for analyses of policy measures taking differences in regional contexts into consideration. CIB analysis has already proven its worth in modeling complex, interdisciplinary systems (see e.g., [8–10]). In our study, we demonstrate its potential for the assessment of impacts of policy measures within heterogenous regional contexts.

In the following we describe our approach in detail. We start by describing the fundamentals of our CIB approach (Section "Method"). Section "Implementation" focusses on the implementation of the approach. Results are presented in section "Results" and discussed in section "Discussion". Section "Conclusions" concludes.

Method

An assessment of policies at regional and subregional levels requires information about socio-technical–economic configurations, including details of interactions and feedback loops. Cross-Impact Balance analysis has proven it feasibility for detail with complex socio-techno-economic systems. As important challenge for application of CIB is the selection of relevant descriptors, the specification of specific states as well as the judgment of interlinkages between the states. Thus, we decided to extend the CIB analysis by conducting a network analysis which includes an intensive assessment of the views of stakeholders on the system. Since the CIB is limited with respect to number of descriptors and condensation of information received by the network analyses is required.

In the following we describe our approach in more detail.

Network assessment

Based on the pre-collected information we are able to create a network map. This map is presented in Fig. 1. The figure shows factors listed in the literature and their interlinkages.

A distinction was made between factors that were considered very relevant and showed inherent dynamics, and factors that were considered less relevant. The differentiation grounded in the assumption that some factors

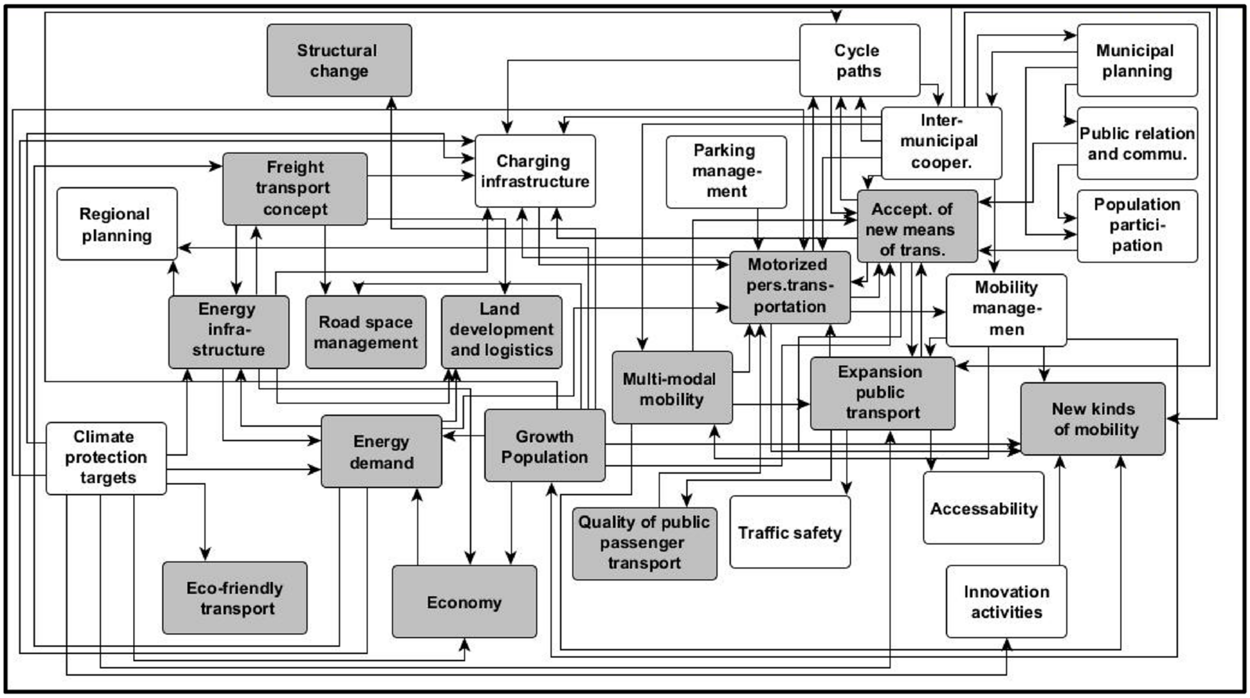

Fig. 1 Network of relevant factors. Remarks: Grey: factors with high relevance for the mobility transition of the regions and being linked with inherent dynamics

represent relatively constant elements or variables, while others embody dynamic developments and changes within the system. This differentiation facilitates the capture of diverse systemic aspects, contributing to a more comprehensive understanding, particularly relevant for informing subsequent research. This comprehensive initial capture contrasts with the practical limitation on the number of descriptors that can be feasibly included in a CIB analysis, highlighting the value of this broader preparatory mapping.

Figure 1 provides the basis for clustering and selecting descriptors. In particular, the figure supports the identification of factors that:

- have to be put at the center of the CIB analysis.
- have to be adjusted; or
- can be used as an exogenous factor.

These factors can be referenced, if necessary, particularly if certain descriptors require discarding or adjustment during subsequent analytical steps. This iterative approach enhances methodological flexibility, ensuring that the final set of descriptors accurately represents the system's key influential factors.

Cross-Impact Balance analysis

An assessment of socio-techno-economic systems requires approaches which can deal with both quantitative and qualitative factors. Cross-Impact Balance analysis (CIB) is a suitable approach in such contexts [11]. CIB has proven its strength in manifold studies focusing on analyses of systems consisting of different kinds of political, societal and economic factors [8, 12].

Usually, after defining system under consideration CIB analysis is conducted in four steps.

1. Identifying relevant descriptors: First, the key factors influencing the system are identified and referred to as "descriptors" [13]. Depending on the system and the type of scenarios, users employ qualitative and/or quantitative descriptors, but a minimum of two is required [14, 15].
2. Defining states for each descriptor: For each descriptor, a range of states or attributes is defined, which represent the spectrum of possible future developments [8]. Scales such as "high/medium/low" [14] can be used alongside more descriptive states that represent the type of transportation mode choice (e.g., bicycle, public transport, private motorized vehicles). States should account for uncertainties regarding future developments of the system and should, therefore, be selected with precision [16].
3. Evaluating the cross-impacts: In this step, a cross-impact matrix is used to examine how the progression of one state affects that of another. The evaluation is usually carried out on a 7-point scale, ranging from −3 (strongly hindering influence) to +3

(strongly promoting influence) [11]. Evaluating cross-impacts is crucial and involves understanding system interconnections.
4. Identifying consistent scenarios: Previously defined consistency criteria serve as a benchmark to verify the internal coherence of the scenarios [8]. The CIB algorithm searches the scenario space (pace of possible context futures) and filters consistent scenarios [15]. Consistent scenarios feature descriptor states that support each other, creating a plausible and coherent vision of the future [17, 18].

Steps 1 to 3 require intensive data collection and preparation. This can be achieved by including expert adjustments and literature analysis, although the sources for each step may differ. To avoid overloading the system, each step requires careful selection and narrowing of information. In section "Implementation" we describe the process of data acquisition and consolidation in more detail.

Network analysis

CIB approaches usually focus on interactions involving 20 to 25 descriptors. To fulfil this requirement, candidates for relevant factors must be scanned and, if possible, clustered. In this study, we employed a network analysis approach to identify relevant factors and their interlinkages, as well as to provide information on the possible clustering of these factors. Network models offer an opportunity to conduct structured network analyses and examine the relationships and structures within multidimensional systems [19]. They enable the representation of complex interconnections between actors, factors and framework conditions (termed 'nodes') and the consideration of the relationships ('edges') between these nodes within a network. Such analyses can provide insights into a system's dynamics by considering the strength of these relationships and the position of actors within the network (e.g. central versus peripheral) [20].

Network models are widely used in network analysis to visually represent and study relationships and structures within complex, multidimensional systems, typically portraying system components as nodes and their interconnections as edges. However, the layout of the model was designed without enforcing a strict hierarchical or chronological structure; rather, the elements were positioned to enhance the readability and comprehensibility of the resulting network. In line with the core principles of CIB, the edges connecting elements within the network model are depicted as either unidirectional or mutual. This visualization is a very helpful preparatory step, offering a broad overview of the system before a more focused analysis of pairwise interactions is performed, as in CIB analysis.

Implementation

Pre -collection of relevant factors

Mobility choices are influenced by a variety of factors, including personal preferences, structural conditions and external influences, such as political measures or technological developments. The use of motorized individual traffic (MIT) can be influenced by costs, travel time, comfort and habits. Private vehicles offer high flexibility and convenience, particularly for work-related travel and in rural areas where public transport options are limited [21]. Regardless of the mode of transport, shorter travel times are preferred, with transfer times, frequency and walking distances potentially extending public transport travel times [22]. Strict parking regulations or high parking fees may encourage people to switch to alternative modes of transport [23, 24]. Batur et al. show that education and age significantly influence environmental awareness and thus the choice of sustainable modes of transport [25]. Younger generations and individuals with higher qualifications often demonstrate a stronger environmental awareness, which increases their willingness to share transportation or utilize autonomous vehicles [25]. Overall habits also contribute to this, as people who are accustomed to travelling by car are less likely to change their mode of transport [24, 26].

However, high expenses for the purchase and maintenance of a car make public transport a cheaper alternative for many people [24]. Since the Germany ticket was introduced in 2023, monthly costs for public transport have been capped at 49 euros per person [27]. In comparison, the maintenance and use of a car incurred monthly costs between 190 and 960 euros [27]. This does not apply to financially fortunate people as this group prefers convenience over costs, further deepening social inequalities [28]. External factors, such as the COVID-19 pandemic, have also impacted the selection of transport modes in recent years [24]. Studies suggest a shift from public transport to MIT due to an increased need for safety or a reduced demand for recurring trips [24]. At the same time, the importance of shared micromobility offerings, such as electric scooters or e-bikes, has grown [29]. In the context of structural changes, the role of energy supply should not be underestimated. Rising energy prices could make MIT use less attractive and increase demand for energy-efficient alternatives. At the same time, widespread availability of charging stations could make the use of electric vehicles and thus individual transport more attractive.

At present, MIT usage is predominant in this region [30]. At the same time, a growing awareness of the need to change the modal split in favor of more sustainable means of transport can be seen [31]. While the expansion of public transport and the promotion of cycling show potential to break MIT dominance, regional concepts show ways in which these developments can be implemented in practice. They envision multimodal hubs that simplify switching between transport modes and link rural areas like Linnich and Hueckelhoven with urban centers such as Cologne and Duesseldorf [32].

The rise of e-mobility is crucial for developing a robust charging infrastructure, particularly for tourism [31]. However, it is not a complete solution due to challenges like building adequate infrastructure and managing network load [33]. A holistic approach is therefore necessary for a successful mobility transition. In addition to infrastructural measures, mobility management is seen as crucial for change. Effective public relations work that informs the population about new mobility options and promotes corporate mobility management contributes to the acceptance and use of sustainable means of transport [34].

The identification and consolidation of influential factors relevant for possible futures of mobility in the context of the selected region was conducted through a multi-stage process. This process encompassed the evaluation of existing concept papers, an expert workshop, and literature research. This method-mix ensures that both practically relevant and scientifically founded perspectives were integrated into this analysis.

In the initial step, central strategy and concept papers developed by regional and supra-regional stakeholders were examined. These documents contained specific objectives and measures in the context of the transformation of the mobility system within two subregions (Kreuzau and Euskirchen), as well as the intercommunal project Indeland and a study on the region a whole entity (Raumstrategie 2038+) [5, 31, 32].

To identify key themes and overlaps, the documents were reviewed to compile a preliminary list of themes representing key topic field framing developments in the region. The list includes in total of seven thematic blocks, each of which was addressed in at least two of the examined concept papers (Table 1). This aligns with methods discussed in the sources where descriptors (key factors) are identified through expert input, literature, and analysis of existing information, often leading to a structured set of themes or factors for further study.

The factors were validated and supplemented through a workshop and extensive literature research. This method aimed to ensure the factors were empirically relevant and scientifically supported. For the workshop, the Future Wheels method.[1] served as the foundational tool for identifying central influential factors and structuring subsequent discussions.

The workshop was attended by experts from academia and local authorities. The participants were involved in the project "RHIVAS – Model-Based Analysis of Transportation and Energy Infrastructure for Successful Structural Transformation in the Rhineland Mining Region" either as researchers or stakeholders, and therefore had in depth experiences of dealing with the topic.

The outcomes from the workshop were manually documented by both participants and facilitators. To evaluate the workshop results, two distinct methodological approaches were applied: Thematic Analysis (bottom-up) and Pre-Defined Categories (top-down). The bottom-up approach involved identifying overarching themes from the qualitative data to derive potential descriptors. Conversely, the top-down method structured and evaluated the results using a set of already defined descriptors. These findings were subsequently presented and discussed within the project framework. Complementary to the workshop findings and insights from concept papers discussed previously, a comprehensive literature review was undertaken (see Tab. 7 in the Appendix). This research aimed to provide scientific grounding for the identified factors and uncover additional relevant influential variables. The results served to supplement the factors identified through the preceding steps and concurrently formed the essential foundation for the subsequent assessment of interactions within the CIB analysis.

