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Avoid, Shift or Improve passenger transport? Impacts on the energy system

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ABSTRACT

Demand-side mitigation strategies have been gaining momentum in climate change mitigation research. Still, the impact of different approaches in passenger transport, one of the largest energy demand sectors, remains unclear. We couple a transport simulation model to an energy system optimisation model, both highly disintegrated in order to compare those impacts. Our scenarios are created for the case of Germany in an interdisciplinary, qualitative–quantitative research design, going beyond techno-economic assumptions, and cover Avoid, Shift, and Improve strategies, as well as their combination. The results show that sufficiency – Avoid and Shift strategies – have the same impact as the improvement of propulsion technologies (i.e. efficiency), which is reduction of generation capacities by one quarter. This lowers energy system transformation cost accordingly, but requires different kinds of investments: Sufficiency measures require public investment for high-quality public services, while efficiency measures require individuals to purchase more expensive vehicles at their own cost. These results raise socio-political questions of system design and well-being. However, all strategies are required to unleash the full potential of climate change mitigation.

1. Introduction

High-income regions like Europe and the United States consume 18 and 24% of their final energy demand for passenger transport, respectively [1,2]. This demand is currently fuelled with fossil oil derivatives that are shipped around the world and impose complex geopolitical inter-dependencies. Their combustion translates into a relevant share of greenhouse gas emissions, which must be fully mitigated by mid-century in order to contribute to the climate targets of the Paris Agreement [3]. In general, there are two complementing paths for emissions mitigation: Decarbonising energy supply and reducing energy demand. Many long-term energy system transformation studies have investigated technological pathways towards full decarbonisation and 100% renewable energy sources (RES) [4–6]. This target coincides with the consistency dimension of sustainable energy systems. However, these studies usually simplify energy demand in passenger transport to the technologies that consume energy, neglecting other demand-side dimensions that go beyond techno-economic analysis. We address this research gap through comprehensive analysis from both perspectives; the energy and transport system.

From a transport perspective, demand and supply have different notions than in energy system research: Human activities within the built environment produce a physical mobility demand that is satisfied (i.e. supplied) by use of transport technologies and their infrastructures. This results in three prominent energy demand mitigation strategies: Avoiding unnecessary traffic, shifting traffic to more energy-efficient modes, and improving transport technologies [7]. While technological improvements have seen much attention in international research and policy, the role of *Avoid* and *Shift* measures remains under-represented [8]. However, these two strategies are not only relevant for demand-side mitigation [9–11], but also create significant co-benefits that increase human well-being [12] and support the Sustainable Development Goals [13]. Accordingly, we formulate two research questions: What is the potential energy system impact of Avoid, Shift, and Improve measures in passenger transport? Is there a preferable strategy?

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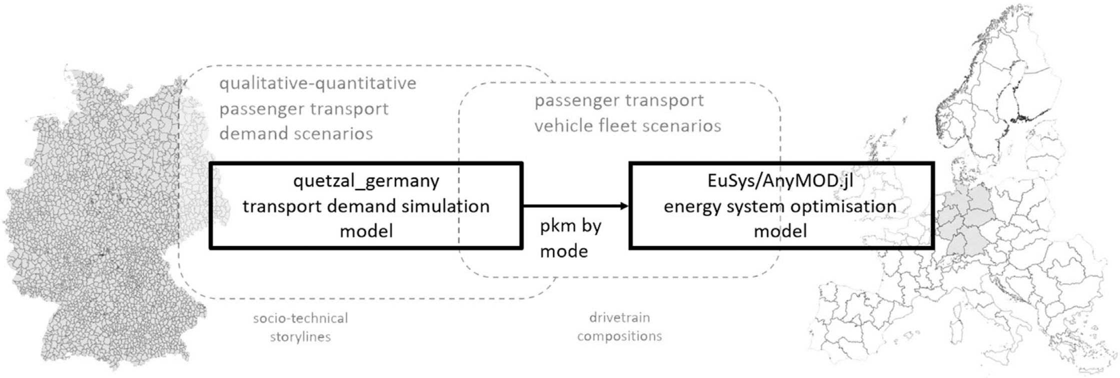


Fig. 1. Research design: The aggregated transport model quetzal_germany simulates German transport demand based on a multitude of technological, economic, organisational, cultural, and political drivers that affect the number, distance, and mode of trips. Resulting passenger-kilometres (pkm) are fed into the EuSys/AnyMOD.jl energy system model to analyse the effect of energy demand scenarios with 100% renewable energy supply. Transport demand scenarios are created in a qualitative-quantitative research design [15], whereas transport supply scenarios contain different drivetrain technology compositions. Both model's geographical resolutions are sketched to the left and right.

Table 1
Scenarios of this model coupling exercise. Four different transport demand characteristics (rows) are further elaborated in Section 2.4 and include no measures (reference), Shift measures only, Avoid measures only, and a combination (Avoid+Shift). Supply characteristics (columns) contain a technology mix with battery-electric vehicles (BEVs), plug-in hybrids (PHEVs), and internal combustion engine vehicles (ICEVs) (values from a recent, well-defined German decarbonisation scenario in Luderer et al. [16]), as well as the Improve case with 100% BEVs. Public transport vehicles are 100% electrified in all scenarios.

	Mix: 56% BEV, 14% PHEV, 30% ICEV	Improve: 100% BEV
reference	Ref+Mix	Ref+Improve
Shift	Shift+Mix	Shift+Improve
Avoid	Avoid+Mix	Avoid+Improve
Avoid+Shift	Avoid+Shift+Mix	Avoid+Shift+Improve

As such, we analyse the impact of comprehensive demand-side mitigation strategies on an optimised, fully defossilised energy system. Germany is selected as case study because it is a high-income country with strong car-dependency [14], where Avoid and Shift strategies play a minor role in past and current transport policy. We model fine-granular Avoid and Shift scenarios in the transport simulation model quetzal_germany (Section 2.1) and couple them to the EuSys/AnyMOD.jl model (Section 2.2). It optimises technological capacities and respective dispatch for the European energy system towards 100% RES in the target year 2040. Fig. 1 sketches the model coupling process. Our scenario suite contains four transport demand scenarios that are combined with a scenario representing a propulsion technology mix and an Improve scenario, respectively (Table 1). We compare resulting energy supply capacities, flexibility indicators, and system cost across all scenario combinations.

Our approach is innovative in two ways. First, the impact of applying comprehensive Avoid, Shift, and Improve strategies in passenger transport on the energy system has never been compared on a national scale, and in such detail (similar approaches found in Anable et al. [17],Brand et al. [18],Venturini et al. [19],Köhler et al. [20]). Second, our research design aims to represent the full transformation potential of passenger transport, which requires addressing common critique in energy and transport modelling. Krumm et al. [21] show that the representation of social aspects in energy modelling can benefit from more elaborate approaches that go beyond the techno-economic realm. In transport modelling, Creutzig [22] suggests that non-place-based approaches are likely to under-estimate the transformation potential. Hence, we couple highly specialised models, which Luh et al. [23] find beneficial to gain deeper insights from different perspectives in complex mobility transformation processes. Still, within detailed transport modelling, Schwanen et al. [24] criticise that reliance on rational choice theory cannot depict the full complexity of human behaviour. We address these issues with our qualitative-quantitative scenario design, as summarised in Section 2.4.

2. Methods and tools

2.1. *Transport model quetzal_germany*

quetzal_germany simulates transport demand as individual decisions of trip frequency, trip destination, and mode of transport. This demand is routed on spatially explicit transport networks, yielding passenger kilometres (pkm). The model is developed in Python under use of the Quetzal open source transport modelling suite [25] and is openly available on github [26].

It follows the method of aggregated transport modelling, having 2225 zones, defined by clustering 4605 municipality unions to similar zone sizes. Aggregated transport models simulate traffic between zones, whereas inner-zonal traffic, accounting for 13% of total traffic, is computed exogenously based on the German National Travel Survey [27].

2.1.1. *Network model and level-of-service attributes*

quetzal_germany incorporates a highly intricate network model that utilises OpenStreetMap data for the road network and GTFS feeds for public transportation (PT) in Germany. It consists of seven distinct network layers, each corresponding to different modes of transportation:

1. Long-distance rail transport: Includes ICE, IC, and EC rail services.
2. Short/medium-distance rail transport: Encompasses local and regional rail services.
3. Local public transport: Comprises bus, ferry, tram, and underground services.
4. Coach transport: Represents connections based on the network coverage of FlixBus in 2020.
5. Air transport: Includes connections between 22 major German airports.
6. Road: Consists of motorways, A and B roads, as well as interconnecting links.
7. Non-motorised transport: Involves straight-line connections between zone centroids, with distances of up to 40 km.

