Lecture Notes in Mobility

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Disrupting Mobility

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Disrupting Mobility: Decarbonising Transport?

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Abstract The transport sector urgently needs to identify decarbonisation pathways. Global demand for mobility is growing. The same applies for emissions from transport, with much of this growth taking place in emerging economies. Numerous scenario studies attempt to determine efficient strategies to decarbonise the transport sector. In this chapter we provide a comprehensive overview of scenario studies and reveal a wide spectrum of options to decarbonisation. Differences in projected GHG emissions, primary energy use and distances travelled are analysed. A typology of scenario studies is elaborated which reveals large differences in possible pathways.

Keywords Decarbonisation · Scenarios · GHG emissions · Primary energy use · Transport · Mobility

1 Introduction

Societies gain enormous benefits from the ability of moving people and goods over space and time. Efficient transportation facilitates interaction of people and the exchange of goods and thus underpins globalisation and human development. However, major challenges are linked to transportation. On the global level climate change is recognised as a major threat to human civilization caused by the extensive use of fossil fuels. The transport sector is uniquely dependent on oil and has grown considerably in the last 50 years. More than a quarter of overall energy use is

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allocated to the transportation-sector [1]. As one of the main emitters of CO_2 the transport sector contributes significantly to global warming. Increasing emissions from the transport sector have the potential to undermine efforts to meet economy-wide, long-term emission reduction targets. On the local level, air pollution, noise and motor vehicle accidents pose significant threats to human and ecosystem health [2]. In the context of accelerating urbanisation, existing infrastructures cannot cope with large increases in traffic volume. Congestion is becoming an increasing problem, especially in urban areas. Simultaneously, demand for mobility is growing. The same applies for emissions from transport, with much of this growth taking place in the non-OECD world [3].

Future global transport and mobility will be fundamentally affected by the need to create more resource-efficient, clean transport technologies and to deploy and maintain sustainable transport systems. A long-term transformation of transport infrastructure and services is required to meet climate change mitigation challenges as well as the travel needs and requirements of a rapidly growing global urban population, but also to enable sustainable economic growth with sustainable freight transport links between global agglomeration and periphery.

Significant efforts are under way to advance post-fossil mobility systems deploying alternative propulsion technologies and integrating renewable energy sources with transport infrastructure [4]. New energy and materials technologies are enabling new forms of post-fossil transport. ICT-enabled web and mobile applications are spawning a plethora of new mobility services [5]. Traditional mobility markets are in flux and new players are emerging with disruptive service offerings [6]. These are challenging traditional demarcations between public transport and private mobility and will increasingly necessitate a co-production of mobility services by both traditional public and new private providers. In addition, demographic trends such as aging populations in some key world regions, significant public health implications and the need to maintain economic growth as well as basic equity in mobility provision to all social groups provide for complex transport politics. The politics and governance of land-use provide an additional contested policy arena.

The combined effect of these developments will have far reaching impact on the way public transport, private mobility and logistics will be organised in the future. Shaping this new public space will be a strategic opportunity and challenge for cities, regions and governments globally.

Given long investment cycles for transport capital investment, governments will be increasingly faced with competing claims on future transport infrastructure and long-range investment pathways. Identifying and evaluating cost-effective, equitable and successful policy regimes and switch-over strategies for global transport systems is a central climate policy challenge.

Transport has remained particularly stubborn to mitigating intervention and CO_2 emissions are projected to continue to rise significantly to 2050 even in benign scenario outlooks [7] and more significant yet as a share of overall CO_2 emissions. Given global commitment to decarbonisation agreed at the Paris COP 21 in 2015, accelerating and achieving meaningful decarbonisation of transport systems—

defined as a reduction of transport-related GHG emissions in absolute terms—by 2050 is a necessary condition of meeting the intended 1.5 °C temperature threshold.

Recent scenarios (cf. Sect. 3) offer little confidence that the policy mix currently deployed towards mitigation will have sufficient decarbonisation impact even under assumed benign transport policy regimes to achieve the primary energy substitution and carbon emissions reductions necessary to meet even the intended targets. Looking out to 2050, recent projections appear to offer a stabilisation of current absolute CO_2 emissions from global transport at best and a rather more probable increase of CO_2 emissions, albeit with a reduced rate of increase. This warrants an examination of the efficacy of current mitigation policy design and the decarbonisation levers deployed.