Table 1 Thematic blocks

• Mobility [1, 2, 3, 4, 5] • Public Transport [1, 2, 3, 4, 5] • Walking and Cycling [1, 2, 3, 4, 5] • Sustainability and Climate[1, 2, 3, 4, 5, 6]	• Regional Development and Cooperation [3, 4, 5] • Energy and Hydrogen [3, 4, 6] • Other Aspects [1, 2, 3, 4, 5]

Sources: [1] [30], [2] [31], [3] [5], [4] [4], [5] [32], [6] [35]

Descriptors, their states and interlinkages

With expert support, we summarized the information from the network assessment and defined the descriptors for the CIB analysis. To enable the results to be used in further energy-policy-related studies, the factors were selected with interfaces with energy-system-related factors, such as electricity demand and prices, taken into account. To delineate the scenario space and operationalize descriptor states, a baseline status quo was established for each state. This status quo serves as a reference point for defining the alternative future states associated with each descriptor.

The Rhenish mining area consists of subregions that differ in terms of characteristics such as population density and economic structure. These differences are considered by using subregion-specific manifestations of descriptor states. Therefore, the states differ between

[1] Future Wheels Method: A brainstorming technique starting with the definition of a central change, followed by the identification of direct (first order), indirect (second and third order) consequences within the group. Finally, the consequences are evaluated [97].

sub-regions, reflecting the existing economic structures of the subregions, as well as the potential for infrastructure development. These differences enable us to consider the heterogeneity of the consequences of policies and developments in the region.

At this point, it is important to understand the difference between 'measures' and 'context'. In principle, measures are factors that can be set by stakeholders, whereas context encompasses all the factors that frame the selection and effectiveness of measures. Empirical examples show that the outcome of the interaction between measures and contexts can have retroactive effects, resulting in adjustments to the measures, for instance. It should also be mentioned that measures at a higher level (e.g. national level) usually serve as the context for lower levels (e.g. subregions). In our study, climate change policy is an example of such a measure. At regional or subregional level, climate change policy is part of the context, as is population growth at national level (see Table 2) (see Tab. A7 in the Appendix).

Alternative states were extracted from the literature and expert adjustments (see Tab. 7 in the Appendix). Where data availability and the nature of the descriptor permit, these states are quantified to provide empirical grounding for potential future developments.

Interaction assessment between descriptors is a fundamental component of the CIB. This involves evaluating the interdependence between various factors within

Table 2 Descriptors and their possible states

	Descriptor	States			Category		
					National level	Regional level	Sub-regional level
A	General climate policy	Unchanged targets	Weakened targets	Tightened targets	M^P	C	C
B	General Hydrogen price and availability	Low price and large quantity	High price and low quantity		C	C	C
C	Population growth in the region	Stagnates	Rises		C	C	C
D	Rural–Urban development	Predominantly urban areas grow	Predominantly rural areas grow		(C)	(C)	(C)
E	Living concept	Sustainable neighborhoods	Conventional multi- and single-family houses		*D*	*D*	*D*
F	Heat-pump-driven household electricity demand	Moderate	High		R	R	R
G	EV-driven household electricity demand	Moderate	High		R	R	R
H	Home office use	Low	High		(M^{HH})	(M^{HH})	(M^{HH})
I	Work-related traffic	Decreases	Increases		*D*	*D*	*D*
J	Non-work-related traffic	Decreases	Increases		*D*	*D*	*D*
K	Use of carsharing	Low	High		(M^{HH})	(M^{HH})	(M^{HH})
L	MIT use (except carsharing)	Unchanged	Increased		(M^{HH})	(M^{HH})	(M^{HH})
M	Expansion of cycle paths	Restrained	Progressive		M^P	M^P	M^P
N	Expansion of public transport	Restrained	Progressive		M^P	M^P	M^P
O	Public transport ticket price	Cheap	Expensive		*(C)*	*(C)*	*(C)*
P	Expansion of public charging points	Restrained	Progressive		M^P	M^P	M^P
Q	Electricity price at charging stations	Cheap	Expensive		*R*	*R*	*R*
R	Expansion of H2 fuel stations	Restrained	Progressive		*R*	*R*	*R*
S	H2 price at fuel stations	Cheap	Expensive		*R*	*R*	*R*
T	Mobility concepts	Not coordinated	Coordinated		M^P	M^P	M^P
U	Local response to energy infrastructure expansion	Resistance	Acceptance		*C*	*C*	*C*
V	Local response to road network expansion	Resistance	Acceptance		*C*	*C*	*C*
W	Local response to rail network expansion	Resistance	Acceptance		*C*	*C*	*C*
X	Tourist traffic	Low	High		M^P	M^P	M^P
Y	Increase in H2 demand in industry	Low	High		*R*	*R*	*R*
Z	Energy-intensive industry	Decrease	Increase		M^P	M^P	M^P
ZA	Driving technology for trucks	Trend to H2 trucks	Trend to battery trucks		*C*	*C*	*C*

M^P Measure; descriptor's state set by policy, (M^P): Measure; descriptor's state set by policy whereas the descriptor is impacted other factors, (M^{hh}): Measure; descriptor's state set by households whereas the descriptor is impacted by other factors, *C* Context; descriptor's state impacts other descriptors significantly without being impacted, (*C*) Context; descriptor's states reflect framework, whereas descriptor's state is partially impacted by other context descriptors, *D* Descriptor is strongly impacted by other descriptors by impacting strongly other descriptors, *R* Results; descriptor with low or no impacts on others a complex system. Specifically, it involves judging how the state of one descriptor influences the potential future state(s) of another descriptor. In this study, we adopted the standard CIB approach, assessing interlinkages using a scale ranging from −3 (strongly restrictive) to + 3 (strongly promotional) [11].

The cross-impact matrix which represents all evaluated cross-impacts, as well as the sources used to assess the interdependencies, is shown as Tab. 11 in the Appendix. The table shows relatively high connections between factors. Since, it difficult to identify context factors that aren't impacted by other descriptors, in addition to the standard categorization of descriptor into "contexts", "measures" and "results" we introduce new categories of descriptors describing descriptors with states partially impacted by other context descriptors, and descriptor being strongly impacted by other descriptors whereby simultaneously impacted strongly other descriptors.

Drill-down approach

In principle, subregions differ with respect to underlying economic, societal and technological structure. Hence, conclusions on impacts of measures as well as developments on regional or national levels can only be applied subregions to a limited extent.

To assess possible developments at the subregional level, caused by changes on national or regional level, we distinct between three different types of descriptors:

> Type 1: Descriptors whose states are universally applicable, i.e., have the same effect across all subregions.
> Type 2: Descriptors with states expressed as percentage changes, which, when combined with subregion specific stock levels, end up in different absolute terms and thus, can be used for describing heterogeneity in the impacts on the subregions.
> Type 3: Descriptors whose states' manifestations differ by subregion. As example, depending on the subregion, a "High" of the descriptor "EV-driven household electricity demand" can mean an increase to 45% whereas in another subregion "High" stands for increase to 90%.

In our case study, as examples the descriptors "A General climate policy", "B General H2 price and availability" and "Q Electricity price at charging stations" belong to the first type of descriptors, the descriptors "C Population growth in the region", "F Heat-pump-driven household electricity demand" as well as "H Home office use" to the second, and the factors "D Rural–Urban development", "E Living concept" and "G EV-driven household electricity demand" to type of descriptors with subregional specific concretizations of states (see Tab. 9 in the Appendix).

In our case study, we describe subregions by using information of the different descriptors types whereas states of type 2 descriptors are scaled up by using information on subregion-specific characteristics of stocks (such number of inhabitants and number of buildings) and type 3 descriptors are considered with their subregional-specific manifestation of the states.

While type 2 descriptors of category support application of the region-based CIB approach flexible for analysis of in manifolds subregional contexts, the fixing of manifestations of states for subregions (type 3 descriptors) limits the application for other contexts.

The information gained by the subregional CIB analyses can serve as input for further research. In particular, it can be used as input factor for additional tools. Examples for such an approach are demonstrated by Pregger et al. [10] and Vögele et al. [36]. In these studies, descriptors states are translated into quantitative figures which afterwards used as input factors in techno-economic models. In this context, a soft-linking approach[2] is particularly suitable, as it allows individual aspects—such as the supply and demand for energy—to be examined in greater detail without 1) requiring socio-economic factors to be firmly integrated into the model and 2) being flexible to apply the tools for assessments of different case studies.

The provision of consistent setting of states in combination with concrete quantifications of the states can support.

- accurate assessment of impact of policy measure on subregions by taking subregion-specific socio-techno-economic context such as possibility for modifications of public transport or changes in tourism into consideration or constraints (and needs) for a transformation of local energy systems and
- serve as starting point for participations processes.

Results

In the following, we apply our approach to identify settings that are internally consistent. In doing so, we demonstrate both the results of the interaction between various factors (incl. contexts and measures) and the range of possible developments (Fig. 2).

Scenario selection

In total, we identified 129 consistent scenarios that represent possible futures. In the following, we examine scenarios associated with different climate change policies to identify the policies' associated constellations.

[2] "Soft linking" means that results are transferred from one model to another without a fixed connection between the models. The results are therefore only transferred when the modeler takes action [98].

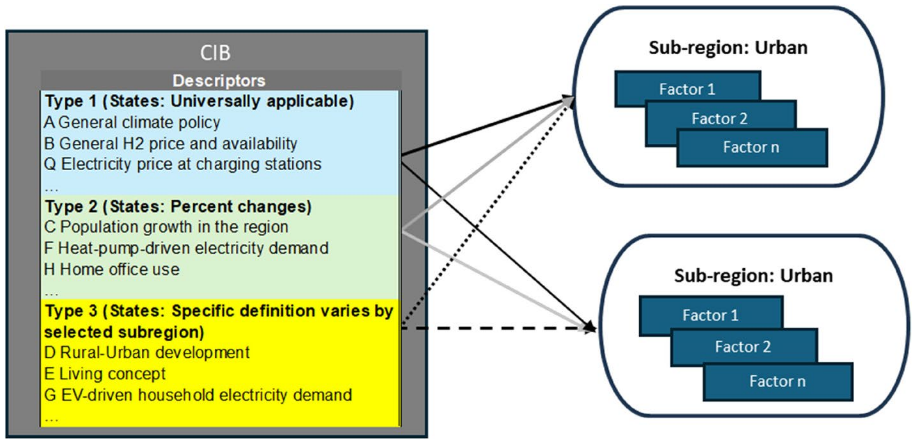

Fig. 2 Drill-down approach. Remarks: Grey arrows: Combination with information on subregional-specific stocks. Dotted arrows: subregional-specific data

Table 3 Distribution of descriptors' states in different scenario settings

		Weakened targets		Unchanged targets		Tightened targets	
		State 1	State 2	State 1	State 2	State 1	State 2
Population growth: Stagnation	K Use of carsharing	low: 12%	high: 89%	low: 37%	high: 63%	low: 0%	high: 100%
	N Expansion of public transport	restr.: 46%	progress.: 54%	restr.: 53%	progress.: 47%	restr.: 0%	progress.: 100%
	P Expansion of public charging points	restr.: 35%	progress.: 65%	restr.: 32%	progress.: 68%	restr.: 0%	progress.: 100%
	Q Electricity price at charging stations	cheap: 31%	expensive: 69%	cheap: 68%	expensive: 32%	cheap: 100%	expensive: 0%
	R Expansion of H2 fuel stations	rest.: 92%	progress.: 8%	rest.: 58%	progress.: 42%	rest.: 20%	progress.: 80%
	S H2 price at fuel stations	cheap: 15%	expensive: 85%	cheap: 42%	expensive: 58%	cheap: 70%	expensive: 30%
	U Local response to energy infrastructure expansion	resist.: 62%	accept.: 39%	resist.: 63%	accept.: 37%	resist.: 35%	accept.: 65%
	W Local response to rail network expansion	resist.: 46%	accept.: 54%	resist.: 53%	accept.: 47%	resist.: 0%	accept.: 100%
Population growth: Increasing	K Use of carsharing	low: 46%	high: 54%	low: 71%	high: 29%	low: 60%	high: 40%
	N Expansion of public transport	restr.: 69%	progress.: 31%	restr.: 57%	progress.: 43%	restr.: 0%	progress.: 100%
	P Expansion of public charging points	restr.: 6%	progress.: 94%	restr.: 7%	progress.: 93%	restr.: 0%	progress.: 100%
	Q Electricity price at charging stations	cheap: 46%	expensive: 54%	cheap: 93%	expensive: 7%	cheap: 100%	expensive: 0%
	R Expansion of H2 fuel stations	rest.: 97%	progress.: 3%	rest.: 79%	progress.: 21%	rest.: 20%	progress.: 80%
	S H2 price at fuel stations	cheap: 6%	expensive: 94%	cheap: 21%	expensive: 79%	cheap: 67%	expensive: 33%
	U Local response to energy infrastructure expansion	resist.: 80%	accept.: 20%	resist.: 71%	accept.: 29%	resist.: 27%	accept.: 73%
	W Local response to rail network expansion	resist.: 69%	accept.: 31%	resist.: 57%	accept.: 43%	resist.: 0%	accept.: 100%

Regarding the interpretation of the results, it should be noted that, since the CIB focuses on consistent scenarios resulting from a system with feedback loops, the setting of the descriptors' states can be both a precondition and a result of the policies.

Results on regional level

Table 3 shows the selected results for the different policies. To account for the impact of changes in population, we distinguish between scenarios with and without significant population growth.