Footpaths are established between PT stops to facilitate seamless connections between different layers. Furthermore, network access/egress links connect each layer to the sources and sinks of transport demand located at the population centroid of each zone. Two attributes, travel time (Eq. (1)) and monetary travel cost (Eq. (2)), are assigned to every network link as indicators of the level of service.

$$TT = T^{\text{iv}} + T^{\text{wait}} + T^{\text{ae}} + T^{\text{walk}} \tag{1}$$

$$TC = \frac{D \cdot c_{\text{d}} + T^{\text{iv}} \cdot c_{\text{t}} + c_{\text{fix}}}{f} \tag{2}$$

In-vehicle time T^{iv} is the result of link speed and length in the network graph. Additionally for PT, there is waiting and walking time, T^{wait} and T^{walk}, respectively, that applies at PT stops during transfer. Access/egress-time T^{ae} depends on the number of parking lots in the origin and destination zone for car transport and on the PT stop density and service level of the corresponding PT mode, respectively. Travel cost TC is composed of distance-specific cost c_{d}, variable in-vehicle time specific cost c_{t}, fix cost c_{fix}, and a split factor f, used for car occupancy rates or average shares of PT subscriptions in the population. Corresponding data, assumptions, and further details can be found in section 3.1 of Arnz [28].

2.1.2. Transport demand model

Classical aggregated transport models simulate demand in three mobility choices: trip frequency, trip destination, and mode of transport. The following paragraphs briefly describe all of these models, while further information can be found in Arnz [28] and Arnz and Krumm [15]. The German National Travel Survey [27] serves as calibration dataset for all forthcoming models, using discrete choice theory. Estimated parameters are given in Greek letters.

All choice models are estimated for each of the six trip purposes reported in the survey, and for households with car available and without car available, respectively. As such, there are twelve demand segments, denoted with index i below. However, compulsory trips (i.e. commuting, education, and business trips) are determined by the distribution of workers and workplaces, or pupils and schools, and hence, computed with a doubly constrained distribution. It takes into account total numbers of attraction points and the corresponding population share in each zone, and uses the logsum of the mode choice utility (equation (6)) as deterrence between zones, connecting the trip distribution to transport system performance. Trips for other purposes (utilities, leisure, and accompany) utilise multinomial logit models to depict trip generation and destination choice, respectively. The generation model's utility function looks as follows:

$$\begin{aligned} V_j^i =& ASC_j + log\left(\text{pop}_z\right) * \alpha_j^i + \text{hh\_size}_z * \beta_j^i \\ &+ \text{hh\_income}_z * \gamma_j^i + \text{is\_working}_z * \delta_j^i \\ &+ \text{is\_learning}_z * \epsilon_j^i + \text{is\_caring}_z * \zeta_j^i \\ &+ \text{acc}_z * \eta_j^i \end{aligned} \tag{3}$$

For all zones z. Choice alternatives $j \in 0, 1, \dots, 5$ describe the number of trips per day with alternative-specific constants ASC being fixed to zero for $j \neq 0$. Zone population pop, average household size hh_size, household income hh_income, and the population share of a certain occupation (is_working, is_learning, is_caring; not for buy/execute trips) influence the decision. Moreover, the trip frequency depends on the accessibility acc, calculated as the average cost of mobility to other zones (the logsum of mode choice model logsums), linking the generation of trips to the transport system design. Building upon the trip frequency for non-compulsory trips, a binary logit model formulates the choice between executing a trip within or beyond the origin zone's boundaries:

$$\begin{aligned} V_{inner}^i &= log\left(\text{pop\_dens}_z\right) * \alpha^i + log\left(1 + \sum_{a_n \in A^i} a_{n,z}\right) * \beta^i \\ V_{inter}^i &= ASC + \text{acc}_z * \gamma^i \end{aligned} \tag{4}$$

Inter-zonal choice utility depends on the zone's accessibility and an ASC, while inner-zonal utility consists of the zone's population density pop_dens and the number of attractions a_n of the attraction categories A^i that are relevant to this demand segment. Those categories are a subset of points of interest data sourced from OpenStreetMap in 2022: $A = \{$childcare, school, higher education, medical, daily leisure, occasional leisure, shop, special shop$\}$

Another multinomial logit model applies for the choice between inter-zonal trip destinations. Its choice alternatives d comprise the full set of model zones except the origin:

$$\begin{aligned} V_d^i =& log\left(\text{pop\_dens}_d\right) * \alpha^i \\ &+ log\left(1 + \sum_{a_n \in A^i} a_{n,z} * exp\left(\beta_n^i\right)\right) * \gamma^i \\ &+ D_{z,d} * \delta^i + D_{z,d}^2 * \epsilon^i + CC_{z,d} * \zeta^i \end{aligned} \tag{5}$$

with $\beta_0 = 0$. The distance $D_{z,d}$ between origin and destination and the squared distance $D_{z,d}^2$ are significant choice variables. Here too, cost of mobility CC influence the distance distribution of trips. It entails the composite cost of the nested logit mode choice model, depending on the route's level-of-service attributes described above. The choice tree contains all modes m of the network model, as listed above, with one nest for rail transport and another nest for use of private car and car sharing. The mode choice model is specified as

$$V_m^i = \text{ASC}_m^i + \mathcal{F}\left(\beta_t^i, TT_m\right) + \beta_c^i \cdot TC_m \tag{6}$$

for each demand segment i with a log-power spline function as proposed in Rich [29]:

$$\mathcal{F}(\beta, x) = \beta \sum_{q=1}^{Q} \lambda_q(x) \left[\theta_q ln(x)^{Q-q+1} + \alpha_q(\beta)\right] \tag{7}$$

$$\theta_q = \frac{Q}{Q-q+1} \prod_{r=2}^{q} ln\left(c_{r-1}\right) \quad \forall q = 2, \dots, Q \tag{8}$$

$$\alpha_q(\beta) = \alpha_{q-1}(\beta) + \frac{(q-1)!\beta}{Q-1} ln\left(c_{q-1}\right)^{Q-q+2} \prod_{r=1}^{q-2} ln\left(c_r\right) \tag{9}$$

2.2. Energy system model EuSys/AnyMOD.jl

For the analysis of renewable energy systems, we employ a linear optimisation model that determines the expansion and operation of technologies to meet final energy demand. The model's objective is to minimise the total system cost, which includes annualised expansion cost, operation cost of technologies, and costs associated with energy imports from external sources. The expansion and operation aspects in the model encompass two components: technologies for energy generation, conversion, or storage, and grid infrastructure for energy exchange between different regions.

To handle high shares of fluctuating renewables and sector integration, the model utilises a graph-based formulation specifically designed for this purpose, allowing for varying temporal and spatial resolutions within a single model [30]. This feature enables the application of high resolutions where the system is sensitive to small imbalances of supply and demand, such as in the power sector, while modelling more inert parts, like gas or hydrogen transmission, at a coarser resolution. This approach reduces computational complexity and captures the inherent flexibility in the energy system. Göke [31] elaborates this approach in greater detail and Göke et al. [32] present a case study including mathematical formulations.

The potential of battery-electric vehicles (BEVs) for flexibility provision in future energy systems remains uncertain and relies on technological and regulatory advancements. On one hand, we anticipate charging flexibility within certain limits and adaptability to supply, although this does not currently align with regulations in all European countries and does not necessitate additional infrastructure [33]. On the other hand, we do not assume that BEVs can supply electricity back to the grid, which is also known as bidirectional charging or vehicle-to-grid, as it requires the use of bidirectional chargers [34]. It is important to note that BEV technologies are not restricted to passenger cars but are also applicable to all forms of road transport.

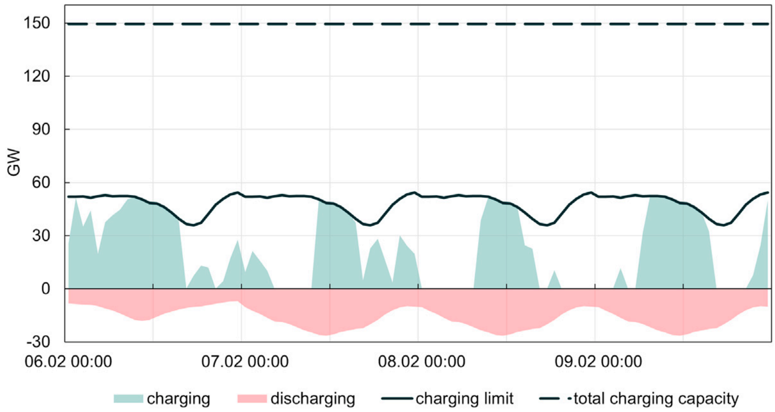


Fig. 2. Exemplary charging and discharging profile for battery electric vehicles. The area above the curve represents the energy used for charging from the grid; the area below discharging for driving. Charging is subject to an upper limit illustrated by the dashed line. This dashed line applies a conservative profile to the total charging capacity of electric vehicles, represented by the solid line.