We proceed below with a historic and comparative analysis of transport decarbonisation scenarios and their key parameters. We aim to argue that advancing our understanding of the performance of current transport decarbonisation policy strategies will assist in the identification and heuristic integration of new and more effective levers of decarbonisation into future policy design. Numerous scenario studies attempt to determine efficient pathways to decarbonising the transport sector. In this chapter, we provide a comprehensive overview of scenario studies and reveal a wide spectrum of possible pathways.

2 Transport Scenarios: Overview and Analysis

Scenarios are used to outline future visions of society. As a prerequisite scenarios have to be at least theoretically feasible. Conclusions on future developments are drawn upon a number of assumptions. However, scenarios cannot account for all cause-effect relationships. Inherently, simplifications have to be made. The reduction of complexity can lead to quite different evaluations of assumptions. The key question is therefore in each case which image of the future is guiding specific scenario studies and which policy levers are proposed in attaining decarbonisation projections.

2.1 Scenarios Taken into Account

We reviewed a large number of transport scenario studies compiled within the last 15 years. We selected a sample of studies that:

- concern the future development of the transport sector and take GHG emissions into account
- describe developments further than 2030
- take passenger transport into account
- have at least a national geographic scale.

We comparatively analysed a sample of 59 transport emissions scenarios dating from 2000 to 2015 to identify key input factors and mitigation levers. Table 1 gives an overview on the scenarios we examined and the corresponding source.

A core sample of scenarios with a global outlook was subsequently chosen for more detailed comparison. We selected a sample of 19 scenarios with a global outlook and compared projections across four parameters: CO_2 emissions, primary energy use and fossil fuel share, as well as global travel demand. In Table 1 these studies are marked bold. A detailed comparison of the core sample of global scenario results is carried out in Sect. 3.

Scenario studies are built on different paradigms, modelling principles and world views. We used a typology of four types of scenario studies. This typology is presented and discussed in Sect. 2.2 below.

Table 1 Scenarios examined

	Scenario	Source
1	**World Energy Outlook 2002**	[8]
2	**World Energy Outlook 2004**	[9]
3	**Mobility 2030**	[10]
4	Foresight for transport	[11]
5	**Pathways to 2050**	[12]
6	VIBAT UK	[13]
7	**World Energy Outlook 2005**	[14]
8	Szenarien der Mobilitätsentwicklung unter Berücksichtigung von Siedlungsstrukturen bis 2050	[15]
9	Intelligent infrastructure futures. The scenarios—towards 2055	[16]
10	**World Energy Outlook 2006**	[17]
11	Mobilität 2020. Perspektiven für den Verkehr von morgen	[18, 19]
12	**Climate change 2007: Mitigation of climate change**	[20]
13	**Transport technologies and policy scenarios to 2050**	[21]
14	A sustainable energy system in 2050: promise or possibility?	[22]
15	World Energy Technology Outlook—WETO H2	[23]
16	International passenger transport and climate change	[24]
17	**International Energy Outlook 2007**	[25]
18	**World Energy Outlook 2007**	[26]
19	Backcasting approach for sustainable mobility	[27]
20	Politikszenarien für den Klimaschutz IV. Szenarien bis 2030	[28]
21	VIBAT India and Delhi	[29]
22	**World Energy Outlook 2008**	[30]
23	Modell Deutschland	[31]
24	Renewbility - Stoffstromanalyse nachhaltige Mobilität im Kontext erneuerbarer Energien bis 2030	[32]
25	European Climate Change Policy Beyond 2012	[33]
26	**Roads toward a low carbon future**	[34]

(continued)

Table 1 (continued)