In Table 3 we focus on the distribution of descriptor states. In principle, the distribution of descriptors' states does not allow us to draw conclusions about probabilities. However, if a descriptor's state does not appear in the resulting set of descriptor states, then it is unlikely that the corresponding scenario is linked to that state. However, if a descriptor state dominates, we can conclude that there are more consistent settings with that descriptor state than with an alternative state.

In the example of stagnating population growth and weakened climate change policies, all descriptor states are possible. In the setting with unchanged policy, no state can be excluded either. Scenarios with tightened climate policy targets are essentially associated with expansions of car-sharing, public transportation systems, and public charging systems. Assuming population growth, the results change. In the case of weakened policy targets, the share of scenarios with an expansion of public charging states increases. Additionally, more scenarios are aligned with the expansion of public charging stations. Unlike the set of scenarios with unchanged policies, the share of scenarios with low electricity prices also rises. In the set of scenarios with tightened targets, the share of scenarios with an increase in electric mobility rises, resulting in reduced car-sharing.

Results on subregional level

Using subregion-specific definitions of states enables us to describe developments at the subregional level. Tab. 4 shows examples of the realization of descriptor states at the subregional level, which differ by subregion. "Kreis Euskirchen" serves as an example of a rural area, whereas "Städteregion Aachen" stands for a predominantly urban/non-rural[3] subregion.

The results are achieved by using the states of type 1 descriptors' as factors and scaled states of type 2 descriptors as general framework for the system. For the scaling we linked the states of type 2 descriptor with structural information. As example we linked "Population growth" with the number of inhabitants and "Changes in electricity demand for heat pumps" with number of households. Subregion-specific manifestations of descriptor states (type 3) complement the systems under consideration.

In the selected examples, high car-sharing usage means that the share of car-sharing in rural areas increases to 0.35%, whereas in urban areas, 1% is expected. More significant are the differences in the shares of households with private charging infrastructure. According to this aspect, we expect a higher potential in urban areas than in city/urban areas, resulting from the availability of roof-based PV.

Table 5 shows how developments at the upper levels impacts development at the subregional level. In the present example, we focus on the impact of an increase in work-related and non-work-related traffic, as well as EV-driven household electricity demand, which serves as an indicator of the combination of e-mobility and private charging infrastructure. As expected, climate policy and changes in the number of inhabitants significantly impact the promotion or restriction of increases in traffic. The impact of these descriptors differs by subregion due to subregion-specific action options. For example, trends toward higher growth in rural subregions are linked with an increase in traffic unless more home office work is a significant option. In addition to this less surprising result, our analysis shows that in urban areas, tightened climate change policies result in lower private electric car charging usage than under an unchanged policy, since an increase in public charging stations and expansion of public transportation are realized.

As mentioned, some descriptor states can be set be stakeholder (in particular by municipal governments). In Table 6 we take closer look on contexts and other factors impacting the corresponding descriptors. As examples we chose "N Expansion of public transport", "T Mobility concepts", and "Z Energy-intensive industry". We assume that municipal governments can decide on the realization of states of these descriptors.

Table 4 Example for manifestation of descriptors' states on subregional level

Tightened targets		**Region**	**Subregions**	
			Rural Region (Example: "Kreis Euskirchen ")	**City/Urban Region (Example: "Städtere-gion Aachen")**
Population growth: Stagnation	K Use of carsharing: Share on modal split	**High**	0.35% in 2030 (0.1% p.a.)	1% (2030)
	G EV-driven household electricity demand: Share of households with private charging infrastructure	**Low**	60% (2045)	30% (2025)
	P Expansion of public charging points	**High**	58 MW (2045)	225 (MW)
	Z Energy-intensive industry	<u>**Low**</u>/high increase	3 new large industry projects/9 projects	2 new large industry pro-jects/7 projects
Population growth: Increase	K Use of carsharing: Share on modal split	<u>**Low**</u>/high*	< 0.35%/> 0.35% (2030)	0.8%/1% (2030)
	G EV-driven household elec-tricity demand: Share of Households with private Charging infrastructure	Low/**high**	60%/90% (2045)	30%/45% (2025)
	P Expansion of public charging points	High	58 MW (2045)	225 (MW)
	Z Energy-intensive industry	<u>**low**</u>/high increase	3 new large industry pro-jects/9 projects	2 new large industry pro-jects/7 projects

[3] Predominantly urban is used by Eurostat as classification for NUTS level 3 regions where more than 80% of the population live in urban clusters [99]. Non-rural is classification used by Thünen Institute for distinguishing regions [42].

Table 5 Impact on states "increase"

Impacting Descriptors			Impacted Descriptors					
			Work-related traffic		**Non-work-related traffic**		**EV-driven household electricity demand**	
Climate change	**Population**	**Rural-Urban development**	**Urban/non-rural area**	**Rural area**	**Urban/non-rural**	**Rural area**	**Urban/non-rural**	**Rural area**
Un-changed	Stag	predom. urban areas grow	2.0	2.0	0.0	0.0	1.0	1.0
	Stag	predom rural areas grow	0.8	1.6	-2.0	-1.6	-1.9	0.1
	Rise	predom. urban areas grow	2.0	6.0	9.0	8.0	5.0	10.0
	Rise	predom rural areas grow	2.0	3.9	3.2	2.8	0.5	3.2
Tightened	Stag	predom. urban areas grow	-1.4	0.6	2.0	3.0	-4.0	-1.0
	Stag	predom rural areas grow	-1.7	0.3	1.7	2.7	-3.7	-0.4
	Rise	predom. urban areas grow	0.3	2.3	4.7	5.7	-1.7	1.7
	Rise	predom rural areas grow	-1.4	2.6	7.0	6.0	4.0	9.0

Corresponding to the standard CIB approach, e.g. −3 means strong restriction and +3 strong promotion by one factor or proportional support by several factors. In this example the numbers reflect the impacts on descriptors' specific states "increase"

Table 6 Impacts on "Measures"

A General climate policy D Rural–Urban development ***T Mobility concepts*** ↓	***T Mobility concepts*** ↓ W Local response to rail network expansion ↓	A General climate policy J Non-work-related traffic M Expansion of cycle paths ***T Mobility concepts*** ↓ ***X Tourist traffic*** ↓	A General climate policy C Population growth D Rural–Urban development ***N Expansion of public transport*** ***T Mobility concepts*** ↓ E Living concept ↓	A General climate policy D Rural–Urban development ***T Mobility concepts*** W Local response to rail network expansion ***X Tourist traffic*** ↓ ***N Expansion of public transport*** ↓	A General climate policy ↓	B General H2 price and availability ↓
N Expansion of public transport			***T Mobility concepts***		***Z Energy-intensive industry***	

Bold: Descriptor of the category "Measures"

According to the information provided in the Cross-Impact Balance matrix, these descriptors are directly influenced by factors which are themselves impacted, for instance, by factors including contextual factors as well as realized states of other "measure"- descriptors. In the case of the specification of a "Expansion of public transport" the measure selection will be impacted by the manifestations of "General climate policy", "D Rural–Urban development", "Mobility concepts" as well as "Local response to rail network expansion" and "Tourist traffic" whereas, for instance, "Tourist traffic" will be impacted by the context descriptor "General climate policy".

The results thus support the notion that a linear relationship between context, intervention and outcome is often absent and that feedback loops and interactions necessitate anticipation of the need for readjustment. Accordingly, interventions should be designed to allow for this.

All in all, our scenarios provide insights into the impacts of policy measure and changes in contexts in complex systems by ensuring consistency within the systems. The scenarios underline the openness of future and thus, the need to be ready for possible adjustments of policies.

Discussion

Practical implications

Current concepts for the region usually point to a continuous, but not radical, transformation. More or less these concepts correspond to our "Climate change policy—Unchanged targets" scenarios. The focus of the spatial strategy 2038 + on a climate-neutral model region [4] supports the strengthened climate goals of the scenarios belonging to "Climate change policy—Tightened targets". The concept indicates a high-performance public transport system, which is assumed to be the best case.

Some concepts reveal aspects that could correspond with our scenarios "Climate change policy—Weakened targets", as they highlight MIT dominance [30]. Gaps in the cycle path network could indicate stagnation or declining expansion [30]. While climate-friendly transport is addressed [31], the necessity of many measures points to possible implementation difficulties due to lack of coordination, similar to the stagnation in the scenarios "Weakened targets". Resistance against certain measures corresponds to the local rejection of railway network expansion [31].

The analyzed concept papers, in comparison to the developed CIB scenarios, exhibit a narrower focus on specific sectors or regions within the Rhenish mining area, while the scenarios adopt a broader, mobility-centric perspective. Furthermore, they focus on different time horizons ranging from 2030 to 2045. It is notable that the concept papers tend to ignore negative development directions and strive for a more desirable future paths, lacking proposals to counteract undesirable developments, although challenges such as acceptance problems are mentioned. The developed cross-impact matrix serves to specify as many aspects of structural change as possible through descriptors and their states.

With regard to positioning within the research context and starting from the central theme of structural change, relevant parallels can be identified with the Lausitz region, another region experiencing profound transformations due to the exit from coal mining [37]. While this study focuses on structural change and the role of integrated mobility concepts for reducing MIT, Heer et al. [37] investigate the development of guiding principles as orientation for regional decision-making in the context of the coal exit in the Lausitz region. The concepts of guiding principles and integrated mobility concepts can be understood as strategic orientation frameworks that are relevant in similar transformation contexts. The insights from Heer et al. [37] on the importance of participatory processes and the requirement for acceptance of future visions are also relevant for the mobility transformation in the Rhenish mining area. A potential research gap could therefore be seen in a more detailed analysis of the link between regional identity change in the region and the acceptance of new mobility concepts, an aspect that plays a role in comparable studies. Providing a tangible application case can leverage uncertainties and offer concrete guidelines for future developments. Our approach can serve as example for an that addresses such aspects.

The "Wirtschafts- und Strukturprogramm", visualizes a model region for a successful structural change, which is achieved through a common, integrative approach [38]. In the sense of the negative extreme scenario, the program addresses measures for quality assurance, monitoring, and evaluation as well as a reference to risk management [38], but no detailed measures for directly counteracting risks or large deviations. Therefore, a possible expansion of the research approach chosen here could be the stronger consideration and concretization of uncertainty factors that go beyond the specific context of structural change (or transition) to further increase the robustness of the developed scenarios. Both national as well as international political developments represent appropriate and important uncertainties that should be more comprehensively illuminated and discussed in the transformation process.

Research gaps can thus be closed, as the presented CIB approach provides a more detailed analysis of the specific challenges and potentials of the mobility transformation in the regional and subregional context. While Heer et al. [37] investigate the development of guiding principles and the described program represents an overarching framework [38], our study addresses the concrete role of integrated mobility concepts in the reduction of MIT in a region strongly affected by the coal phase-out. This includes the consideration of specific infrastructural, economic, and social factors of the underlying complex system.

In our study we showed how CIB being implemented for a region can be modified and applied for assessment on subregional level. Network analysis supports the selection of relevant descriptors, their possible states and the interactions between them. Hence, it serves as a helpful pillar for being able for conduction the CIB analysis.

Of course, the selected approach can be used for assessment of policies as well as changes in contexts in other regions consisting of heterogenous subregions and being coped with structural changes. Type 2 and type 3 descriptors can be used to easily assess subregional-level developments and could be implemented in standard CIB approaches with low effort.

Like in the Rhenish mining area usually effects of policy measures on regional or subregional are assessed by conducting socio-economic studies with different kinds of participation processes including employing partially techno-economic models as starting point for participation processes (see e.g., [39–41]).

As mentioned, application of CIB supports the identification of consistent socio-techno-economic scenarios taking perspective of different stakeholders into consideration and thus, enables to assess impacts of policies on complex systems consisting of qualitative and quantitative elements.

Limitations

Although a versatile and useful instrument for the analysis of complex systems, the method exhibits several limitations. A central criticism concerns the considerable resource requirements necessitated by conducting a CIB analysis, which inevitably leads to an aggregated consideration of the system and can therefore not seen as substitute for in-depth research [11]. Moreover, the principle of consistency, upon which the CIB method is based, also entails potential limitations. By focusing on internally consistent scenarios, there is a risk of potentially fruitful visions, which include inconsistent factor configurations, being excluded [8]. Despite its systematic approach, the CIB method cannot eliminate subjective elements. One's own worldview and that of all participants significantly influence the compilation of descriptors and the interpretation of results and can ultimately lead to specification errors or neglecting scenarios [13]. This became particularly clear through the absence of states expressing decline in the scenarios. Although the method increases overall objectivity through changing perspectives, research bias and subjective expert assessments can distort the results [8]. Lastly, quantitatively harmonizing differing opinions on identical relationships is complex and not easily achievable. Therefore, it is important to emphasize that the CIB method is not a substitute for quantitative analyses or independent research. It is primarily suitable for processing qualitative information that is unsuitable for quantitative modeling and for a starting point for deeper analyses. Adequate mapping of temporal complexity is particularly critical to consider. The project objective strongly depends on a set timeline, and the results are to be presented in three anchor years. However, disruptions, delays, and fluctuations are difficult or impossible to capture [14].

Further research

The results showed that the effectiveness of integrated mobility concepts significantly depends on a supportive overall societal and political framework conditions resulting from the interplay of contexts and measures. Further studies could therefore investigate how such a context can be created and maintained, for example, by analyzing acceptance factors in the population, the influence of political control mechanisms, or the role of public relations. A more detailed consideration of the strategic implementation of integrated mobility concepts could also contribute to maximizing the opportunities for a sustainable mobility transition in the region.