The model implements flexible charging of battery vehicles. For this purpose, it tracks how charging and discharging electricity changes the storage level of the battery. In addition, a profile limits charging to reflect the share of vehicles connected to the grid. Furthermore, discharging is fixed to the electricity required for driving. Fig. 2 shows an exemplary charging pattern from actual model results for four days in February. The dashed line shows the profile restricting the charging of BEVs; the solid line shows the total charging capacity. The discharging pattern corresponds to the area below the curve. The charging pattern is flexible as long as charging does not exceed the available capacity and the storage level is always sufficient to supply the discharging pattern. The assumed maximum charging capacity amounts to 10 kW and the battery capacity to 50 kWh for private vehicles. BEVs for public passenger and heavy road transport have maximum charging rates of 150 kW [35]. The patterns for discharging and the limit on charging build on Most [36]. We further reduce these profiles by a factor 75% for an additional safety margin, assuming that not all parked vehicles are connected to the grid of available for flexible charging.

Since charging is flexible within the described limits and part of the system optimisation, extreme load peaks due to uncontrolled charging cannot occur. Instead, the model will balance the adverse effects of load peaks, like additional back-up capacities, against the benefits, and high charging will only occur at times of excess electricity supply. Real-time pricing for electricity consumers can achieve a corresponding charging behaviour in the real world. Under this assumption, an increase in maximum charging capacity from electric vehicles will not adversely affect residual load peaks. Even with corresponding price incentives, consumers who do not have the option but must charge faster since they are connected to the grid less frequently can induce higher peaks. We must assume that the above profiles account for this behaviour since they represent an average across all consumers.

The AnyMOD.jl framework is applied to the region of Europe, covering all countries of the European Union, along with the United Kingdom, Switzerland, and the Balkans. Those 33 countries are divided into 92 regions by clustering NUTS3-level regions. The model's time frame encompasses a single year. It takes a brownfield approach, utilising the available transmission infrastructure and hydro power plants without additional expansion cost. The model encompasses a comprehensive set of 22 distinct energy carriers, which can be stored and converted among each other using 120 different technologies. These technologies cover various sectors such as heating, transportation, industry, and the production of synthetic fuels. The graph-based approach allows different temporal resolutions for different energy carriers. The most demanding energy vector, electricity, is modelled in 15 min time intervals, including seasonality within the time series. The full documentation of the case study model can be accessed in Göke et al. [32]. Fig. 3 depicts available transport technologies and their energy carriers. Air transport is exogenously defined as a static demand for liquid fuels, depending on scenario assumptions on domestic and international aviation. Efficiencies, cost, and reference case load factors for transport technologies come from Robinius et al. [37].

2.3. Model coupling process and assumptions

The coupling process of the two models is one-directional: Passenger travel demand feeds into the energy system model by mode of transport and region within Germany. We refrain from iterative hard-linking by implementing an interchange of energy prices for two reasons: First, transport demand is relatively inelastic to fuel price changes as compared to transport system design – especially travel time – [38], which makes an iterative coupling disproportional to its computational cost. Second, the definition of prices differ between both models. The energy system model calculates marginal prices, while the transport model uses consumer prices including taxes and supply revenues. Making assumptions about the latter factors is as good as assuming consumer prices in total.

In general, we assume a yearly inflation rate of 1.5% applying to all fuel prices and public transport fares. The average charging cost for electric vehicles amount to 0.4 EUR/kWh, based on 2022 prices. The double applies for trips that use public charging, representing a realistic business model for public charging station operators, approximated as half of all shopping and execution trips. Plug-in hybrid electric vehicles are assumed to have an electric driving range of 80 km, which is fully utilised before switching to synthetic fuels because these are more expensive (i.e. the same as inflation-adjusted petrol prices in 2022).

Extending the transport demand scenarios to other countries would require other national transport models, which are very resource-intensive and inaccessible [39]. Assuming the same macroscopic transport demand changes as in Germany for other countries is problematic because the socio-cultural and infrastructural conditions vary widely. Our approach to corresponding scenarios relies on fine-granular drivers of change (see the next section) that most probably differ from country to country. Hence, we focus our study to the region of Germany. Still, comprehensive passenger transport demand-side mitigation scenarios have never been studies for a region as large and populated.

However, the energy system model optimises the full European energy system, as described above. We fix other countries to a reference case in order to coarsen the energy system analysis to Germany, too. Specifically, we run the optimisation problem for the reference+Improve scenario for all of Europe, yielding the cost-optimal energy system. Non-German capacities are then fixed to this solution for all other scenario runs. This allows us to study impacts of German passenger transport demand only on German energy capacities.

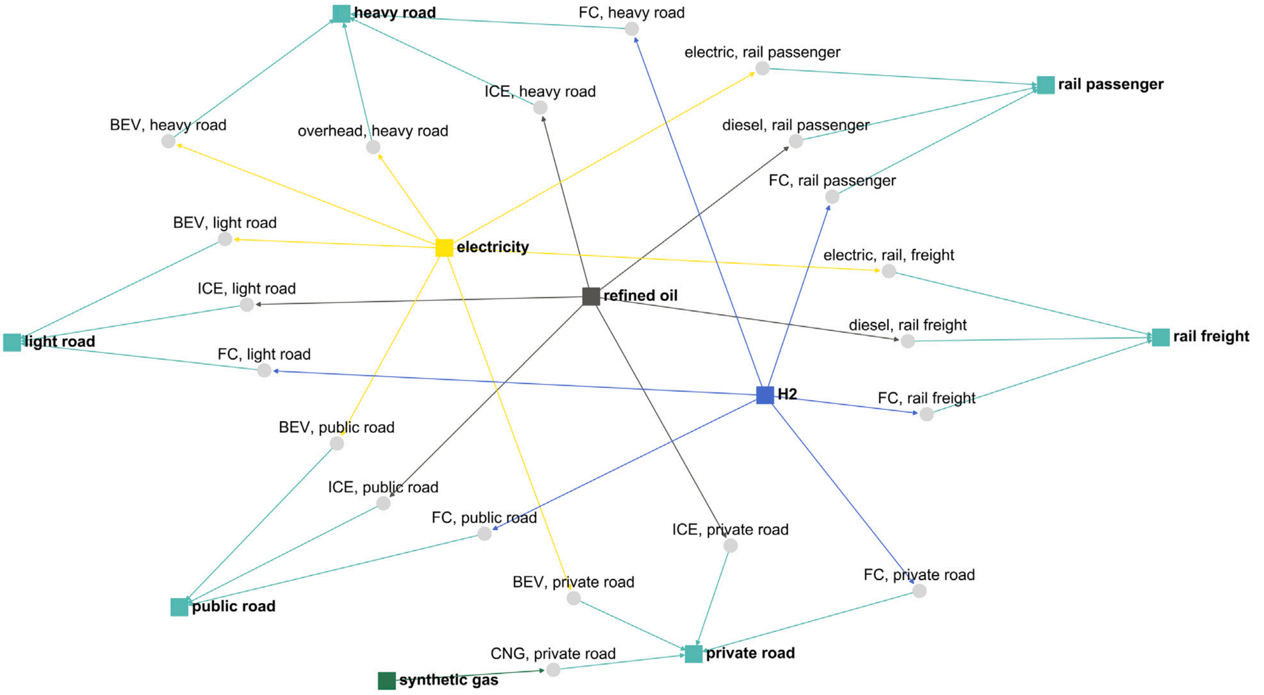


Fig. 3. Sub-graph of transport technologies and corresponding energy carriers. Vertices in the graph either represent energy carriers, depicted as coloured squares, or technologies, depicted as grey circles. Entering edges of technologies refer to input carriers; outgoing edges refer to outputs. Green squares are the mobility demand of each mode. Our scenarios do not modify freight transport.

Other countries cannot trade more energy with Germany, as in the reference+Improve case. Fixing Europe to the reference+Mix scenario would generate large generation capacities for synthetic fuels in southern Europe, which is then available in all other scenarios, omitting the impacts of transport demand changes.

International air travel is not affected by our scenarios, as we can only model intra-German transport. We do not make assumptions about medium- and long-distance flight reductions because they are not covered by our qualitative-quantitative research design and would outweigh other levers of change. Air travel is expected to account for more than half of German passenger transport's energy demand in 2045 [40]. Air transport technologies are not expected to change, except for the adoption of 100% synthetic fuels.

Public transport vehicles, on the contrary, are assumed to be fully electrified in all scenarios by 2040. The German rail operator already announced full climate neutrality by 2038 and the European Union's clean vehicles directive is a strong driver for electrified drivetrains in public road transport.

Finally, the assumptions for vehicle occupancy are as follows. No changes apply for air transport. Car occupancy rates differ by scenario, as defined in its quantification process (see next section): 1.5 applies for the reference and Shift scenarios, 1.8237 for the Avoid and Avoid+Shift scenarios. For public transport, the relative increase in road and rail use per pkm is calculated, and this increase is multiplied by the corresponding average occupancies found in the energy system model's input data set [37]. We ensure no overcrowding of transport carriers by setting a cap of 70% occupancy, under which all scenarios stay below. The Shift scenarios introduce on-demand ride pooling services, which account for 90% of road PT traffic. Zech et al. [41] suggest high ride pooling system efficiencies with average loads of 6 persons in 8-person vehicles. However, due to the spatial and temporal periphery of these services, the average occupancy is set to 3, which is still a progressive assumption.