	Scenario	Source
27	Getting into the right lane for 2050	[35]
28	**World Energy Outlook 2009**	[36]
29	Energieszenarien für ein Energiekonzept der Bundesregierung	[37]
30	Energy 2050: Lifestyles subproject	[38]
31	Politikszenarien für den Klimaschutz V	[39]
32	iTREN 2030	[40]
33	ADAM	[41]
34	**World Energy Outlook 2010**	[42]
35	EU transport GHG: routes to 2050?	[43]
36	Langfristszenarien und Strategien für den Ausbau der EE in Deutschland	[44]
37	Renewbility II	[45]
38	The future energy and GHG emissions impact of alternative personal transportation pathways in China	[46]
39	**Global travel within the 2 °C climate target**	[47]
40	**Influence of travel behaviour on global CO2 emissions**	[48]
41	The future of mobility. Scenarios for the United States in 2030	[49]
42	ITF Transport Outlook 2013	[50]
43	Potenziale des Radverkehrs für den Klimaschutz	[51]
44	Treibhausgasneutraler Verkehr 2050	[52]
45	Politikszenarien für den Klimaschutz VI	[53]
46	Economic assessment of low carbon vehicles	[54]
47	eMobil 2050. Szenarien zum Klimaschutzbeitrag des elektrischen Verkehrs	[55]
48	Re-programming mobility	[56]
49	Shell Pkw-Szenarien bis 2040	[57]
50	**World Energy Outlook 2014**	[58]
51	**CECILIA 2050. Optimal EU climate policy**	[59]
52	**IPCC Climate Change 2014: Mitigation to climate change**	[3]
53	**ITF Transport Outlook 2015**	[7]
54	Beyond traffic 2045	[60]
55	Nutzen statt besitzen	[61]
56	Urban mobility system upgrade	[62]
57	World Energy Outlook 2015	[1]
58	Vision Mobilität Schweiz 2050	[63]
59	DEFINE	[64]

2.2 Typology of Scenario Studies

Mobility futures and possible reductions in transport-related GHG emissions are evaluated in numerous model-based and explorative studies. These studies can be distinguished by scope, disciplinary background and modelling approaches. These studies also propose different decarbonisation pathways and mitigation options. In our analysis we built on a typology proposed by Creutzig [65]. We expanded this typology and distinguish four types of studies on transportation futures:

- Integrated assessment models (IAM)
- Transportation-sector models
- Culture- and society-based models and studies
- Explorative studies.

Integrated assessment models (IAM) evolve a global, aggregate perspective on transportation futures. While other models focus on specific sectoral strategies, IAMs aim to project impacts of cross-sectoral, economy-wide mitigation strategies. Therefore, IAMs deploy market-based equilibrium concepts and mainly focus on fuel choices and GHG emissions. The narrative focus is on the decarbonization of energy supply, which implies for the transport sector a fuel shift from oil to electricity, hydrogen and/or biofuels.

A serious disadvantage of this approach is the tendency to focus on mitigation strategies in the power sector. This effect is due to the fact that transport-specific mitigation options are usually more cost-intensive than options in other sectors [66]. GHG emission reductions are mainly realised by fuel shift and generic efficiency improvement. Corresponding measures can easily be operationalized in monetary costs. Other options like modal shift, behavioural change or infrastructural options are not sufficiently captured by the modelling algorithms used in IAMs [65]. While IAMs delineate economy-wide decision pathways and proffer systemic levers such as carbon-pricing, they proceed from models and assumption spaces rather than observed data. Some scholars have hence and perhaps unfairly criticised IAMs for creating "a perception of knowledge and precision that is illusory, and can fool policy-makers into thinking that the forecasts the models generate have some kind of scientific legitimacy" [67: 1].

Transportation-sector-specific models evolve a sectoral perspective on mitigation strategies and ignore inter-sectoral equilibrium effects. This means, for example, that a shift in the power sector from fossil fuels towards renewable energies is taken for granted and transport-specific technologies are optimised within this boundary consideration. Optimal mitigation strategies across sectors are ignored [34].

While IAMs often deploy very long time-scales up to 100 years, transportation-sector-specific models often focus on the next decades up to 2050. Compared to IAMs, demand side strategies like infrastructure and modal shift options are better represented. Some direct transport externalities such as road safety or congestion are addressed.