All in all, CIB analyses can be seen as an important starting point for carrying out consistent scenario which can serve as starting of further activities including stakeholder consulting processes or techno-economic analyses.

Conclusions

In our study, we presented an example of how to create possible development paths for a region with subregions in a structured way, taking into account a variety of factors and using different sources of information including factors individual stakeholders are interest in. Methodologically, we demonstrated that CIB analysis in combination with network analysis can be readily employed for drill-down analyses, considering, for instance, the differential impact of policy measures on subregions. Thus, it became apparent that the limitation of CIB analysis to a small number of descriptors does not have to constrain the analysis of complex systems.

Based on the results of the developed scenarios, it can be concluded that integrated mobility concepts can assume a significant, albeit conditional, importance. Their ability to make a substantial contribution is significantly linked to the presence of certain promoting framework conditions, while their effect remains limited under the influence of inhibiting factors. Broad societal acceptance of these changes, particularly the development of the rail network, and structural changes that reduce individual mobility demand, reinforce this effect.

Given the limitations of the CIB method, especially regarding the mapping of temporal complexity and potential subjective influences, complementary quantitative analyses and the development of dynamic models could provide valuable insights for more detailed and robust futures research in the field of mobility in the region.

Accompanying research can unravel the impacts of these projects on the regional economy, the labor market, and the social structure. Furthermore, the effectiveness of relevant stakeholders, in the governance and coordination of structural change and the engagement of various stakeholders should be investigated.

Appendix

Table 7 Network-analysis: factors

Factors	Description	Type of source*
Acceptance of new means of transport	Creation of practical alternatives to cars in order to increase acceptance of new modes of transport	C, R, W
Expansion of public transport	Expansion of the public transport network and local rail passenger transport (SPNV), especially in terms of frequency, connections, and networking	C, R, W
Accessibility	Expansion of accessibility throughout the entire municipal area is necessary to ensure participation in mobility	C, R
Participation of the population	Active involvement of the population in the planning process and raising awareness of sustainable mobility	C, W
Energy demand	Population growth and structural change results in changes in energy demand	C, W
Land development and logistics	Integration of logistics concepts and the development of commercial and industrial areas into mobility planning	C, W
Freight transport concepts	Development of concepts for freight and goods transport that is compatible with the community, with the aim of reducing heavy goods traffic	C, W
Focus on innovation	Promotion of innovations and technologies in the field of mobility	R
Inter-municipal cooperation	Coordination and cooperation with surrounding municipalities for networked mobility	C, W

Table 7 Network-analysis: factors

Factors	Description	Type of source*
Climate protection goals	The need to reduce greenhouse gas emissions, which requires the development of low-carbon and sustainable forms of mobility	C, R, W
Municipal planning & Prioritization	Prioritization of eco-friendly transport (public transport > cycling > walking > motorized individual transport) in municipal planning	C, W
Charging infrastructure	Expansion of the charging infrastructure for electric vehicles in public spaces	C, R, W
Mobility management	Operational, neighborhood, and school mobility management to promote sustainable mobility	C, W
Multimodal mobility	Linking different modes of transport and creating multimodal transfer points	C, R
New forms of mobility	Introduction of new forms of mobility such as car sharing, bike sharing, and on-demand transport	C, R
Public relations & communication	Targeted public relations and mobility campaigns to raise awareness of sustainable mobility	C, W
Parking space management	Development of parking space concepts to reduce parking pressure in district centers	C, R
Quality of public transport	Quality of vehicles, stop facilities, digital information boards, and barrier-free access being relevant for the attractiveness of public transport	C, R
Cycling infrastructure	Expansion and improvement of cycling infrastructure, including cycle paths, parking facilities, and uniform cycle routing	C, R, W
Spatial planning	Plannings taking basic functions (living, working, education, leisure) into account to support short distances mobility	C, R, W
Motorized individual transport	Share of motorized individual transport (MIT) in the modal split	C, W
Eco-friendly transport	Promotion of public transport, cycling, and walking as sustainable alternatives to motorized individual transport	C
Road space management	Adapting of road space design to the needs of all road users, especially eco-friendly transport	C, R
Structural change	Taking into account structural change caused by the phase-out of coal phase-out and its effects on the region	C, W
Energy infrastructure	Phase-out of lignite will lead to changes in supply chains and voltage qualities	C, W
Economy	Political measures and the phase-out of lignite are leading to changes in the regional economic structure	C, W
Traffic safety	Improving traffic safety	C, R

Remarks: * (C) Concepts, (R) literature review, (W) workshop

Table 8 Comparison factors identified by network analysis and descriptor being used by CIB

Factors (Network-analysis)	Corresponding Descriptors (CIB)
Accessibility Participation of the population Land development and logistics Freight transport concepts Inter-municipal cooperation Municipal planning & Prioritization Multimodal mobility Public relations & communication Parking space management Quality of public transport Spatial planning Road space management Eco-friendly transport Traffic safety	Part of T Mobility concepts
Acceptance of new means of transport	U Local response to energy infrastructure expansion V Local response to road network expansion W Local response to rail network expansion
Expansion of public transport	N Expansion of public transport
Energy demand	F Heat-pump-driven household electricity demand Y Increase in H2 demand in industry
Focus on innovation	ZA Drive technology for trucks
Climate protection goals	A General climate policy
Charging infrastructure	P Expansion of public charging points

Table 8 Comparison factors identified by network analysis and descriptor being used by CIB

Factors (Network-analysis)	Corresponding Descriptors (CIB)
Mobility management	T Mobility concepts
New forms of mobility	K Use of carsharing
Cycling infrastructure	M Expansion of cycle paths
Motorized individual transport	I Work-related traffic X Tourist traffic J Non-work-related traffic
Structural change	D Rural–Urban development
Change in energy infrastructure	R Expansion of H2 fuel stations
Economy	Z Energy-intensive industry
Population growth	C Population growth in the region
	B General H2 price and availability E Living concept H Home office use L MIT use (except carsharing) Q Electricity price at charging stations R Expansion of H2 fuel stations S H2 price at fuel stations

Table 9 Classification of subregions of the "Rhenish mining area"

Kreis Düren	Rhein-Erft-Kreis	Kreis Eus-kirchen	Kreis Heinsberg	Städteregion Aachen	Mönchengladbach	Rhein-Kreis Neuss	Source
Rural	Non-rural	Rural	Rural	Non-rural	Non-rural	Non-rural	[42]
Intermediate	Predominantly urban	Intermediate	Intermediate	Predominantly urban	Predominantly urban	Predominantly urban	

Table 10 Descriptors and their states

	Kreis Düren	Rhein-Erft-Kreis	Kreis Eu-skirchen	Kreis Heinsberg	Städteregion Aachen	Mönchengla-dbach	Rhein-Kreis Neuss	Sources for specification of descriptors
	DEA26	DEA27	DEA28	DEA29	DEA2D	DEA15	DEA1D	
General climate policy								
• weakened targets	The current climate protection targets are not being prioritized by politicians							
• unchanged targets	Policy aims to archive current climate protection targets							
• tightened targets	Policy aims to achieve climate protection targets earlier and thus, reduction measures will be extended or reinforced							
General H2 price and availability								[43]
• low price and large quantity	Less than €7.88/kg H2 and more than 0.86 million tons of H2 per year available in North Rhine-Westphalia for industry and mobility							
• high price and low quantity	Over €8.91/kg H2 and less than 0.86 million tons of H2 per year available in North Rhine-Westphalia for industry and mobility							
Population growth in the region								
• stagnates	0% p.a							
• rises	> 1% p.a							
Rural–Urban development								
• predominantly urban areas grow	Growth: Urban areas + 5%, rural areas 0%							
• predominantly rural areas grow	Growth: Urban areas + 0%, rural areas 5%							
Living concept								
• sustainable neighborhoods	In urban areas: 1.9% of flats and in rural area 0.5 are located in sustainable quarters							
• conventional multi- and single-family houses	In urban areas: 0.19% of flats and in rural area 0.05 are located in sustainable quarters							

Table 10 Descriptors and their states

	Kreis Düren	Rhein-Erft-Kreis	Kreis Eu-skirchen	Kreis Heinsberg	Städteregion Aachen	Mönchengla-dbach	Rhein-Kreis Neuss	Sources for specification of descriptors
Heat-pump-driven household electricity demand								
• moderate	Share households using heat pumps: 30%							
• high	Share households using heat pumps: 50%							
EV-driven household electricity demand								
• moderate	Percentage of households with private charging infrastructure 2045: Urban 30%, rural: 60%							
• high	Percentage of households with private charging infrastructure 2045: Urban 45%, rural: 90%							
Home office use								[44]
• low	On average, employees work 0.5 working days per week from home							
• high	On average, employees work one day per week from home							
Work-related traffic								
• decreases	higher unemployment rate (+ 0.2%) and hence, less work traffic							
• increases	Lower unemployment (1%) and hence, more work traffic							
Non-work-related traffic								[45]
• decreases	More cultural offerings in the region, nearby educational institutions, shops, and local medical care will reduce the distance traveled for these purposes by around 10% compared to 2025							
• increases	Due to fewer cultural offerings in the region, nearby educational institutions, shops, and local medical care, the distance traveled for these purposes will increase by about 5% compared to 2025							
Use of carsharing								[46]
• low	Increase: Less than 0.1%/year							
• high	Increase: More than 0.1%/year							
MIT use (except carsharing)								[31, 47]
• decreased	MIT share in modal split decreases by 5.6% until 2030, decreases by 11.3% until 2038, decreases by 16.2% by 2045 in the Rhenish Region (according to region-specific results of the "Shift" scenario from Arnz and Krumm (2023), including a range of pull measures towards public and active transport)							
• increased	MIT share in modal split stays constant overall years (constantly observed share across the last three "Mobilität in Deutschland" studies for Germany is around 57%)							
Expansion of cycle paths								
• restrained	Closing of gaps in cycle highways to urban centers and workplaces							
• progressive	No closing of gaps in cycle highways to urban centers and workplaces							
Expansion of public transport								
• restrained	not defined in detail							
• progressive	not defined in detail							
Public transport ticket price								
• cheap	Price increase less than 5% p.a,							
• expensive	Prices increase more than 8% p.a,							
Expansion of public charging points								[48]
• restrained	2045: 95,738 kW	2045: 82,812 kW	2045: 32,845 kW	2045: 91,248 kW	2045: 118,411 kW	2045: 73,561 kW	2045: 129,290 kW	
• progressive	2045: 106,641 kW	2045: 179,890 kW	2045: 58,187 kW	2045: 95,123 kW	2045: 225,704 kW	2045: 98,118 kW	2045: 163,574 kW	
Electricity price at charging stations								[43]
• cheap	Less than 0.55 Euro/kWh							
• expensive	More than 0.55 Euro/kWh							
Expansion of H2 fuel stations								
• restrained	< 1 p.a	< 0.8 p.a	< 1.4 p.a	< 0.7 p.a	< 0.8 p.a	< 0.19 p.a	< 0.65 p.a	
• progressive	> 1 p.a	< 0.8 p.a	> 1.4 p.a	> 0.7 p.a	> 0.8 p.a	> 0.19 p.a	> 0.65 p.a	
H2 price at fuel stations								[49]
• cheap	350 bar: less than 13.75€/kg, 700 bar: less than 15.25€/kg							
• expensive	350 bar: more than 13.75€/kg, 700 bar: more than 15.25€/kg							
Mobility concepts								
• not coordinated	No change							
• coordinated	One integration concept per district every two years							

Table 10 Descriptors and their states

	Kreis Düren	**Rhein-Erft-Kreis**	**Kreis Euskirchen**	**Kreis Heinsberg**	**Städteregion Aachen**	**Mönchengladbach**	**Rhein-Kreis Neuss**	**Sources for specification of descriptors**
Local response to energy infrastructure expansion								
• resistance	Not defined in detail							
• acceptance	Not defined in detail							
Local response to road network expansion								
• resistance	not defined in concrete numbers							
• acceptance	not defined in concrete numbers							
Local response to rail network expansion								
• resistance	not defined in concrete numbers							
• acceptance	not defined in concrete numbers							
Tourist traffic								[50]
• Restrained	< 529,470 overnight stays p. a	< 1,145,718	< 719,521	< 222,000	< 1,326,040	< 318,269	< 779,144	
• Increased	> 529,470 overnight stays per year	> 1,145,718	> 719,521	> 222,000	> 1,326,040	> 318,269	> 779,144	
Increase in H2 demand in industry								
• Low	not defined in detail							
• high	not defined in detail							
Energy-intensive industry								[43]
• decrease	No more than 5 industrial projects until 2038, then none more after that	No more than 6 industrial projects until 2038, then none more after that	No more than 3 industrial projects until 2038, then none more after that.,	No more than 4 industrial projects until 2038, then none more after that	No more than 2 industrial projects until 2038, then none more after that	No more than 3 industrial projects until 2038, then none more after that	No more than 4 industrial projects until 2038, then none more after that	
• increase	16 industrial projects until 2045	18 industrial projects until 2045	9 industrial projects until 2045	13 industrial projects until 2045	7 industrial projects until 2045	10 industrial projects until 2045	12 industrial projects until 2045	
Driving technology for trucks								[51]
• Trend to H2 trucks	35% of all trucks are hydrogen powered in 2045							
• Trend to battery trucks	99% of all trucks are battery electric (incl. hybrid overhead wire) in 2045							

Table 11 Bibliography cross-impact influences

Effect	**Literature**	**Reason (Own translation)**
A ➜ B	[51]	"At the same time, investment in conventional vehicles will be increased. H2 will be promoted as a fuel. [...] PtX and BtX are available in large quantities and will be promoted in the transport sector with the aim of reducing greenhouse gas emissions."
A ➜ E	Interview with stakeholder	
A ➜ F	[52]	P. 313ff. "German policymakers have already identified heat pumps as a key technology for climate protection in the heating sector. [...] In all scenarios, the target set by the traffic light coalition of 80 percent renewable energy in electricity consumption will be achieved. This includes the electricity consumption of electric vehicles and electrolysis hydrogen. The additional electricity required by heat pumps must be covered entirely by additional renewable energy sources over the course of a year in all scenarios."
A ➜ G	[53]	Esp. p. 149ff. "In particular, it will be important to closely track the uptake of electric 2/3Ws[a] and their role in oil displacement: electric 2/3Ws may displace active modes of travel such as walking or cycling, rather than just fossil-powered transport, which is the assumption underlying the STEPS and APS. This highlights that while EVs are an important component of transport decarbonization, they are far from being the only one."
A ➜ K	[54]	"Although EV use in carsharing fleets declined in favor of gasoline-electric hybrid vehicles in the early to mid-2000s, improved technology and favorable policy has led to an emerging resurgence of EVs in shared-mobility services."