2.4. Transport demand scenarios description

The qualitative-quantitative transport demand scenarios are a crucial element for the novelty and extent of this study because they allow analysis beyond techno-economic assumptions and shed light into socio-cultural processes. Fig. 4 demonstrates the steps of scenario creation. The following paragraphs briefly describe the process, while the fully detailed description can be found in Arnz and Krumm [15].

In the first phase, we collect drivers of change towards sufficiency for the German passenger transport system by consulting 15 transport and sufficiency experts from various disciplines. The guided brainstorming process results in 133 sufficiency drivers, encompassing infrastructure, social, individual, and systemic factors. These drivers are categorised as policy interventions, individual mindset changes, corporate actions, and consumption changes. To construct the storylines, we classify the drivers as traffic avoidance, mode shift, or both, with the help of expert knowledge. Three storylines are created: one with traffic avoidance drivers only, one with mode shift drivers only, and one incorporating all drivers of change. We employ the Multi-Level Perspective framework to analyse transition dynamics, considering the interactions between niches, regimes, and landscapes. The storylines provide insights into the outcomes, processes, and actors involved in achieving sufficiency in German passenger transport. A summary of the storylines can be found in Table 2, while their written form with further explanation is available in Appendix B (adapted from Arnz and Krumm [15]).

The translation of storylines into modelling scenarios involves quantifying model parameters. Out of the 133 sufficiency drivers, 64 have a direct impact on the transport model, and each of them corresponds to one or more distinct model parameters. To enhance transparency and reproducibility, a survey method is used to inform the quantification process. The survey is distributed among all experts who were invited to the sufficiency driver workshop. It consists of 59 questions related to different action fields, and the responses from 12 participants are used to generate average values for the model parameters. These quantitative values define three modelling scenarios based on the sufficiency storylines, along with a reference scenario that serves as a comparison. Some parameters require implementation of specific levers into the model logic, which is – together with all other drivers, their specifications, corresponding survey question, and responses – accessible in the supplemental material.

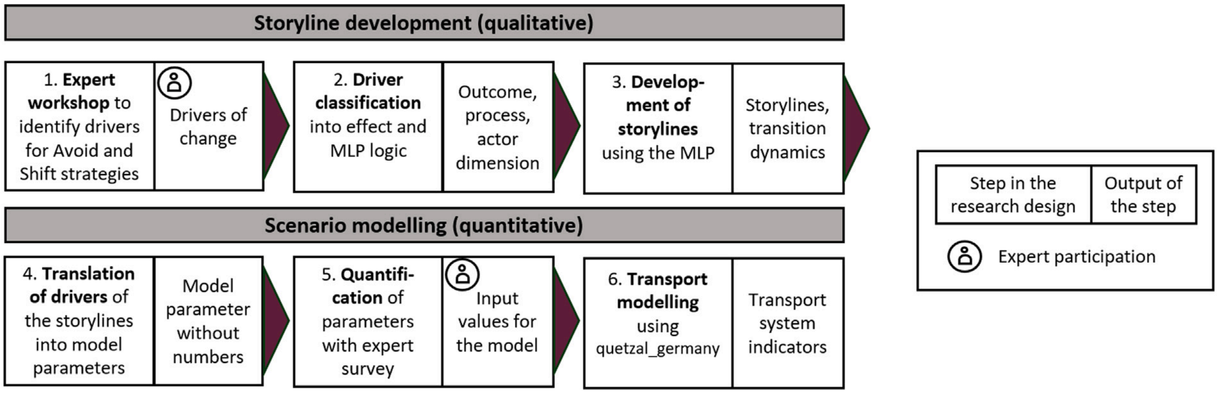


Fig. 4. Research design divided into a qualitative and quantitative phase. Steps 1 and 5 involve mobility and sufficiency experts.
Source: Source: Arnz and Krumm [15]

Table 2
Summary of sufficiency storyline outcomes.
Source: Arnz and Krumm [15]

	Avoid	Shift	Avoid+Shift
outcome dimension	High availability of goods, services, amenities, and social activities in local environment; digitisation in work relations and distant social contacts	Minimum car dependency; efficient, attractive, interconnected PT; safe and comfortable cycling infrastructure; increased public health	Main aspects in addition to Avoid and Shift: New core principles of integrated transport and spatial planning; private cars as anti-status symbol
transition dynamics (drawing upon Multi-Level Perspective)	Several digitalisation niche developments with large momentum reduce the need for traffic; local and shared economies (niches) build up momentum, while landscape developments put the economic growth imperative under large pressure; the welfare state regime stabilises	Strong niches advance diverse mobility offers, helping public and non-motorised transport regimes stabilise and grow (enabled by a large number of landscape developments)	In conjunction with Avoid and Shift dynamics: Radical landscape changes exert large pressure on the automobile regime, which becomes subaltern; further landscape pressures and formerly small niches challenge materialism
driver classification	moderate policy intervention (56 %) and large cultural shifts from equal shares of mindset and consumption changes, as well as corporate action	largely driven by policy intervention (73 %) and corporate action (17 %) with minor mindset shifts (7 %)	60 % policy interventions, 21 % individual mindset changes, 14 % corporate action, 5 % consumption changes

2.5. Car stock modelling for private vehicle expenditures

We construct a simplified car stock model in order to depict the private vehicle stock development towards the target year, and calculate corresponding expenditures. Noteworthy, this model is not designed for accuracy, neither does it include elaborate methods. It is a simple collection of mathematical formulations that provides two things: a rough estimate about the total cost of car sales, and an impression about the required sales rates per technology in each scenario. All assumptions and data are included in the supplemental material. Here is a brief summary.

We differentiate in three different drivetrain technologies: BEVs, plug-in hybrid electric vehicles (PHEVs), and internal combustion engine vehicles (ICEVs). Fuel-cell electric vehicles are not part of our vehicle stock because they are not expected to play a role by the year 2040 in the reference case of any major national scenario [16,40]. The vehicle fleet's drivetrain composition of our Mix scenarios corresponds to the "Mix" scenario in the German national *Ariadne* project in the year 2040 [16], as described in Table 1. We use this scenario because it employs the highly detailed *Vector21* car stock model and its assumptions are broadly accepted in the community.

Our cost data stems from E3-Modelling [42], linearly interpolated between five-year steps, as can be seen in the supplemental material. The source diversifies into three vehicle size groups (small, medium, and large), which we adopt. The reference and Shift scenarios retain the same size distribution as of 2020 in Germany [43], while the Avoid and Avoid+Shift scenarios shift 50 and 100% of large vehicles to small vehicles, respectively. The shift occurs linearly towards 2040.

BEV adoption is not linear, but a progressive exponential function that is tuned to yield the final year's BEV proportion of the corresponding scenario's total vehicle stock. The latter comes from the transport demand scenarios and we assume a linear decrease in car ownership. The adoption function is capped to the scenario's maximum car sales per year, which is the final year's total car stock divided by the lifetime of a vehicle (15 years, in line with input data of the energy system model). PHEVs are linearly adopted towards the final stock and ICEVs make up the rest.

We do not account for BEV production capacities because they stay uncertain and the global BEV distribution is up to future market dynamics. All Mix scenarios stay within bounds of foreseeable BEV availability in Germany by 2030 [44]. In the Improve case, only the Avoid+Shift scenario stays under the threshold of 9.6 mio. BEVs in 2030, which the authors of the study find reasonable after confidential dialogues with car manufacturers. The reference+Improve scenario accounts for 15.9 mio. BEVs, exceeding this threshold by two thirds.