At the core, however, are traditional considerations of incremental efficiency improvements in vehicles, fuel economy and related sectoral technology. The potential for cross-sectoral infrastructure optimisation (or sector coupling), alternative concepts of behavioural change, or place-based shift and avoid strategies is not considered [68]. In this respect there is a broad consistency with IAMs (Fig. 1).

The third type of models and studies is rooted deeper in societal and cultural studies. Starting point of these studies is the assertion that the complex relation between human behaviour, transport and climate change has to be central for elaboration and evaluation of mitigation strategies. It is argued that effective transition strategies rely on a deeper understanding of societal transitions and human–technology interactions. Studies that solely focus on an economic perspective like IAMs and transportation-specific-models wholly ignore complex cultural, societal and political relations. Therefore, culture and society-based studies focus on place-based shift and avoid strategies and underline local best practices as well as the effect of local demand and supply-side policy instruments. Additionally, the set of objectives is further widened in these studies. Beyond road safety and congestion, these studies also consider air quality, spatial and health impacts and deploy urban design and active transport levers. While providing an integrated approach to transport transformation and offering promising decarbonisation potential, these strategies often remain local in ambition and it is yet unclear how their results can be synthesised and scaled beyond local (or regional) best practice solutions. More

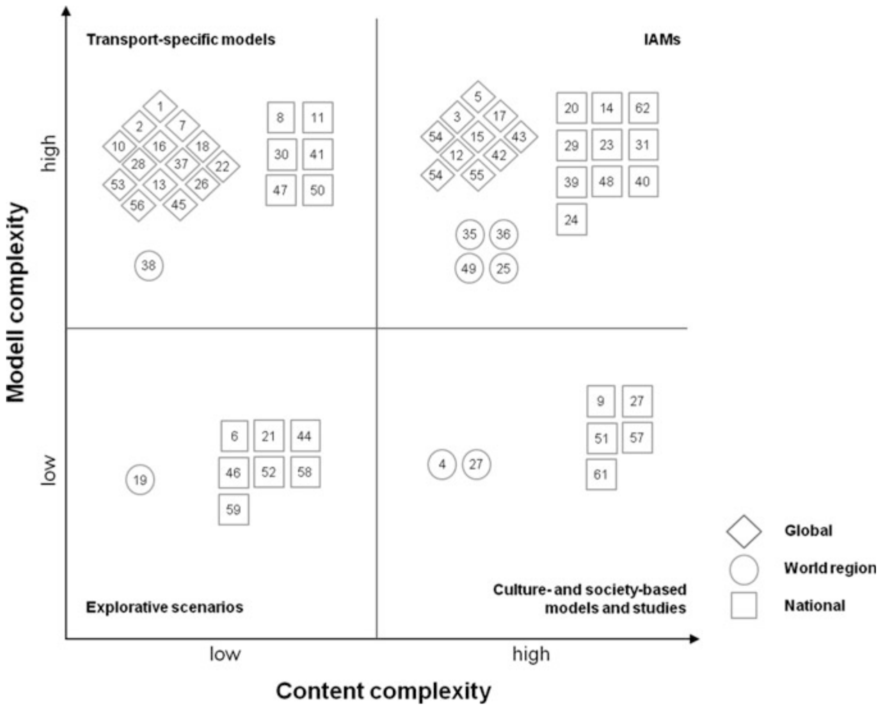

Fig. 1 Classification of observed scenarios

empirical data is also needed on the long-term impact of local transformative transport regimes.

Explorative studies explore trends and describe possible futures in form of narratives and storylines or visualisations rather than numerical estimates. These studies can be especially helpful to explore solution spaces for radical shifts towards low carbon economies [69]. While IAMs and transportations-specific-studies characterise change as being rather slow and incremental over long time periods, explorative studies discuss pathways for rapid change in transport policy or travel patterns and focus on counterfactual scenarios based on disruptive technologies and events [e.g. 6]. In most cases explorative studies remain speculative and are beyond the scope of (global) modelling efforts.

3 Analysis and Comparative Evaluation of Selected Global Scenarios

The EU and other OECD countries have announced very ambitious GHG reduction targets. While even in these world regions increasing emissions from the transport sector have the potential to undermine efforts to meet emission reduction targets, a more critical situation is emerging in other world regions. In non-OECD countries rapid growth of transport volumes is almost unanimously anticipated and threatens to massively accelerate transport-related GHG emissions growth to 2050.