Table 11 Bibliography cross-impact influences

Effect	Literature	Reason (Own translation)
A ➞ L	[55]	"The goal of a 1.5-degree-compatible transport policy must therefore be to create new framework conditions in which emission-free mobility can flourish. However, as the Expert Council for Climate Issues points out in its 2022 biennial report [5], it is not enough to create incentives for emission-free mobility while incentives for fossil-fuel-based mobility remain similarly high."
A ➞ M, N, O	[55]	The source and the concepts emphasize that motorized individual transport must be replaced or substituted as far as possible by alternatives. This means that both sides must take the relevant climate targets into account
A ➞ P	[56]	"Electric mobility […] will become a central component of the transport transition with the ban on combustion engines from 2035 recently agreed by European countries. […] The market for electric vehicles will grow strongly in the coming years [,] […] resulting in fundamental decisions on the direction to take for the development of the charging infrastructure."
A ➞ Q	[57]	"The additional electricity demand from electric vehicles also improves grid utilization. The combination of these two effects can lead to a reduction in specific grid fees in the low-voltage sector. The grid fee is part of the electricity price and represents a kind of rent for using the electricity grid. By smoothing the consumption curve, the grid is used more efficiently and the "rent" per unit of electricity consumed decreases."
A ➞ R	[58]	"Germany is committed to the ambitious targets set out in the European Regulation on the deployment of alternative fuels infrastructure (AFIR). The BMDV therefore supports the development of a robust and widely available alternative refueling infrastructure."
A ➞ S	[51]	See A➞ B: The scenarios envisage a large-scale and demand-oriented expansion of the H2 infrastructure for trucks, which is a necessary consequence if hydrogen is to play a significant role in achieving strict climate targets in the transport sector. A well-developed infrastructure can potentially contribute to more efficient logistics chains and thus to lower prices at filling stations
A ➞ X	[59]	"Since tourism is a cross-cutting industry and most countries do not have a separate tourism policy, climate-friendly tourism must also be managed through other policy areas and sectors, in particular transport and energy policy, but also construction policy, which is relevant for tourist accommodation. […] Legal and normative instruments can aim to ensure that the full climate costs are passed on to transport modes – for example, through the taxation of emissions, as has already been introduced in the form of the CO_2 tax."
A ➞ Y	[51]	see A➞ B: The scenarios imply a corresponding energy demand depending on which infrastructure is promoted and expanded
A ➞ ZA	[51]	See A➞ B: The promotion of H2 as a CO_2-neutral energy source suggests a shift in heavy-duty transport
B ➞ R, S, Y, Z, ZA	[51]	According to the T45-H2 scenario, high availability and low prices for hydrogen would lead to the large-scale development of a hydrogen filling station infrastructure for truck traffic. Although the source does not describe the industrial use of hydrogen in detail, it can be inferred that cheap and abundant hydrogen could make its use in industrial processes for decarbonization more attractive
C ➞ D	[60]	Despite the fact that growth in urban regions has declined in recent years, urban regions generally grow faster than rural areas
C ➞ E	Conclusion from the interview with stakeholder	In rural regions, there is often more space available for single-family homes and multi-family homes, so it can be assumed that these will be built simultaneously with sustainable neighborhoods. In cities, on the other hand, there is often a lack of space, which makes neighborhoods and similar solutions necessary
C ➞ F, G	[58, 61]	bpb: "In recent decades, the number of households has grown significantly faster than the population." Vattenfall: Per capita electricity consumption varies depending on the type of living space but decreases with each additional member of the household. For example, a 1-person household in an apartment building consumes 1,400kWh per year, while a 3-person household consumes 2,600kWh per year
C ➞ I, J	[62]	"The future growth in travel demand and in traffic would therefore arise essentially from population increase and other demographic changes. […] The implications of population increase for travel demand depend importantly on where the additional population is located, both as regards employment and residence."
C ➞ K, L	[63]	"Our findings highlight the importance of including analysis of subgroups based on density and/or population size in future studies of traffic congestion." Assuming that general traffic demand increases with rising population, it can be assumed that motorized individual transport will continue to be the predominant mode of transport for the Rhenish mining area. At the same time, public transport and similar alternatives (car sharing) will continue to be used and will become increasingly popular
C ➞ M, P	Interview with stakeholder	Cities grow through immigration and natural population growth, which leads to new construction projects, densification, and expansion of city boundaries. However, the corresponding expansion is already planned
D ➞ E	Conclusion from the interview with stakeholder	In rural areas, there is often more space available for single-family homes and multi-family homes, so it can be assumed that these will be built simultaneously with sustainable neighborhoods. In cities, on the other hand, there is often a lack of space, which makes neighborhoods and similar solutions necessary
D ➞ G, I, J, K, L	Conclusion from the interview with stakeholder	Based on the sources used for C➞ G, I, J, K, L, energy consumption and transport demand increase with rising population. It is assumed here that consumption and demand will therefore increase depending on population shifts to rural or urban regions

Table 11 Bibliography cross-impact influences

Effect	Literature	Reason (Own translation)
D ➞ M	Conclusion from the interview with stakeholder	The expansion of the cycle path network has been decided across municipalities. Growing municipalities may have a slight influence
D ➞ N	[64]	Rural regions show a clear dominance of private motor vehicle transport, while urban regions generally have a 15–25% share of public transport in the modal split. Cities are constantly striving to make public transport more accessible for growing populations and thus increasing passenger numbers. In rural regions, growth does not necessarily lead to more progressive expansion, but it can facilitate it
D ➞ N	[65]	"The positive correlation between population density and public charging points means that an increase in population density of 100 inhabitants per square kilometer is accompanied by an average increase of 2.2 public charging points per 100,000 inhabitants." Accordingly, demand for public charging stations is lower in rural areas, as many people can charge their vehicles at home or at work
D ➞ U	[66]	"The dynamic regulation of the energy transition by European and federal policy, which is often opaque to local politicians and administrators, leads to frustration and uncertainty at the regional and municipal levels. […] Another problem is that the burdens and benefits of expanding renewable energies are unevenly distributed. Local communities experience the burdens, such as the visibility of plants, emissions, and land use, directly, while the benefits, such as energy security and the contribution to regional climate protection, are not always directly apparent."
D ➞ W	[67]	"In addition to a well-developed infrastructure, it is important for sustainable mobility in rural areas to have infrastructure, it is important to have a local public transport system that is as dense and well-coordinated as possible. The federal government is providing the states with substantial financial support to help them meet this challenge with financial resources under the Regionalization Act." The source also emphasizes the increase in attractiveness resulting from the expansion, which implies fundamental approval
E ➞ C	Conclusion from the interview with stakeholder	More affordable housing makes municipalities more attractive to more people
E ➞ F, G	[61]	Neighborhoods are more energy-efficient than conventional housing options. The overall energy demand is therefore rather moderate in sustainable neighborhoods
E ➞ I, J	Conclusion from the interview with stakeholder	Sustainable neighborhoods encourage short commutes thanks to their structure. This can also reduce leisure traffic (shopping, playgrounds, etc.), but this varies greatly from person to person. The impact here is therefore weaker
E ➞ K	[68]	Car sharing is a central component of sustainable neighborhood development in North Rhine-Westphalia. It is being introduced in a targeted manner in sustainable neighborhoods and communities in order to reduce private car ownership, save space, and support the mobility transition
E ➞ L	[68], Concepts	Although the aim is to reduce motorized individual transport, the dominance of cars in the scenarios must be taken into account
E ➞ M	Interview with stakeholder	The expansion of bike paths is planned in both the concepts and the neighborhood planning
E ➞ P	[69]	There are special subsidies for charging infrastructure in apartment buildings and neighborhoods—with grants of up to €1,500 per charging point and additional subsidies for grid connections and basic installations
E ➞ T	Our conclusion	Subsidies and overarching projects such as QuartierNRW could encourage municipalities to coordinate other planning projects
E ➞ U	Own conclusion from [70]	51ff.: If the expansion of energy infrastructure for sustainable neighborhoods is perceived as favoring conventional building designs, resistance groups could form that see their own interests (e.g., preserving the option to build conventional single-family homes/multi-family homes) as threatened
G ➞ K	[64]	Our conclusion from p. 33ff.: Charging your own electric car at home can significantly increase your electricity bill, especially if household electricity prices rise or the grid connection (e.g., in apartment buildings) is limited. Car sharing offers an alternative here, as the costs for electricity, maintenance, and charging infrastructure are included in the usage price and are not incurred individually
H ➞ I, J	[71]	Working from home a lot leads to shorter or less frequent commutes. Leisure travel, on the other hand, is individual. Working models such as "workation" can also play a role here
I ➞ G	[48]	More commutes generally lead to more mileage and thus to higher energy demand in the transport sector, especially if these journeys are made with electric vehicles. Since the majority of electric car users charge their vehicles at home (50–74% of home charging by 2030, depending on the study), an increase in commuting with electric vehicles means that more electricity will also be needed in households for charging
I ➞ J	[72]	"Part-time teleworkers commute less than those who never telework There is a rebound effect on non-work travel for part-time teleworkers."
I ➞ L	[47]	More frequent or longer commutes lead to an increase in personal mobility needs. Most commutes are made by car

Table 11 Bibliography cross-impact influences

Effect	Literature	Reason (Own translation)
I ➜ V	Own conclusion	If most people drive to work, it can be assumed that road network expansion (and thus alternative routes) will be welcomed
J ➜ G	See I G	Argument transferable
J ➜ I	See I J	Argument transferable
J ➜ K, L	Own conclusion	As private mobility needs increase, so does the use of cars, car sharing, and alternative means of transportation
J ➜ X	Own conclusion	Tourism traffic can be considered private mobility in this context. If private mobility declines, tourism traffic will decline as well
K ➜ G	[73]	Carsharing vehicles are charged centrally, often at special stations. The electricity required to charge the carsharing fleet is thus shifted from individual households to the operators of the carsharing services. However, depending on usage, electricity can also be charged at home
K ➜ L	Own conclusion	When car sharing usage is high, it represents an alternative to motorized individual transport. If usage is low, people will drive more
L ➜ G	[74]	Most charging takes place at home, so charging an electric car significantly increases the electricity bill
L ➜ J	Conclusion from I	An increase in motorized individual transport tends to lead to more private rather than work-related mobility. Most commutes are made by car, so an increase tends to indicate non-work-related traffic
L ➜ K	See K L	Argument transferable
L ➜ M	[75]	p. 21: "The distribution of public road space often does not correspond to that of traffic volume, i.e., the proportions the types of traffic on the roads. Motorized individual transport is allocated a disproportionate amount of space. This reduces the attractiveness of active forms of mobility."
L ➜ P	See L M and E P	Infrastructure expansion is already planned and is being promoted. If motorized individual transport use were to decline, an inhibiting effect would be expected. Otherwise, more motorized individual transport would favor expansion
M ➜ H	Own conclusion	There is no clear evidence that good bicycle infrastructure directly influences the use of home offices. However, a weak influence can be assumed, as good bicycle infrastructure can lead to people using bicycles more often for their everyday journeys
M ➜ I	[76]	p. 124: "Those respondents who use a bicycle frequently did so primarily in their free time, for example to meet friends, go to the cinema, or ride to the park." It can therefore be assumed that leisure travel would increase with well-developed and safe bike lanes
M ➜ K	[76]	"In addition, ten of the respondents used their bikes to get to their parked cars or to the nearest public transport stop." Cycling is directly linked to public transport use, including car sharing, and would also promote this
M ➜ L	Own conclusion	As explained, motorized individual transport dominates, so the expansion of bike lanes alone will not lead to a decline. Neglecting to expand bike lanes, on the other hand, could lead to an increase in motorized individual transport use
M ➜ X	[77]	Cycling tourism is an important economic factor, especially for rural regions. High-quality cycle paths, clear signage, rest areas, e-bike charging stations, and digital route planners make regions more attractive to tourists and offer an optimal experience
N ➜ E	[78]	The expansion of public transport is a key component in the development of sustainable neighborhoods. However, its expansion (or lack thereof) has no influence on the expansion of single-family and multi-family homes
N ➜ J	[79]	An attractive and well-developed public transport system makes it easier for people to do leisure activities without a car. Services such as the Deutschlandticket or special leisure lines and routes that connect specific destinations encourage people to use public transport for excursions and leisure trips
N ➜ K	See [73] (K G)	A well-developed public transport system encourages people to use their own cars less often and instead use public transport and complementary services such as car sharing
N ➜ L	Own conclusion	Providing alternatives and, where appropriate, prioritizing the expansion of public transport reduces the number of private cars and the demand for parking spaces in public spaces
N ➜ M	[48]	Cycling and public transport are considered complementary components of the eco-mobility alliance. They complement each other perfectly, as many routes lead from the bicycle to the public transport stop and vice versa
N ➜ O	[80]	The expansion of public transport means higher running costs (e.g. for personnel, energy, infrastructure). These additional costs must be covered either by public subsidies or by higher ticket prices
N ➜ T	Own conclusion	Better developed regional public transport raises the need for inter-municipal networking and thus cooperation. Mobility is addressed in all concepts, so expansion could be a starting point for coordination
N ➜ X	[81]	A well-developed public transport system has a significant positive impact on tourist traffic P. 3: "Tourist traffic can maintain public transport services, especially in structurally weak rural regions, and make a significant contribution to their financing."