3. Results

3.1. Transport demand changes

The proposed transport demand scenarios (i.e. Shift, Avoid, Avoid+Shift) are connected to a paradigm shift in German passenger transport. They comprise 133 infrastructural, socio-cultural, organisational, and regulatory drivers of change, which were collected, translated, and quantified in a participatory, interdisciplinary research design [15]. On the qualitative side, this process resulted in socio-technical storylines, which show co-benefits of sufficiency-oriented system design on human well-being (see Arnz and Krumm [15]). The Shift scenario decreases car dependency to a minimum through strong initiative towards rail transport reliability and capacity, as well as safe and fast cycling networks, and attractive on-demand ride pooling

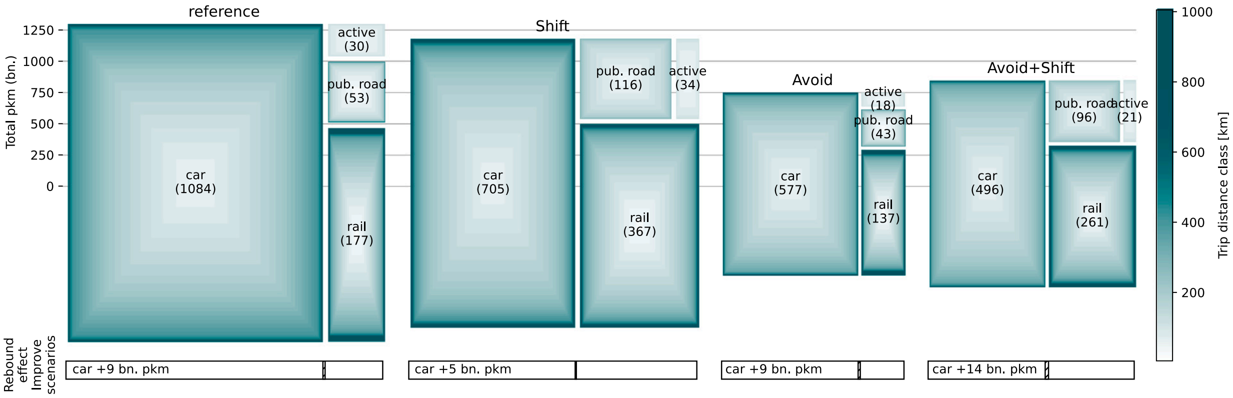
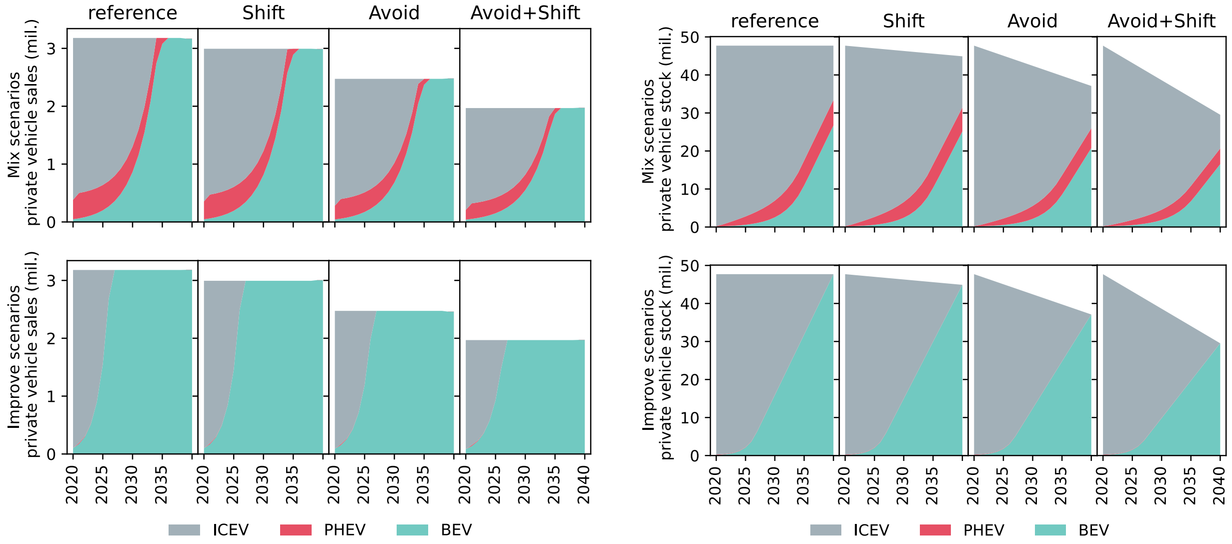


Fig. 5. Results of the transport demand scenarios. Passenger-kilometres (pkm; in parentheses) can shift to public and non-motorised modes or decrease starkly in the Shift and Avoid scenarios, respectively. Trip distance distributions (indicated by the colour scale) shift to shorter distances in the Avoid scenarios. The private vehicle drivetrain change in the Improve scenarios causes more kilometres driven by car, as operation cost decrease, a phenomenon known as the rebound effect (depicted in the lower bars).



(a) Private car sales

(b) Private car stock

Fig. 6. Private vehicle sales (a) and corresponding stocks (b). The vehicle stock model reproduces fleet development towards the target year, as defined in the scenarios (see Table 1).

systems. The Avoid scenario, on the other hand, depicts sufficiency-oriented lifestyles that feature strong local economies, social cohesion, and supply structures, combined with remote work across sectors. The Avoid+Shift scenario combines both of the previous scenarios, and adds strong push measures against private car driving. Here, industry policy and regulatory frameworks are fully tailored towards sustainable transport and equity.

Fig. 5 shows quantitative results of these storylines, generated with quetzal_germany. The reference case is dominated by car transport over all distance classes and involves an increase of total passenger-kilometres (pkm) against 2020 due to increased household incomes. The Shift scenario is able to replace 33% of the car trips by other modes with only slight decreases in car ownership. The total number of trips slightly increases, even though total pkm decrease by 9%. This is due to disruptive mobility concepts that make short and medium distance travel overly attractive. The Avoid scenario shows a different transport system with 42% less pkm, especially on long-distance segments that were previously dominated by car travel. The combined scenario shows even fewer trips, especially by car due to strong push measures, but more pkm in total, as the public transport system becomes more connected and attractive.

The Improve scenarios on the transport supply side show similar results as the Mix scenarios, despite higher shares of car travel. This is due to reduced operation cost of private vehicles, as the share of electric driving increases to 100%. This effect accounts for less than 1% in the reference case, but 2.6% in the Avoid+Shift scenario, where car driving is heavily taxed and, thus, the marginal utility of lower operation cost increases. The private car stock development differs strongly between transport supply scenarios. While Mix scenarios show a moderate uptake of electric vehicle sales, Improve scenarios show a radical increase of BEV sales in order to match the scenario targets. Sales reach 100% BEV share in the mid-2020s, which takes a decade longer in the Mix scenarios. Fig. 6 depicts the radical shift in private car technologies, deduced with the simplified car stock model. It also shows car ownership development as outcome of the transport demand scenarios. The car stock declines as low as 29.5 mil. vehicles in the Avoid+Shift scenarios, interpolated linearly over the scenario period for sake of simplicity. In this study, we neglect possible energy demand implications from changes in industry capacities.

3.2. Impact on the energy system

All transport sector scenarios correspond to a reduction of energy supply, compared to the reference+Mix scenario. Two different effects

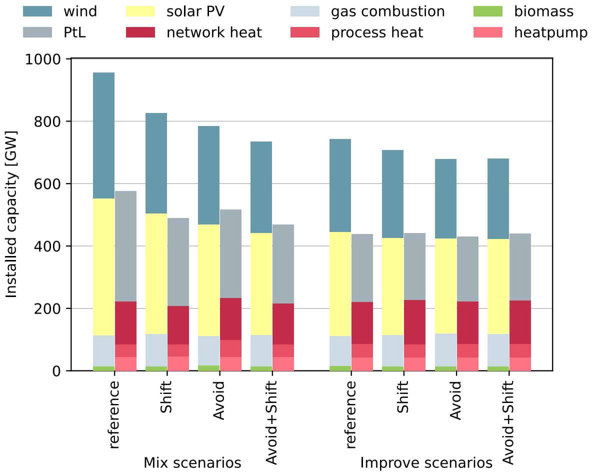


Fig. 7. Installed capacities in a 100% RES-based German energy system, separated by generation (left bar) and conversion (right bar) technologies. Transport demand and supply strategies show similar capacity reductions that decrease when strategies are combined.

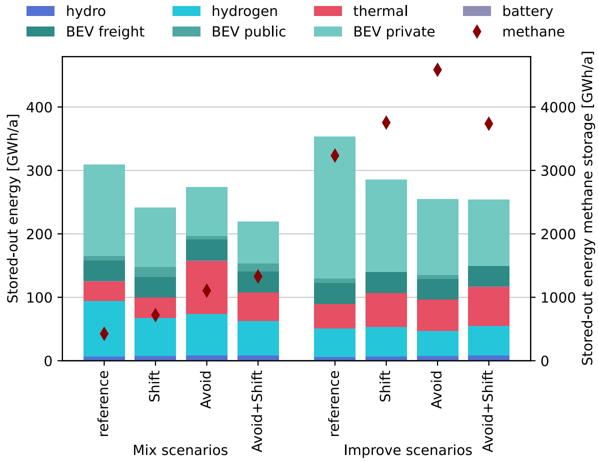


Fig. 8. Stored-out energy by storage technology, cumulative for the target year. Avoid and Avoid+Shift scenarios reduce the private vehicle stock drastically so that some flexibility is shifted to the heat sector, some to methane storage (secondary axis). The loss of synfuel facilities in the Improve scenarios increases methane storage starkly.

can be distinguished here: First, changes in technology adoption between the Mix and Improve scenarios, i.e. the switch from internal combustion engine vehicles to BEVs, greatly reduce the demand for synthetic fuels by 83% (without transport demand changes). The remaining share is used primarily for international aviation and shipping, which uses biomass as primary input. Compared to the Mix scenarios, the additional demand for hydrogen to produce these synfuels decreases, and ultimately also electricity generation, the input for hydrogen production. As a result, the required wind and solar capacities decrease by 25% in the Improve scenarios. Furthermore, the electrical capacity of electrolysers drops from 153 to 63 GW in the reference case. Since the creation of synfuels requires carbon filtered from the atmosphere as well, finally, capacities for direct air capture are reduced from 12 GW to zero. Fig. 7 depicts aggregated capacities across scenarios, and Figs. 10 and 11 in Appendix A demonstrate changes in underlying energy flows.