To review the potential performance of transport decarbonisation policies at the global level, we selected 19 global scenario studies and compared BAU and policy projections across four parameters: travel demand, GHG emissions, primary energy and fuel use.

3.1 Distances Travelled

Almost all scenarios share the assumption that global demand for mobility is growing. But only two scenario studies explicitly provided projections for global travel demand. As shown in Fig. 2 Girod et al. estimated travel demand for three [39], respectively five [40] different scenario computations. All eight scenarios show a steep increase in travel demand within the next 85 years.

Projections of travel demand are missing in the other 17 studies; however, all studies expect rapid population growth within the next decades. GDP growth is equally anticipated in all selected studies leading to implicit projections of global travel demand.

Reduction of travel demand is computed in one scenario only. The World Energy Council [21] estimates the potential of a reduction of passenger kilometre travelled of 30% in industrial countries by 2050. While of considerable impact on

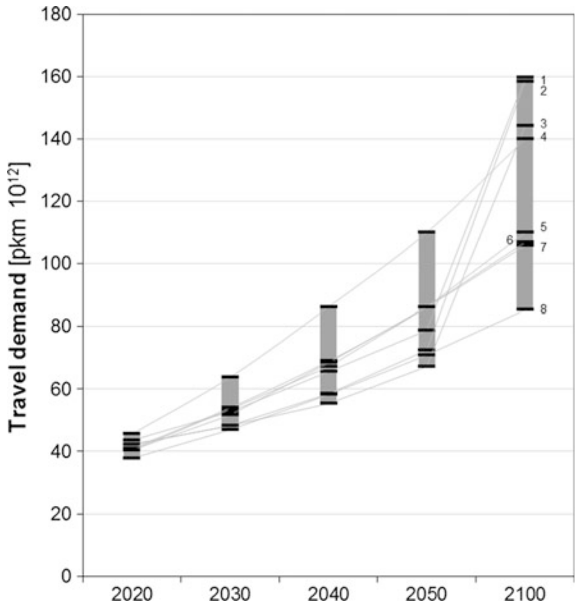

Fig. 2 Global travel demand in different scenarios. *Sources* (*1*) Baseline [39], (*2*) Scenario A [39], (*3*) Scenario B [39], (*4*) POLES [40], (*5*) TIMER [40], (*6*) IEA [40], (*7*) GCAM [40], (*8*) GET [40]

carbon emissions, accelerating travel demand at the global level is projected to neutralise the carbon mitigation effect of even such a significant reduction in transport demand across the OECD. With regard to the policy objectives rapidly growing travel demand marks an extremely challenging starting point.

3.2 Target Goal: GHG Emissions

All global BAU scenarios considered in our analysis are projecting increasing and accelerating emission pathways (Fig. 2).

Our review of scenario projections of the last fifteen years reveals that scenario outlooks have had to be adapted over time and that the outlook for GHG emission pathways has progressively worsened. Decarbonisation milestones have also been moved outward in time across a number of policy scenarios, necessitating deeper and faster cuts in emissions in the future then were projected ten years ago. Achievement of these policy milestones appears to become less rather than more probable. As an example, 2030 BAU emission levels projected by the IEA in 2007 are today expected by the IEA [1] to be only achievable under its alternative policy scenario (cf. Figs. 3 and 4).

This illustrates how transport emissions have become of “run-away” concern, as the near-term outlook for even the stabilisation of CO_2 emission has become more negative. More radical path corrections need to be assumed beyond 2030 to achieve any real mitigation effect to 2050.