Table 11 Bibliography cross-impact influences

Effect	Literature	Reason (Own translation)
O ➞ K, L	Own conclusion	Cheaper public transport tickets generally lead to greater use of public transport and can replace car journeys. Low public transport prices can encourage people to use their own cars less often and instead opt for a combination of public transport and car sharing, especially in cities with good services
P ➞ G	[73]	Progressive expansion enables the early integration of smart grid technologies and load management. This allows electric vehicles to smooth out electricity demand and avoid peak loads. This reduces the need for grid expansion and lowers electricity prices
P ➞ J	[48]	A denser network of public charging stations will make it possible to plan longer leisure trips spontaneously and without range anxiety A need-based expansion of public charging infrastructure will ensure that people without their own charging facilities can also participate in leisure travel
P ➞ K	[73]	In urban areas in particular, a good charging infrastructure enables car sharing vehicles to be used flexibly and as needed without incurring high charging costs
P ➞ L	[82]	A denser network of public charging stations lowers the barriers to switching to electric cars, especially for people without their own charging facilities
P ➞ Q	[83]	Progressive expansion reduces the need for grid expansion and lowers electricity prices: "As a result, the rising electricity production costs are more than offset by the falling grid fees, even with low local penetration. Electricity costs for households without electric vehicles therefore fall by up to 3.7% even with low penetration of electric vehicles
P ➞ U	Our conclusion	A cautious expansion will reinforce regional differences (e.g., urban–rural divide in charging stations), which can lead to inequalities and acceptance problems
P ➞ X	[84]	A well-developed network of public charging stations makes tourist destinations more attractive to electric car users and becomes a competitive factor. Accommodation, restaurants, and leisure facilities benefit from longer stays during the charging process and additional income from charging fees
P ➞ ZA	[85]	Rapid, coordinated expansion promotes the close integration of infrastructure, mobility, and the economy. Municipalities and regions are increasingly developing local master plans that take a holistic view of charging infrastructure, power grid expansion, traffic planning, and economic development
O ➞ X	[85]	Cheap public transport tickets such as the €9 ticket or the Germany ticket have boosted tourism in Germany. With the introduction of cheap tickets such as the €9 ticket, the number of train passengers in typical rural tourist regions rose by up to 80 percent, and by 28 percent in urban tourist areas
Q ➞ J	[86]	High electricity prices at public charging stations are considered a major obstacle to the spread and use of electric cars. If prices are reduced, the economic incentive to use electric cars more frequently will increase, especially for longer journeys such as day trips or vacations
Q ➞ L	Our conclusion	If charging is cheaper than refueling, electric cars will also become more attractive compared to combustion engines – this could increase overall car use, especially for electric cars
R ➞ ZA	[51]	The results of the long-term study show that the availability of infrastructure is considered a decisive factor in the choice of drive system for heavy commercial vehicles. It is explicitly stated that these filling stations should enable unrestricted long-distance operation for commercial vehicles from 2030 onwards
S ➞ R	[51]	Scenario T45-H2 assumes that hydrogen technologies will be available at low cost for mobile applications in the medium term and that H2 will be promoted as a fuel. Simultaneous nationwide expansion is planned here
S ➞ ZA	[51]	Argument transferable (R➞ ZA)
T ➞ C, D	[87]	The involvement of all relevant stakeholders and the development of clearly defined achievable goals are essential for acceptance and effectiveness. In regions with well-coordinated concepts, it is possible to halt migration or even generate an influx of new residents – especially if jobs are created, infrastructure is improved, and quality of life is enhanced. This allows both rural areas and cities to grow
T ➞ E	[88]	Coordinated concepts promote cooperation between different departments (e.g., urban planning, energy, mobility, social affairs) and stakeholders (administration, business, civil society). This allows conflicts of interest to be identified at an early stage and synergies to be created, for example between climate protection, social integration, and economic development
T ➞ J	Concepts	The concepts, especially the Spatial Strategy 2038 +, address the marketing of the RR as a recreational area following structural change. An increase in tourism will also lead to a sharp rise in leisure traffic
T ➞ K	Concept	The planned strengthening of public transport can be transferred to car sharing, as this (like bicycle use) is growing or should grow in tandem with public transport
T ➞ L	Own conclusion	Coordinating mobility services across district and city boundaries can remove barriers to the use of sustainable modes of transport. Concepts alone will not reduce car use, but they can counteract the increase
T ➞ M, N	Concept	Appropriate expansion is set out in regional concepts. Coordinated concepts can prevent conflicts of interest and strengthen joint growth

Table 11 Bibliography cross-impact influences

Effect	Literature	Reason (Own translation)
T ➜ O	[89]	Cooperation between transport associations and the development of superregional fare structures will remove fare barriers and create uniform, comprehensible ticket systems. Examples include the introduction of joint association fares between regions or state-wide umbrella fares, which significantly simplify the fare system for passengers
T ➜ P	[90]	Coordinated regional concepts significantly accelerate and improve the expansion of public charging stations for electric vehicles. The development of regional or municipal charging infrastructure concepts involves the systematic analysis and coordination of locations, charging requirements, and expansion targets
T ➜ V, W	[91]	Coordinated regional concepts have a positive impact on local responses to the expansion of road and rail networks in several ways: citizens and local stakeholders can be involved in planning processes at an early stage, they can help minimize conflicts of use, and coordination leads to more realistic infrastructure planning
T ➜ X	[92]	Coordinated concepts enable a strategic, sustainable, and efficient approach that takes into account the needs of both visitors and the region
U ➜ B	Conclusion based on [93]	Local approval enables the rapid expansion of production facilities (e.g., electrolysers), pipelines, and storage facilities. This allows both domestic production capacities and import opportunities to be efficiently developed
U ➜ C	[90]	If infrastructure (e.g., transportation, social facilities, housing) is expanded quickly and comprehensively with local approval, the region becomes more attractive to new residents and businesses. Resistance to infrastructure projects often leads to delays, limited expansion, or even project cancellations. Regions with poor or stagnating infrastructure lose their appeal, which encourages migration and population decline
U ➜ P, R	[93]	High local approval usually leads to rapid planning and implementation of infrastructure projects. Acceptance among the population reduces the risk of delays due to protests, lawsuits, or political blockades
V ➜ C	[90]	See U➜ C
V ➜ M	Conclusion based on [93]	Approval favors road expansion and integration of bike lanes
V ➜ P, R	Conclusion based on [93]	See U➜ P, R. Effect weaker here, as road expansion implies but does not require the expansion of gas station infrastructure
W ➜ C	[90]	See U➜ C
W ➜ N	Conclusion based on [93]	Approval of infrastructure expansion has a significant influence on public transport expansion
X ➜ J	[82]	Tourism accounts for a significant proportion of leisure travel. The increase is therefore happening simultaneously
X ➜ K, L	[82]	Both leisure and tourism traffic are predominantly handled by private cars, which increases traffic congestion in destination areas. Car sharing can be seen here as a more individual or "private" form of public transport, as it is generally accessible yet private
X ➜ N	[82]	Increasing tourist traffic is driving up demand for public transport, especially in tourist regions and at peak times. This necessitates investment in capacity expansion, more frequent services, and new connections
X ➜ O	[94, 95]	In order to increase the use of public transport – including for tourism – funds are being made available to reduce ticket prices, such as the BW tariff in Baden-Württemberg, where ticket prices have been reduced by up to 35%
X ➜ P	See [84] (P X)	In vacation and excursion areas, the influx of travelers with electric cars significantly increases the demand for public charging infrastructure, especially during peak travel times
Y ➜ B	[96]	"It is expected that technological advances, a reduction in vehicle costs, and falling prices for propulsion energy will make both technologies economically competitive with diesel trucks."
Y ➜ ZA	[96]	A trend toward hydrogen-powered trucks in heavy-duty transport would significantly increase hydrogen demand in the transport sector and thus influence demand in industry—initially through greater competition for limited quantities, but in the medium term also through incentives for accelerated expansion of hydrogen production and infrastructure
Z ➜ H	[89]	Growth in energy-intensive industries would increase the proportion of employees in sectors with limited opportunities for working from home and could therefore even lead to a slightly lower proportion of home office work, as working from home is rarely feasible in these sectors
Z ➜ I	Conclusion from Z H	More people working in industry cause more commuter traffic
Z ➜ Y	Own conclusion	More H2-intensive industry automatically leads to higher H2 demand caused by industry
ZA ➜ P, R	[51], conclusion from S, R ZA	Depending on the type of drive, the expansion of charging stations or H2 filling stations is necessary

[a] 2/3Ws: Two/three-wheelers

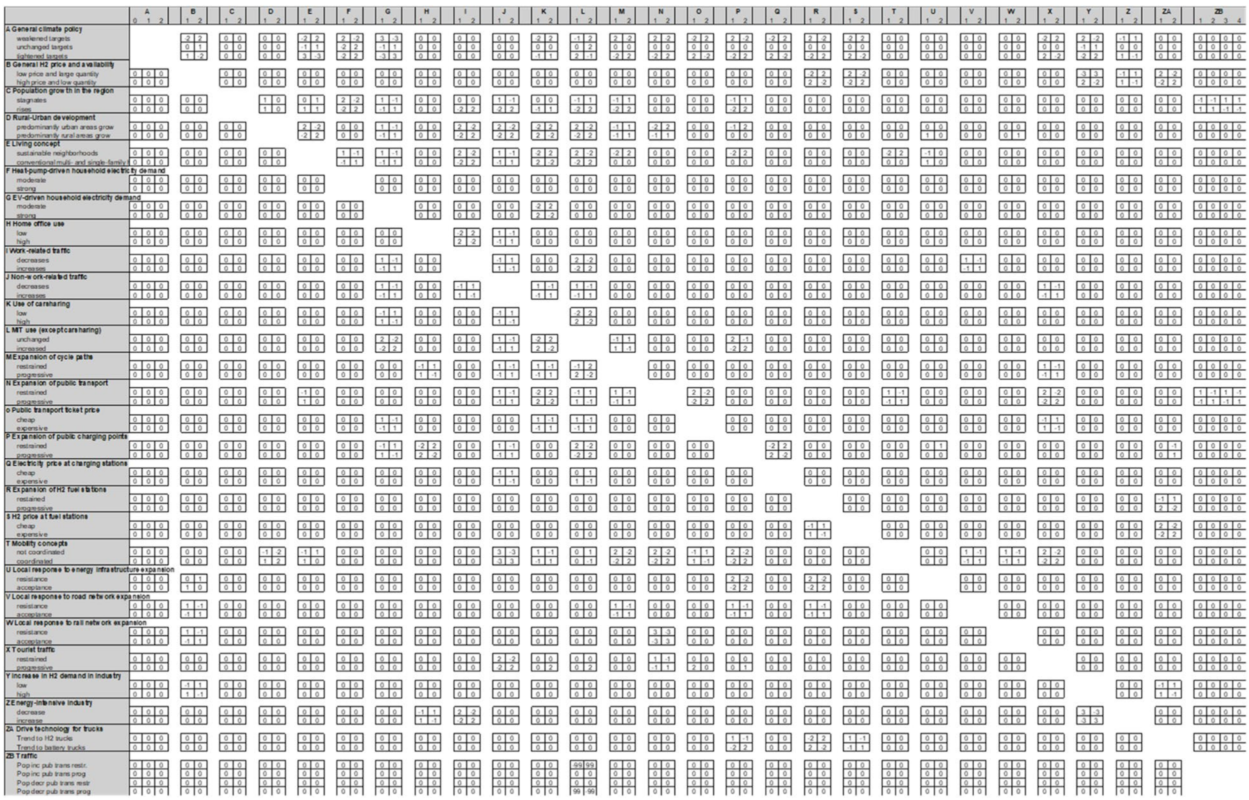

Fig. 3 Cross-impact matrix

Acknowledgements
During the preparation of this work, the authors employed DeepL Write for language editing purposes. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Authors' contributions
JH: Conceptualization, Data curation, Formal analysis, Investigation, Resources, Writing—original draft. SV: Conceptualization, Investigation, Methodology, Project administration, Software, Visualization, Writing—original draft. DR: Validation, Writing—review & editing. JL: Writing—review & editing, Funding acquisition.