The second effect does not relate to technology adaption but to the utilisation of these technologies, i.e. the transport demand scenarios. In the Avoid+Shift case, the reduction of transport demand and the shift towards more efficient public transportation reduces the overall energy demand significantly. Impacts differ between the Improve and Mix scenarios: In the Mix scenario, a significant amount of 318 TWh/a can be saved since traffic reduction and public transport replace inefficient private combustion vehicles. In the Improve case, total savings are smaller, amounting to 92 TWh/a, since comparatively efficient BEVs already dominate the vehicle fleet. Concerning the other transport demand scenarios, a shift to public transport has smaller energy saving potentials than the radical reduction of traffic in the Avoid scenarios.

Changes in the transport sector also affect the provision of flexibility in the power system, which is a critical feature of energy systems reliant on fluctuating wind and solar power. Flexible charging of electricity contributes to the system's flexibility and must be substituted, if the share of BEVs is reduced (as in the transport demand scenarios). Furthermore, the level of hydrogen demand affects the flexibility provision starkly since electrolysers in combination with hydrogen storage add flexible demand. The Improve scenarios show large shifts of flexibility from synfuels (both facilities and demand) to methane storage. Correspondingly, gas use increases from 0.7 to 8.2 TWh/a in the reference+Improve scenario (Fig. 11(a)), but it is mainly used for flexibility provision through higher gas engine capacities. Since the scenarios with Avoid character show significantly smaller stocks of electric vehicles, they result in more stationary batteries and gas storage vice versa (Fig. 8). Similarly, the larger public vehicle stock compensates flexibility demand in the Shift+Mix scenario. It should be noted that stationary batteries are a comparatively expensive flexibility option, which is why the model does not expand them to large scales, but makes use of sector coupling opportunities.

Gas and batteries alone cannot compensate for all flexibility from synfuels, which provide the largest share of flexibility in the Mix scenarios. Thermal storage more than doubles on average for the Improve scenarios, as the heat sector adapts to the new energy system configuration and thermal storage is comparably cheap. In the Avoid+Shift+Mix scenario, combined heat and power plants are replaced with gas engines to provide flexibility, whereas the opposite is the case in the Avoid+Shift+Improve scenario. Here, both capacities increase due to the largest deficit of flexibility from passenger transport across scenarios. In general, changes in storage capacity are roughly equivalent to changes in stored energy.

3.3. Energy and transport system cost

As an addition to the energy system model's output of component cost, we carried out a cost analysis for every infrastructure- or vehicle stock-related driver of the transport scenarios after their setup. Hence, we did not select Avoid and Shift drivers or their intensity based on a cost–benefit analysis, which is common in transport economics, but included every possible measure, following the rationale of the original study [15]. We use annualised cost with static interest rates of 5% and 15 or 50 years for vehicles or infrastructure, respectively (matching with the energy system model settings). Specific assumptions for each transport system driver can be found in the supplemental material. We also include an estimate of the low-voltage grid expansion cost for BEV charging, which is deemed a relevant cost component [45], based on Agora Verkehrswende et al. [46]. The results are depicted in Fig. 9: Reductions in final energy demand translate into cost reductions for the energy system, but demand-side measures add other types of cost.

Energy savings through lower transport demand have a higher impact on cost of generation and conversion capacities in the Mix scenarios than in the Improve scenarios, where vehicle technologies are less energy-intensive. The Improve scenarios require additional capacities in energy storage in order to compensate for flexibility that is provisioned by synfuel facilities in the Mix scenarios, but the impact on total cost is small (less than 1 bn. EUR/a). Shifting traffic to public modes has a smaller energy system cost reduction potential as avoiding traffic – 14 bn. EUR/a versus 15 bn. EUR/a less than the reference in the Mix case –, though at comparably high transport

Fig. 9. Scenario cost by component. Private vehicle stocks make up the largest share and increase in Improve scenarios. Shift and Avoid scenarios add infrastructure cost for public transport and living (multiplex buildings, provisioning), making cost without private vehicles exceed the reference. Energy system cost decrease stronger on the transport supply axis (vertically) than on the transport demand axis (horizontally) due to less Power-to-Liquid (PtL) facilities and corresponding renewable energy generation.

infrastructure cost (32 bn. EUR/a). The Avoid case, on the other hand, saves some expenditures for road infrastructure in new settlements and adds cost for living infrastructure, which includes buildings for living and provisioning systems with corresponding technical infrastructure (13 bn. EUR/a). The Avoid+Shift scenarios reduce energy system cost the most, but add both, transport and living infrastructure investment. The most significant factor, whatsoever, is private vehicle cost. These are direct results from vehicle sales in the car stock model, which – as can be seen in Fig. 6 – decline drastically in the Avoid and Shift scenarios. The number of BEVs also determines the low-voltage grid expansion cost, which account for 5% of total infrastructure cost in Avoid+Shift+Mix and 28% in reference+Improve.

4. Discussion

Our results show that intra-German passenger transport's final energy demand can be reduced from 381 TWh/a to 152 TWh/a through Avoid, Shift, and Improve measures. They imply ambitious levels of change on the transport demand- and supply-side, resulting in transport energy demand of 1.8 MWh/a/cap. That is 7% lower than the Global North in the IPCC Sixth Assessment Report's most ambitious illustrative modelling pathway [47]. This Low Energy Demand scenario highlights the crucial role of energy demand-side mitigation measures for keeping global warming below 1.5 degrees Celsius without reliance on carbon dioxide removal. At the same time, our per capita energy demand lies nearly four times above the absolute minimum needed to satisfy basic human needs in mobility with maximum technological efficiency [48]. However, these studies are highly stylised, while our study examines the German context comprehensively and in ample detail.

National studies in Germany compute passenger transport final energy demands between 1.2 MWh/a/cap with strong assumptions for sufficiency and efficiency [49] and 2.1 MWh/a/cap with moderate behavioural change and moderate adoption of BEVs [40]. Assumptions for transport demand and reported pkm differ from ours, but these studies do not employ detailed transport models or comprehensive approaches to transformation drivers. Yet more importantly, vehicle efficiency is lower in our input data [37]. This conservative approach nuances the differences between scenario results, as it stresses the energy supply system. For the same effect, we restrict energy imports from Europe and put imports from non-European countries at prohibitive prices. This study targets a sustainable energy system, and energy imports from non-European countries currently come with large uncertainties regarding social and environmental sustainability [50,51].

In general, sustainability concerns three complementary strategies: sufficiency, efficiency, and consistency. This study addresses consistency by targeting 100% RES, and efficiency through 100% directly electrified drivetrains, even though further techno-economic measures like lightweight design or technological efficiency improvements would be possible. Sufficiency is not clearly defined in transport literature, but it corresponds to Avoid and Shift strategies in the context of energy sufficiency [15,52,53]. The Avoid+Shift scenario describes a maximum sufficiency threshold by employing a systemic perspective that goes beyond individual lifestyle changes (see Appendix B and Table 2). It thereby alters the mobility system towards equity, i.e. equal access to mobility, by reducing car dependency. Here, the current mobility system in Germany scores low, as rich households own most cars and produce most traffic [27], while low-income households are forced to spend over-proportional amounts of their income on car travel because the public transport system does not suffice [14]. The connection of pull measures towards public transport and push measures against car driving highlights other positive effects of the sufficiency strategy: increased public health and well-being through increased use of active modes [54,55]; reducing traffic externalities like pollutants, noise [56], and road fatalities [57]; strengthening social cohesion in the local habitat through fundamental changes in the built environment [58]. As such, sufficiency appears as multi-objective solving strategy, which is more than just co-benefits of climate change mitigation strategies [as framed in12,13]. In a policy context, it should be framed as a strategy to promote well-being because it puts the human at the centre of transport policy, not the car.

However, the sufficiency strategy comes at a cost. It saves similar amounts of energy generation capacities and corresponding energy infrastructure cost as the efficiency strategy, but it requires public investment into public services and infrastructure. Specifically, this amounts to annualised cost of 18 bn. EUR/a for transport infrastructure and 13 bn. EUR/a for housing infrastructure, although it saves 2.7 bn. EUR/a in low-voltage grid expansion for BEV charging. This is not an optimal cost assessment, as we do not select sufficiency measures based on their cost-benefit ratio, but include everything. As a result, some drivers might contribute under-proportionally for their cost. For example, 66% of the transport infrastructure investments are spent on the high-speed rail network, which is only relevant for long-distance travel. Further research should pursue cost–benefit analysis, taking into account the various types of cost and actors for infrastructural, educational, regulatory, economic, and socio-cultural drivers.