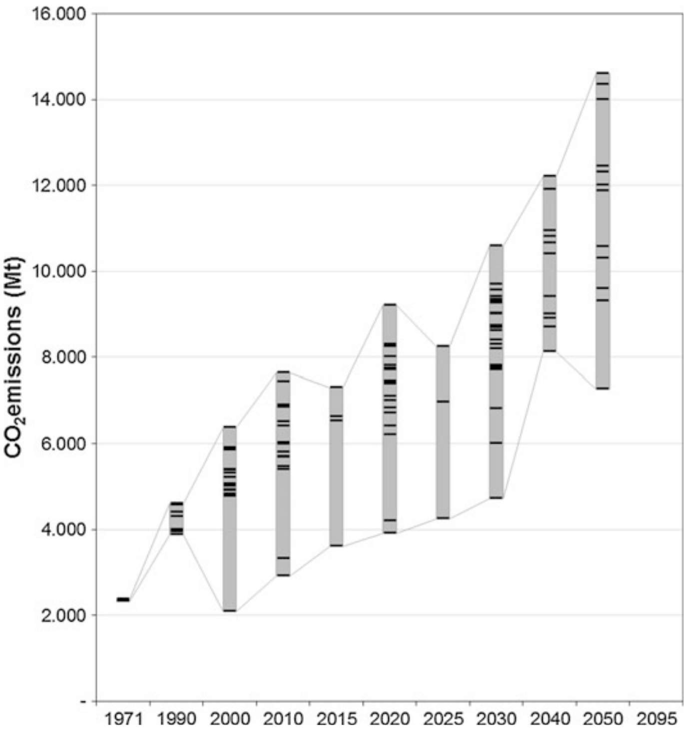

Fig. 3 GHG emissions: BAU scenarios; *grey bars* indicate the range of projected (and historic) CO_2 emissions; *black lines* indicate values of specific scenarios (see Appendix—Tables 2 and 4 for scenarios and values)

3.3 Target Goal: Primary Energy Use

Primary transport energy demand is only projected in a few scenarios. Compared to the results on CO_2-emissions, the variance of the estimates is much smaller and oil retains a dominant share of global transport energy mix in both BAU and policy scenarios. Across all scenarios fossil fuel use in transport is reduced as a share of primary energy source to differing degree; however fossil fuel use remains relatively stable in absolute terms across most policy scenarios. No significant change in fuel use is anticipated in policy scenarios before 2040. Even most benign scenarios of transport decarbonisation project for global transport to consume an equal amount of fossil fuel in 2050 as it does today. This appears a relatively weak ambition of current decarbonisation policy design.

Current demographic, land-use and motorisation trends appear to neutralise projected incremental fuel efficiency and substitution strategies. Some scenarios

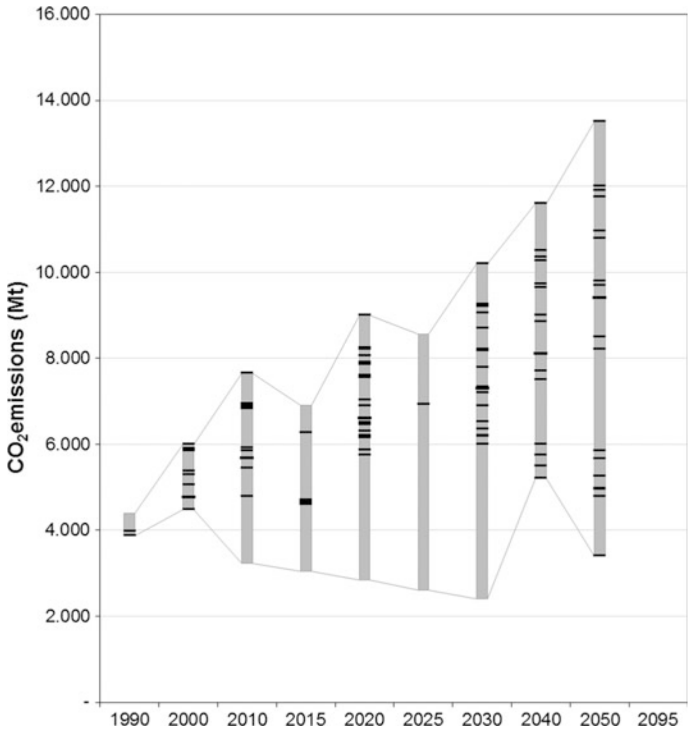

Fig. 4 GHG emissions: policy scenarios; *grey bars* indicate the range of projected CO_2 emissions; *black lines* indicate values of specific scenarios (see Appendix—Tables 3 and 5 for scenarios and values)

deploy assumptions of end-of-pipe CO_2 mitigation such as CCS technology to accomplish required emissions targets to 2050. These leave underlying primary energy and fossil fuel use intact and reveal a potential myopia of type 1 and 2 policy scenarios.