Funding
Open Access funding enabled and organized by Projekt DEAL. This work was supported in part by the Helmholtz Association under the program "Energy System Design" and the project "Model-based analysis of transport and energy infrastructures for successful structural change in the Rhenish mining region (Rhivas, 19FS2065A)" which is funded by the mFund innovation initiative of the Federal Ministry for Digital and Transport Affairs. Open Access is funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) (491111487).

Data availability
The article includes all data and materials.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
There are no competing interests.

Received: 17 November 2025 / Accepted: 7 April 2026
Published online: 27 April 2026

References

1. Ministry of Economic Affairs; Industry, Climate Action and Energy of the the State of North Rhine-Westphalia (2025) Strukturwandel im Rheinischen Revier. 09./09./2025. https://www.wirtschaft.nrw/strukturwandel-im-rheinischen-revier
2. Aring M, Breul M, Revilla Diez J (2022) Energy transition in the Rhenish mining area – implications of project funding for green path development. Raumforschung und Raumordnung | Spatial Research and Planning 80(5):588–600. https://doi.org/10.14512/rur.174
3. Zukunftsagentur Rheinisches Revier (2024) Meilensteine Rheinisches Revier. 09/05/2025. https://www.rheinisches-re-vier.de/fileadmin/Content/Seitenstruktur/05_Service/05_Downloads/01_Zentrale_Dokumente_zum_Strukturwandel/Ziel-_und_Meilensteinplan_Rheinisches_Revier.pdf
4. Revierknoten Raum. Ergebnispräsentation Mehrfachbeauftragung - Raumstrategie 2038+. 2022; https://www.youtube.com/watch?v=7EkzHmwgH-k
5. Zukunftsagentur Rheinisches Revier (2022) Ergebnisse, RaumStrategie 2038+. 29/11/2024. https://www.raum-strategie.de/uebersicht-ergebnisse
6. ARL – Akademie für Raumentwicklung in der Leibniz-Gemeinschaft (2022) Braunkohlenplanung, Strukturwandel und Kohleausstieg in Deutschland. Hannover https://www.arl-net.de/system/files/media-shop/pdf/pospapier/pospapier_135.pdf
7. Zukunftsagentur Rheinisches Revier (2020) Wirtschafts- und Strukturprogramm für das Rheinische Zukunftsrevier 1.0. 08/05/2025. www.rheinisches-revier.de/themen/wirtschafts-und-strukturprogramm
8. Weimer-Jehle W, Vögele S, Hauser W, Kosow H, Poganietz W-R, Prehofer S (2020) Socio-technical energy scenarios: state-of-the-art and CIB-based

approaches. Clim Change 162(4):1723–1741. https://doi.org/10.1007/s10584-020-02680-y
9. Broska LH, Vögele S, Shamon H, Wittenberg I (2022) On the future(s) of energy communities in the German energy transition: a derivation of transformation pathways. Sustainability. https://doi.org/10.3390/su14063169
10. Pregger T, Naegler T, Weimer-Jehle W, Prehofer S, Hauser W (2020) Moving towards socio-technical scenarios of the German energy transition—lessons learned from integrated energy scenario building. Clim Change 162(4):1743–1762. https://doi.org/10.1007/s10584-019-02598-0
11. Weimer-Jehle W (2023) Cross-Impact Balances (CIB) for Scenario Analysis: Fundamentals and Implementation. Contributions to Management Science. Cham: Springer Nature Switzerland. ISBN: 978–3–031–27229–5 978–3–031–27230–1
12. Schweizer VJ, Jamieson-Lane AD, Cai H, Lehner S, Smerlak M (2023) Pathways for socio-economic system transitions expressed as a Markov chain. PLoS One 18(7):e0288928. https://doi.org/10.1371/journal.pone.0288928
13. Weimer-Jehle W (2006) Cross-impact balances: a system-theoretical approach to cross-impact analysis. Technol Forecast Soc Change 73(4):334–361. https://doi.org/10.1016/j.techfore.2005.06.005
14. Weimer-Jehle W, Buchgeister J, Hauser W, Kosow H, Naegler T, Poganietz W-R, Pregger T, Prehofer S, Von Recklinghausen A, Schippl J, Vögele S (2016) Context scenarios and their usage for the construction of socio-technical energy scenarios. Energy 111:956–970. https://doi.org/10.1016/j.energy.2016.05.073
15. Schweizer VJ, Kurniawan JH (2016) Systematically linking qualitative elements of scenarios across levels, scales, and sectors. Environ Model Softw 79:322–333. https://doi.org/10.1016/j.envsoft.2015.12.014
16. Kopfmüller J, Weimer-Jehle W, Naegler T, Buchgeister J, Bräutigam K-R, Stelzer V (2021) Integrative scenario assessment as a tool to support decisions in energy transition. Energies 14(6):1580. https://doi.org/10.3390/en14061580
17. Vögele S, Hansen P, Poganietz W-R, Prehofer S, Weimer-Jehle W (2017) Building scenarios for energy consumption of private households in Germany using a multi-level cross-impact balance approach. Energy 120:937–946. https://doi.org/10.1016/j.energy.2016.12.001
18. Broska LH, Vögele S, Shamon H, Wittenberg I (2022) On the future(s) of energy communities in the German energy transition: a derivation of transformation pathways. Sustainability 14(6):3169
19. Freeborn L, Andringa S, Lunansky G, Rispens J (2023) Network analysis for modeling complex systems in SLA research. Stud Second Lang Acquis 45(2):526–557. https://doi.org/10.1017/S0272263122000407
20. Flossdorf J, Jentsch C (2021) Change detection in dynamic networks using network characteristics. IEEE Trans Signal Inf Process Netw 7:451–464. https://doi.org/10.1109/TSIPN.2021.3094900
21. Romão J, Bi Y (2021) Determinants of collective transport mode choice and its impacts on trip satisfaction in urban tourism. J Transp Geogr 94:103094. https://doi.org/10.1016/j.jtrangeo.2021.103094
22. Marra AD, Sun L, Corman F (2022) The impact of COVID-19 pandemic on public transport usage and route choice: evidences from a long-term tracking study in urban area. Transp Policy 116:258–268. https://doi.org/10.1016/j.tranpol.2021.12.009
23. Ibrahim ANH, Borhan MN, Yusoff NIM, Ismail A (2020) Rail-based public transport service quality and user satisfaction – a literature review. Promet 32(3):423–435. https://doi.org/10.7307/ptt.v32i3.3270
24. Das S, Boruah A, Banerjee A, Raoniar R, Nama S, Maurya AK (2021) Impact of COVID-19: a radical modal shift from public to private transport mode. Transp Policy 109:1–11. https://doi.org/10.1016/j.tranpol.2021.05.005
25. Batur I, Asmussen KE, Mondal A, Khoeini S, Magassy TB, Pendyala RM, Bhat CR (2023) Understanding interest in personal ownership and use of autonomous vehicles for running errands: an exploration using a joint model incorporating attitudinal constructs. Transp Res Rec 2677(2):541–554. https://doi.org/10.1177/03611981221107643
26. Schmidt K, Sieverding T, Wallis H, Matthies E (2021) COVID-19 – a window of opportunity for the transition toward sustainable mobility? Transp Res Interdiscip Perspect 10:100374. https://doi.org/10.1016/j.trip.2021.100374
27. Peiseler F, Runkel M, Collmer F, Zahn P (2024) MIV und ÖPNV im Kostenvergleich: Einsparung gesellschaftlicher Kosten durch den öffentlichen Personennahverkehr. https://foes.de/publikationen/2024/2024-04_FOES_OEPNV.pdf
28. Agora Verkehrswende (2023) Kosten der Mobilität: Zahlen und Fakten zu den Preisen im Straßen- und Schienenverkehr sowie deren Bedeutung für die Gesellschaft und den Klimaschutz. Agora Verkehrswende, Berlin
29. Reck DJ, Martin H, Axhausen KW (2022) Mode choice, substitution patterns and environmental impacts of shared and personal micro-mobility. Transp Res Part D Transp Environ 102:103134. https://doi.org/10.1016/j.trd.2021.103134
30. Muschwitz C, Monheim H, Möller L, Bard N (2023) Bestandsaufnahme, Grundlagensichtung und Raumstrukturanalyse. raumkom – Institut für Raumentwicklung und Kommunikation, Trier
31. Muschwitz C, Monheim H, Möller L, Bard N (2024) Maßnahmenkonzept Mobilitätskonzept für die Gemeinde Kreuzau, Erstellt im Auftrag der Gemeinde Kreuzau. raumkom – Institut für Raumentwicklung und Kommunikation, Trier
32. indeland GmbH (2016) Masterplan indeland 2030. 07/02/2025. https://indeland.de/fileadmin/Downloads/Masterplan-indeland-2030-Web.pdf
33. Leung DYC, Mok WC, Lee YL (2021) Challenges and Considerations in Migrating towards a Sustainable e-Mobility City. in 2021 9th International Conference on Smart Grid and Clean Energy Technologies (ICSGCE). IEEE. https://doi.org/10.1109/ICSGCE52779.2021.9621697
34. Lill S, Zeiss C (2023) Partizipationsformate im Rheinischen Revier: eine Übersicht über Beteiligungsformate im Revier 2020–2023. IN4climate.RR: Grevenbroich https://epub.wupperinst.org/frontdoor/index/index/docId/8680
35. Raphael J, Kramp P (2023) Das Wasserstoffkernnetz und dessen Bedeutung für die Papierregion Düren-Euskirchen https://www.ihk.de/blueprint/servlet/resource/blob/6027538/dc80f8758e609873acfa138f0e81e6ad/bedeutung-wasserstoffkernnetz-papierregion-dn-eu-data.pdf
36. Vögele S, Poganietz W-R, Kleinebrahm M, Weimer-Jehle W, Bernhard J, Kuckshinrichs W, Weiss A (2022) Dissemination of PV-Battery systems in the German residential sector up to 2050: technological diffusion from multidisciplinary perspectives. Energy 248:123477. https://doi.org/10.1016/j.energy.2022.123477
37. Heer S, Wirth P, Knippschild R, Matern A (2021) Guiding principles in transformation processes of coal phase-out. The German case of Lusatia. Extr Ind Soc 8(1):159–167. https://doi.org/10.1016/j.exis.2020.07.005
38. Zukunftsagentur Rheinisches Revier (2021) Wirtschafts- und Strukturprogramm für das Rheinische Zukunftsrevier 1.1 (WSP 1.1). 05/05/2025. https://www.wirtschaft.nrw/sites/default/files/documents/final_wsp_1_1_webversion.pdf
39. Réseau Action Climate France (2011) Centre international de recherche sur l'environnement et le développement, Germanwatch, Potsdam Institute for Climate Impact Research, and International Network for Sustainable Energy Europe. Local and regional low carbon scenarios methodology, challenges and opportunities. https://www.lowcarbon-societies.eu/index.php?id=25
40. Mohlakoana N, Lokhat M, Dolšak N, Prakash A (2023) Varieties of just transition: public support in South Africa's Mpumalanga coal community for different policy options. PLoS Clim 2(5):e0000205. https://doi.org/10.1371/journal.pclm.0000205
41. Svobodova K, Everingham J-A, Mackenzie S, Witt K (2026) Designing community participation for mine closure and social transition. Sustain Dev 34(S1):197–209. https://doi.org/10.1002/sd.70176
42. Thünen-Institut (2025) Thünen-Landatlas, 06/10/2025. https://www.landatlas.de
43. Welder L, Ryberg DS, Kotzur L, Grube T, Robinius M, Stolten D (2018) Spatio-temporal optimization of a future energy system for power-to-hydrogen applications in Germany. Energy 158:1130–1149. https://doi.org/10.1016/j.energy.2018.05.059
44. Hans Böckler Stiftung (2023) Studien zu Homeoffice und mobiler Arbeit 05/09/2025. https://www.boeckler.de/de/auf-einen-blick-17945-Auf-einen-Blick-Studien-zu-Homeoffice-und-mobiler-Arbeit-28040.htm
45. Agora Verkehrswende (2021) Pendlerverkehr in Deutschland. Zahlen und Fakten zu den Wegen zwischen Wohn- und Arbeitsort. www.agora-verkehrswende.de
46. Doll C, Krauss K (2022) Nachhaltige Mobilität und innovative Geschäftsmodelle, Studie zum deutschen Innovationssystem | Nr. 10–2022. https://www.e-fi.de/fileadmin/Assets/Studien/2022/StuDIS_10_2022.pdf
47. Federal Ministry of Transport (2025) Verkehr in Zahlen. https://www.bmv.de/SharedDocs/DE/Anlage/G/verkehr-in-zahlen24-25-pdf.pdf?__blob=publicationFile
48. NOW GmbH (2024) Charging infrastructure after 2025/2030: Scenarios for market ramp-up – New edition 2024. https://www.now-gmbh.de/wp-content/uploads/2024/06/Studie_Ladeinfrastruktur-2025-2030_Neuauflage-2024.pdf
49. H2 MOBILITY Deutschland (2023) H2 MOBILITY führt zum 1.10.23 dynamisches Preismodell ein. https://h2-mobility.de/news/3125/
50. Landesbetrieb Information und Technik Nordrhein-Westfalen (2025) Ankünfte, Übernachtungen und durchschnittliche Aufenthaltsdauer nach Herkunftsländer der Gäste. Available from: https://www.landesdatenbank.nrw.de/ldbnrw/online/