Here, distributional impacts are particularly policy-relevant. The sufficiency strategy imposes half the cost for vehicles on private households compared to the efficiency strategy. Additional investment in public infrastructure accounts for one fifth of these savings. As such, transformation cost in the efficiency strategy are bared by private households with cars, whereas in the sufficiency strategy, transformation cost are bared by all, guaranteeing mobility infrastructure for all. The present study cannot assess distributional impacts, but in general, high-quality public infrastructure acts beneficial for high levels of well-being with low environmental impact [59], while private car use is the single most significant factor for intra- and international inequity [60].

This study is designed to compare different demand-side mitigation options in passenger transport in terms of energy demand and cost. The sufficiency strategy shows synergies with well-being, while the efficiency strategy is connected to rebound effects towards car use. We suggest a better connection between climate policy and social policy to make certain policies more effective in solving multiple issues and in communicating them. However, we highlight that every scenario comprises unprecedented levels of ambition and change, making it improbable (though feasible) within the limited time. Increasing the probability of large-scale energy demand reduction requires employing all strategies simultaneously. We do not account for greenhouse gas emissions, but it is certain that high-income countries like Germany cannot leave any demand-side mitigation option unexploited in order to contribute limiting global warming to 1.5 degrees Celsius.

CRediT authorship contribution statement

Marlin Arnz: Conceptualization, Formal analysis, Methodology, Software, Writing – original draft, Validation, Edited the paper. **Leonard Göke:** Conceptualization, Formal analysis, Methodology, Software, Validation, Edited the paper. **Johannes Thema:** Conceptualization, Validation, Edited the paper. **Frauke Wiese:** Conceptualization, Validation, Edited the paper. **Niklas Wulff:** Conceptualization, Validation, Edited the paper. **Mario Kendziorski:** Conceptualization, Validation, Edited the paper. **Karlo Hainsch:** Conceptualization. **Philipp Blechinger:** Validation, Edited the paper. **Christian von Hirschhausen:** Validation, Edited the paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All scenario data is included in the article and supplementary material; all models are open source; energy system model base data is available upon request.

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Appendix A. Energy flows

Even though we summarise the most important results of the energy system model in the article, it is difficult to sketch a full picture of the resulting energy system configurations. Sankey diagrams allow for a more intuitive understanding of these configurations by depicting energy inputs, outputs, flows, intermediate steps, efficiencies, and technologies. Figs. 10 and 11 describe energy flows in the Mix and Improve scenarios, correspondingly.

Appendix B. Storyline descriptions

The *Shift storyline* describes a radical pull strategy that reduces car dependency to the absolute minimum. Drivers of this process mainly concern strengthening of public transport (PT) and cycling, transport planning, and digitised mobility services. Rapidly increasing the reliability and capacity of the rail network is of particularly high priority, as well as the establishment of comprehensive on-demand ride-pooling systems. Transport planning and its increased budget is fully directed towards PT. As juridical underpinning, road traffic regulations give cycling and PT priority in the traffic flow. Moreover, wide and secure cycling highways between urban and suburban regions incite more active mobility.

Technological and organisational innovations, such as mobility hubs in metropolitan areas, free bicycle entrainment, or bike sharing hubs at train stations, enable comfortable multi-modality. Shared e-bikes and cargo bikes support the shift to active mobility additionally. Digital mobility services are emerging that are easy to understand, include all transport services and can be used nationwide. In any case, all PT schedules are well coordinated and a uniform tariff system throughout Germany facilitates easy use and reduces prices in remote regions. There, too, and at off-peak times, autonomous on-demand shuttles provide high service quality and flexibility.

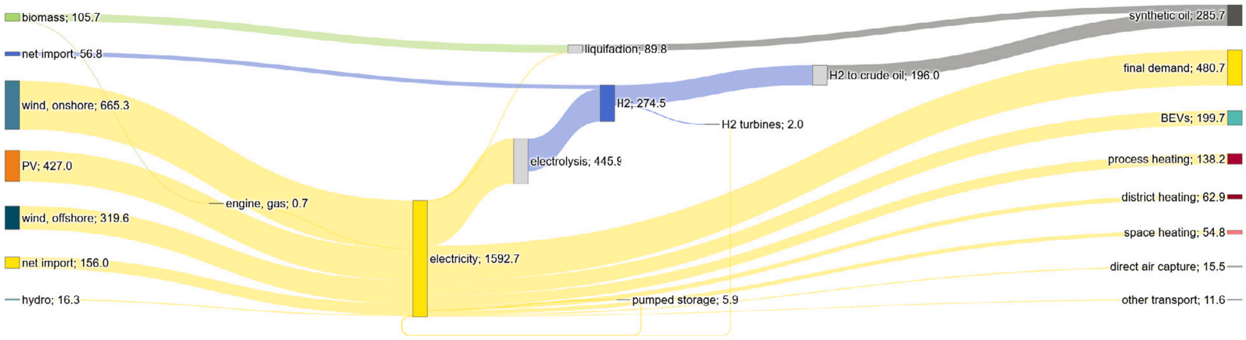
This completely new prioritisation also involves a lot of education work among the population. The most important actor here is the federal government in cooperation with local transport planning. Besides these strong top-down initiatives, innovative business models are also driving the process. Society plays a minor role and adjusts its mobility culture to the new transport system with a temporal delay.

The *Avoid storyline* describes cultural and economic change resulting in traffic avoidance — eliminating the need for long and many trips. The initiative comes from two different directions: Top-down and bottom-up. Urban and spatial planning focuses exclusively on densification of existing settlement areas instead of new development, as well as improvements in quality of life and diversity in the local habitat. In this way, many journeys by motorised vehicles become unnecessary, because the environment in walking distance offers shopping, errands and recreational opportunities, as well as space for social activities.

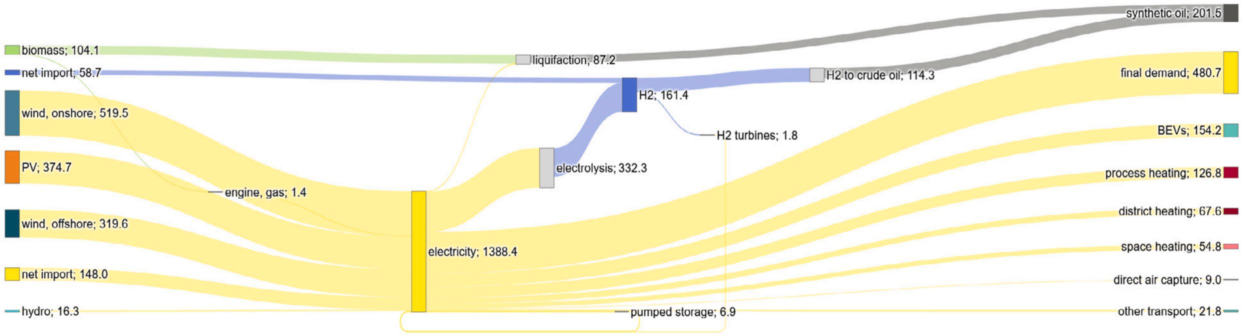
At the same time, various new bottom-up initiatives establish local economies and restorative, local lifestyles. The former strengthen local coherence and make the decentralised offer of products, services, and amenities economically attractive. The prerequisite for this is a less growth-oriented economic policy and rejection of materialism throughout a critical mass in society. Car sharing systems, which emerge throughout the country, support this trend: Following the slogan “from ownership to access”, they lead to reduced car dependence and ownership. The new lifestyles are characterised by local cohesion, while social contacts and work relationships that lie outside the local area are primarily cultivated in digital space. To this end, structures and rights for remote work are comprehensively established and their conditions favoured. This goes beyond office work and comprises remote control of industrial sites.

The *Avoid+Shift storyline* combines three elements: the radical pull strategy of a reliable and interconnected public transport system (as in the Shift storyline), resilient local lifestyles (as in the Avoid storyline), and a fundamental restructuring of transport planning and economic activity. While the Shift storyline minimised car dependency, the fundamental restructuring aims at maximum human-centred mobility planning and minimum car ownership (as a main driver of transport externalities), facilitated through strong top-down initiatives and large-scale shifts in individual mindsets. The necessary money comes from the expansion stop of roads and airports, comprehensive parking pricing in public urban and suburban spaces, and the reduction of climate-damaging or car-friendly subsidies.