While scenario studies of type 3 (culture- and society-based models and studies) and type 4 (explorative studies) seek to elaborate alternative pathways to individual and fossil motorisation, scenario studies of type 1 and type 2 attach little importance to these option and focus exclusively on combustion-fuel efficiency and incremental fuel substitution along existing mode shares. Underlying patterns of modal share, travel demand and land-use are not analysed or deployed as scenario levers.

It is worthy to note also, that those BAU and policy scenarios extending to 2095/2100 anticipate an extreme increase in overall transport primary energy demand after 2050 (Figs. 5 and 6).

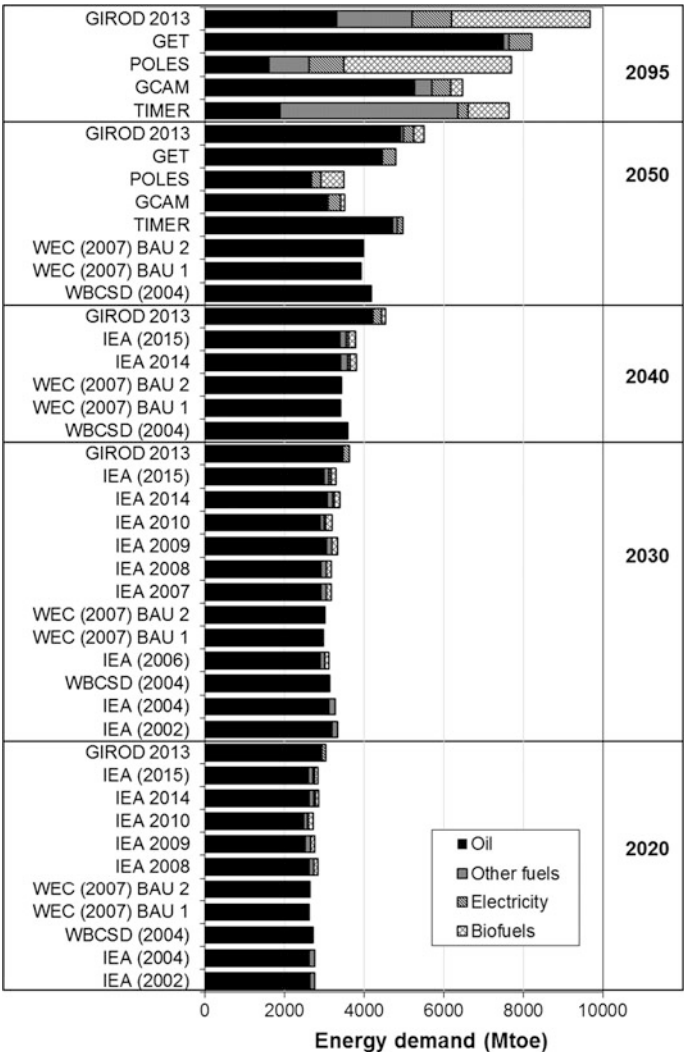

Fig. 5 Primary energy use: projected trends in fuel use in BAU scenarios

4 Conclusion and Research Outlook: Disrupting Mobility?

Based on current scenario projections, a more radical transformation of transport systems appears to be required to achieve decarbonisation targets and is likely to become a significant policy challenge. Global mitigation scenarios currently focus mainly on incremental fuel efficiency and fuel substitution as the key levers for decarbonisation.