51. FHG-ISI, Consentec, ifeu, and TU Berlin (2025) Langfristszenarien 3 - Transport sector. https://langfristszenarien.de/enertile-explorer-en/scenario-explorer/transport.php
52. Roth A, Gaete-Morales C-l, Guéret A, Kirchem D, Kittel M, Schill, Wolf-Peter (2022) Heat pumps instead of natural gas heating: Supporting the transition through the expansion of solar energy. DIW Weekly Report 89(22):311–320. https://www.diw.de/documents/publikationen/73/diw_01.c.842119.de/22-22-1.pdf
53. International Energy Agency (2024) Global EV Outlook 2024: Moving towards increased affordability. https://iea.blob.core.windows.net/assets/a9e3544b-0b12-4e15-b407-65f5c8ce1b5f/GlobalEVOutlook2024.pdf
54. Shaheen S, Martin E, Totte H (2020) Zero-emission vehicle exposure within U.S. carsharing fleets and impacts on sentiment toward electric-drive vehicles. Transp Policy 85:A23–A32. https://doi.org/10.1016/j.tranpol.2019.09.008
55. GermanZero (2023) Framework condi-tions for climate-neutral mobility by 2035. GermanZero's climate emergency measures in the transport sector. https://germanzero.de/blog/dossier-verkehr
56. Institute for Ecological Economy Research (2022) Replaceable batteries or charging stations? Study on the resource-efficient expansion of e-mobility launched. https://www.ioew.de/news/article/wechselakkus-oder-ladesaeulen-studie-zum-ressourcenschonenden-ausbau-der-e-mobilitaet-gestartet
57. Fraunhofer Institute for Energy Infrastructure and Geotechnologies (IEG) (2021) Investigation of the influence of electromobility on loads in electricity distribution networks. https://www.ieg.fraunhofer.de/de/presse/pressemitteilungen/elektromobilitaet.html
58. Federal Ministry of Digital and Transport (2023) BMDV promotes expansion of public hydrogen filling stations for heavy-duty vehicles. https://bmdv.bund.de/SharedDocs/DE/Pressemitteilungen/2023/023-wissing-wasserstofftankstellen-fuer-lkw-und-busse.html
59. Lund-Durlacher DS, Wolfgang (2021) On the future of travel. https://www.bpb.de/shop/zeitschriften/apuz/344471/zur-zukunft-des-reisens/
60. Federal Statistical Office (2024) Large urban regions in transition. Available from: https://www.destatis.de/DE/Themen/Querschnitt/Demografischer-Wandel/Aspekte/demografie-grossstadtregionen.html#
61. Vattenfall (2024) Infowelt Energie - Average electricity consumption for 1–2–3–4-person households. https://www.vattenfall.de/infowelt-energie/strom-ratgeber/durchschnittlicher-stromverbrauch-im-1-2-3-4-personen-haushalt
62. Metz D (2012) Demographic determinants of daily travel demand. Transp Policy 21:20–25. https://doi.org/10.1016/j.tranpol.2012.01.007
63. Chang YS, Jo SJ, Lee Y-T, Lee Y (2021) Population density or populations size. Which factor determines urban traffic congestion? Sustainability 13(8):4280
64. Association of German Transport Companies (VDv) (2025) Moving more now: Modernization and expansion of public transport. https://www.vdv.de/jetzt-mehr-bewegen-modernisierung-und-ausbau.aspx
65. Römer D, Salzgeber J (2022) Elektromobilität in Deutschland: Ausbau der Ladeinfrastruktur muss Schritt halten (Electric mobility in Germany: Expansion of charging infrastructure must keep pace,) in: KfW Research Fokus Volkswirtschaft. 379. https://www.kfw.de/PDF/Download-Center/Konzernthemen/Research/PDF-Dokumente-Fokus-Volkswirtschaft/Fokus-2022/Fokus-Nr.-379-April-2022-Ladeinfrastruktur.pdf
66. Öko-Institut (2024) Co-Transformation – jointly mastering the regional energy transition in rural areas. https://www.oeko.de/blog/co-transformation-gemeinsam-die-regionale-energiewende-im-laendlichen-raum-meistern/
67. Federal Ministry of Food and Agriculture (2020) Das Land lebt! Third report of the Federal Government on the development of rural areas. https://www.bmel.de/SharedDocs/Downloads/DE/_laendliche-Regionen/regierungsbericht-laendliche-raeume-2020.pdf?__blob=publicationFile&v=5
68. State Government of North Rhine-Westphalia (2022) Mobility and mobility management: New guidelines enable the promotion of sharing services and neighborhood garages for municipalities. https://www.land.nrw/pressemitteilung/mobilitaet-und-mobilitaetsmanagement-neue-richtlinie-ermoeglicht-foerderung-von
69. State Government of North Rhine-Westphalia (2025) Charging electricity for everyone: State launches campaign to expand charging options at workplaces and in apartment buildings. https://www.land.nrw/pressemitteilung/strom-tanken-fuer-alle-land-startet-kampagnen-fuer-ausbau-von-lademoeglichkeiten
70. Pichurina M (2023) Municipal factors influencing sustainable neigh-borhood planning: challenges, conflicts, and instruments for successful implementation. https://mediatum.ub.tum.de/doc/1725327/1725327.pdf
71. Hook A, Court V, Sovacool BK, Sorrell S (2020) A systematic review of the energy and climate impacts of teleworking. Environ Res Lett 15(9):093003. https://doi.org/10.1088/1748-9326/ab8a84
72. Wöhner F (2022) Work flexibly, travel less? The impact of telework and flex-time on mobility behavior in Switzerland. J Transp Geogr 102:103390. https://doi.org/10.1016/j.jtrangeo.2022.103390
73. Bundesverband CarSharing. Traffic reduction through CarSharing. n.d., https://www.carsharing.de/sites/default/files/uploads/bcs_factsheet20_verkehrsentlastung_0.pdf
74. Muratori M (2018) Impact of uncoordinated plug-in electric vehicle charging on residential power demand. Nat Energy 3(3):193–201. https://doi.org/10.1038/s41560-017-0074-z
75. Raimund W (2022) Active mobility – walking and Cycling. Short study as part of the "Sustainable Mobility Transition" (NaMoW) project. https://www.umweltbundesamt.at/fileadmin/site/publikationen/dp167.pdf
76. Gerike R, Koszowski C, Hubrich S, Wittwer R, Wittig S, Pohle M (2020) Active mobility: Better quality of life in urban areas. Final report. Final report. Commissioned by the Federal Environment Agency. https://www.umweltbundesamt.de/sites/de-fault/files/medien/5750/publikationen/2020_12_03_texte_226-2020_aktive_mobilitaet.pdf
77. Tourism Network Rhineland-Palatinate (2025) Tourismus ist ein Plus für unsere Radwege. https://rlp.tourismusnetzwerk.info/2025/03/31/tourismus-ist-ein-plus-fuer-unsere-radwege/
78. Zukunftsnetz Mobilität NRW (2025) The basis for sustainable mobility management: Mobility management in neighborhood development. https://www.zukunftsnetz-mobilitaet.nrw.de/schwerpunkte/stadt-und-dorfentwicklung/mobilitaetsmanagement-in-der-quartiersentwicklung
79. State of North Rhine-Westphalia (2023) A sustainable start to leisure time with public mobility | Land.NRW. https://www.land.nrw/pressemitteilung/nachhaltig-die-freizeit-starten-mit-oeffentlicher-mobilitaet
80. Future Network Public Transport (2025) Public transport balance sheet 2024: More passengers, rising costs, uncertain financing. 07/08/2025; https://www.zukunftsnetzwerk-oepnv.de/aktuelles/news/oepnv-bilanz-2024-mehr-fahrgaeste-steigende-kosten-unsichere-finanzierung
81. German Tourism Association (2018) Position paper. We are mobilizing tourism in Germany! Positions – Mobility and tourism in Germany. https://www.deutschertourismusverband.de/fileadmin/user_upload/Themen/Mobili-taet/Positionspapier_Mobilitaet_2018.pdf
82. Renaud-Blondeau P, Boisjoly G, Dagdougui H, He SY (2023) Powering the transition: public charging stations and electric vehicle adoption in Montreal, Canada. Int J Sustain Transp 17(10):1097–1112. https://doi.org/10.1080/15568318.2022.2152403
83. Wietschel M, Kühnbach M, Stute J, Gnann T, Marwitz S, Klobasa M (2018) Impact of electric mobility on household electricity prices in Germany (No. S21/2018). Working Paper Sustainability and Innovation. https://publica-rest.fraunhofer.de/server/api/core/bitstreams/f6721096-3165-4f04-8184-bfcd42c74f94/content
84. National Platform Future of Tourism (2024) Charging in tourist regions: Impulses for the tourism-oriented expansion of the charging infrastructure in Germany. https://plattform-zukunft-tourismus.de/wp-content/uploads/Impulse-fuer-den-tourismusgerechten-Ausbau-der-Ladeinfrastruktur-in-Deutschland.pdf
85. Federal Ministry of Digital and Transport (2022) Master Plan - Charging Infrastructure II of the Federal Government. 05/09/2025. https://bmdv.bund.de/SharedDocs/DE/Anlage/G/masterplan-ladeinfrastruktur-2.pdf?__blob=publicationFile
86. Hamida KB (2025) Energy transition: Flexible prices at electric charging stations, Wirtschaftsdienst. https://www.wirtschaftsdienst.eu/inhalt/jahr/2025/heft/1/beitrag/energiewende-flexible-preise-an-e-ladesaeulen.html
87. Grüttner A, Kröhnert S, Lenk T, Ragnitz J, Röhl K-H, Stiller S (2011) Shrinking regions – problems and opportunities, Wirtschaftsdienst. https://www.wirtschaftsdienst.eu/inhalt/jahr/2011/heft/4/beitrag/schrumpfende-regionen-probleme-und-chancen.html
88. Riechel R (2024) Potential of the neighborhood level for urban transformation, Synthesis Paper. https://www.nachhaltige-zukun-ftsstadt.de/downloads/6._Synthesebericht_SynVerZ_Nachhaltige_Quartiersloesungen.pdf
89. Federal Statistical Office (2024) People in employment working from home. Available from: https://www.destatis.de/DE/Themen/Arbeit/Arbeitsmarkt/Qualitaet-Arbeit/Dimension-3/home-office.html
90. Buchert M, Sutter J, Wagner T (2023) Ecological impacts of integrated inner development concepts on the infrastructures of urban growth regions. https://www.umweltbundesamt.de/sites/de-fault/files/medien/11850/publikationen/2023-07-18_texte_68-2023_oekologische_auswirkungen_integrierter_0.pdf

91. Federal Institute for Research on Building, Urban Affairs and Spatial Development (2019) Konzepte für den Stadtverkehr der Zukunft (Concepts for urban transport of the future). BBSR online publication 08/2019. https://www.bbsr.bund.de/BBSR/DE/veroeffentlichungen/bbsr-online/2019/bbsr-online-08-2019-dl.pdf?__blob=publicationFile&v=1
92. indeland GmbH (2025) Tourism strategy for the Rhineland mining region is complete. https://indeland.de/aktuell/tourismusstrategie-fuer-das-rheinische-revier-ist-fertig
93. Frey RL, Schaltegger CA (2000) Compensation for infrastructure facilities? Large-scale projects between resistance and acceptance. https://www.aramis.admin.ch/Default?DocumentID=64414&Load=true
94. Andor MA, Dehos FT, Gillingham KT, Hansteen S, Tomberg L (2025) Public transport pricing: an evaluation of the 9-Euro ticket and an alternative policy proposal. Econ Transp 42:100415. https://doi.org/10.1016/j.ecotra.2025.100415
95. Staatsministerium Baden-Württemberg (2018) Millions to reduce public transport fares. 09/09/2025. https://stm.baden-wuerttemberg.de/de/service/presse/pressemitteilung/pid/millionen-zur-senkung-der-oepnv-tarife/
96. Gerstein D, Sorayaei M, Wagner PL (2023) Sustainable heavy-duty transport: Status quo and requirements for the expansion of refuling and charging infrastructure for climate-friendly commercial vehicles in Germany, German Energy Agency (dena). https://www.dena.de/fileadmin/Plattform_nachhaltiger_Schwerlastverkehr/Dokumente/Hintergrundpapier_-_Tank-_und_Ladeinfrastruktur.pdf
97. Bengston DN (2016) The futures wheel: a method for exploring the implications of social–ecological change. Soc Nat Resour 29(3):374–379. https://doi.org/10.1080/08941920.2015.1054980
98. Keppo I, Al Khourdajie A, Gardumi F, Holtz G, Nikas A, Xexakis G, Ferreras-Alonso N, Fragkos P, Frilingou N, Ghadaksaz H, Hawkes A, Mateo A, Mittal S, Parrado-Hernando G, Peters GP, Rinaldi L, Rocco MV, Sognnæs I, Ven D-J, Zamanipour B (2026) Model linking for low-carbon transitions: technical and conceptual challenges and best practices. Renew Sustain Energy Rev 226:116384. https://doi.org/10.1016/j.rser.2025.116384
99. Eurostat (2025) Glossary: Urban-rural typology. 25/09/10. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Urban-rural_typology

Publisher's note