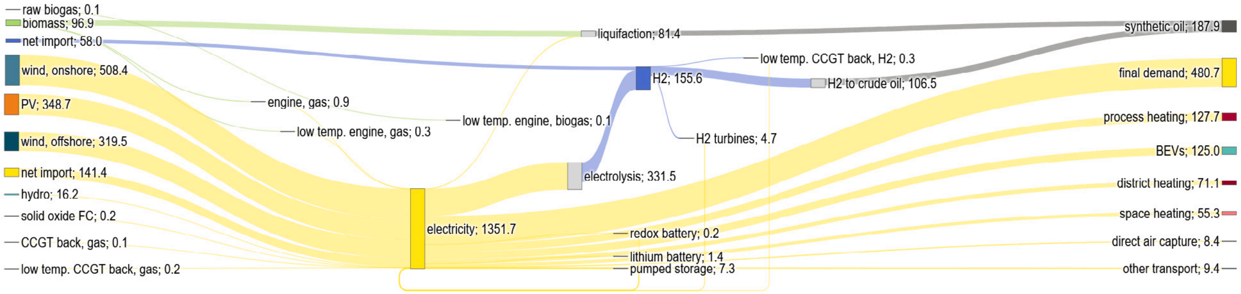
The regulatory framework is subject to particularly strong adaptation. Interdepartmental mobility policy bans cars from cities, leads



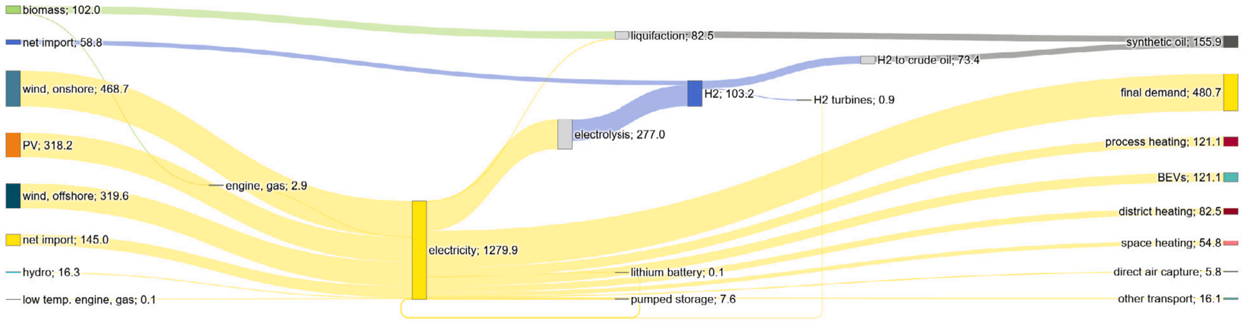
(a) reference+Mix



(b) Shift+Mix



(c) Avoid+Mix

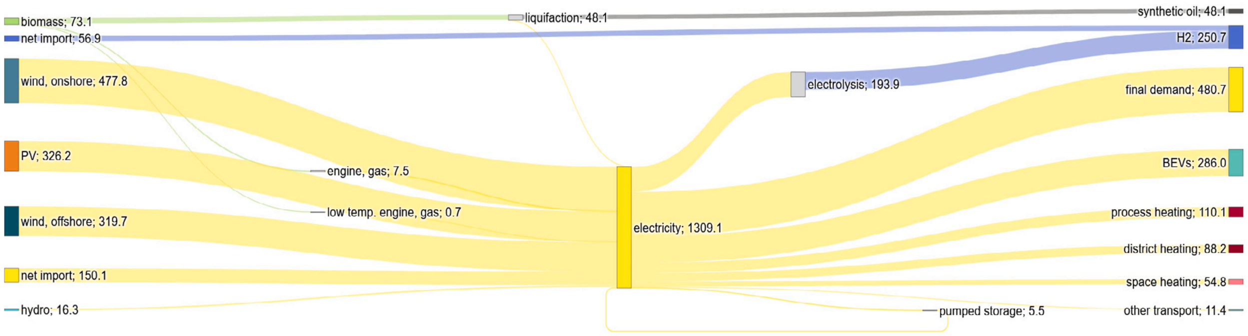


(d) Avoid+Shift+Mix

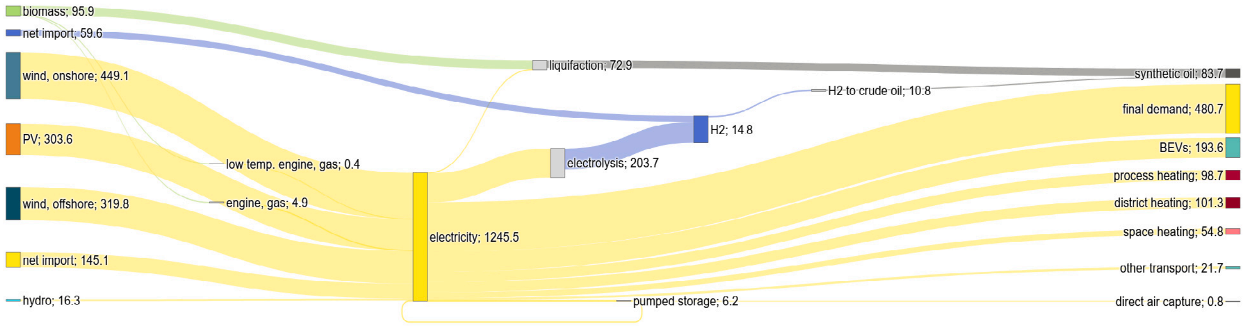
Fig. 10. Mix scenarios have a vehicle stock drivetrain composition of 56% BEVs, 14% PHEVs, and 30% ICEVs.

industrial policy to the necessary shift towards PT, bans car advertising (because of the severe consequences for health and life) and reforms the tax system to incentivise PT use and disincentivise car ownership. Hence, ousting of the automobile lobby from party politics is necessary. At the same time, transport planning becomes more people-centred, more diverse, better staffed and better integrated with urban and spatial planning. Its guiding principles are equity (in terms of reducing car dependency and guaranteeing accessibility to everyone), health (fostering active mobility and lowering transport externalities), and diversity (including all perspectives of society into transport planning).

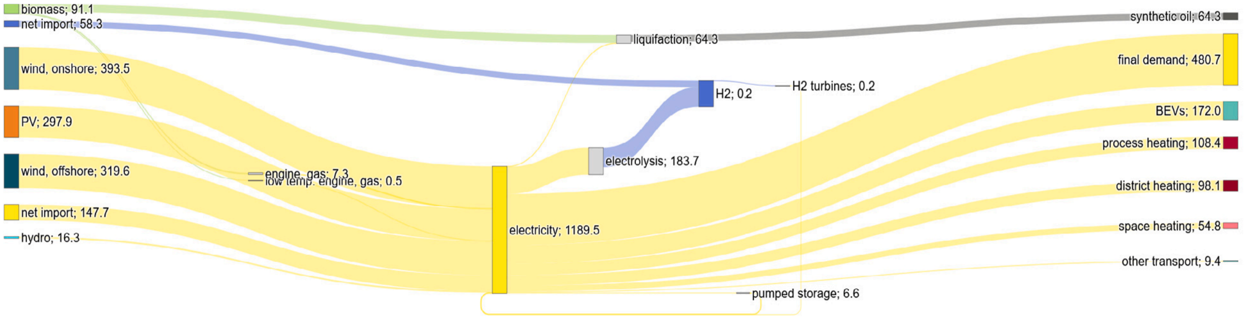
On a cultural level, climate protection, social justice and health – corresponding to the new mobility planning principles – are becoming more important in the consciousness of the population, while economic growth and materialism are losing relevance. Comprehensive criticism



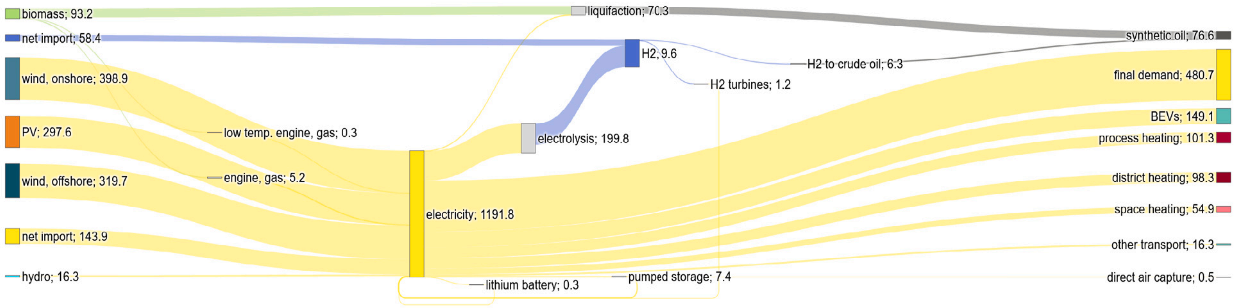
(a) reference+Improve



(b) Shift+Improve



(c) Avoid+Improve



(d) Avoid+Shift+Improve

Fig. 11. Improve scenarios have a 100% BEV share.

of consumption manifests itself in sufficiency-oriented lifestyles, which is demonstrated by role models from the rich and influential classes and slowly spreads through all layers of society. Socially, the car is not only losing its status, but is becoming an anti-status symbol for a critical mass of the population. This is made possible by an ongoing global restructuring of the economic system with the aim of decoupling prosperity from growth, as the neo-liberal economic system is coming under strong pressure due to the social and geo-physical consequences of climate change.

Appendix C. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.esr.2024.101302.

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