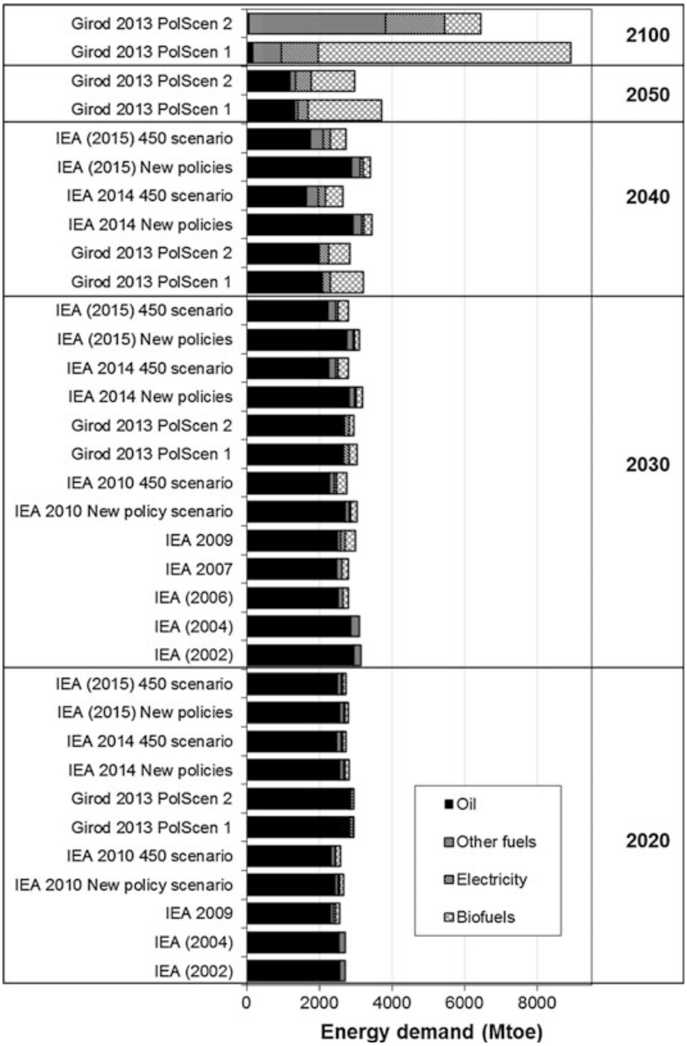

Fig. 6 Primary energy use: projected trends in fuel use in Policy scenarios

Given global demographic and socioeconomic trends and the attendant acceleration of individual motorisation in Asia, South America and Africa, fuel efficiency measures—while impacting on overall carbon efficiency—do not appear to be sufficient to achieve the necessary absolute reductions in fossil primary fuel use and CO_2 emissions. Fuel substitution strategies can offer improved impact but do not address the spatial, resource and economic inefficiency of current individual automobile motorisation. While important other levers such as modal shift and demand and land-use management are included in some scenarios, they are not sufficiently represented, explored or weighted as decarbonisation levers in the core sample of global mitigation scenarios. They do, however, offer significant decarbonisation potential that is under recognised in global policy strategies.

Future research efforts should focus on evaluating the combined and synergetic effects of integrating urban energy, infrastructure and mobility systems and of more resolute modal shift measures, mass transit expansion and sustainable land-use governance.

New Technologies and Service Models

The comparison of global scenarios indicates a path-dependency of current transport policy calculus. Policy remains focused on incrementally optimising existing individual motorisation modes and automobile technologies rather than on leveraging integrated transport strategies and sustainable technologies. Breaking this path-dependency is a key innovation challenge.

Notably, these scenarios do not yet fully incorporate the innovation dynamics of recent years. The potential carbon mitigation performance of emerging new technologies and services such as electric, autonomous and on-demand individual mobility which are currently capturing public attention has not yet been extensively evaluated, in particular in their integrated application. It is yet to be established, whether and which specific new technology systems or service models—either as stand-alone or integrated application—can contribute to meaningful transport decarbonisation to 2050. None of the global scenarios analysed include significant assumptions relating to these proposed technology systems and their potential systemic impact.

Moving forward, and in order to achieve meaningful transport decarbonisation, new mobility systems, technologies and services should be examined with regard to their balanced, simultaneous and effective contribution across the core transport decarbonisation levers available:

- Fuel/vehicle efficiency
- Fuel substitution
- Modal shift
- Demand and land-use management.

Energy Transition as a Driver for Transport Transition

While extensive electrification of existing modes of individual motorisation would provide for significant carbon reduction effects if renewable power is deployed, it would not address issues such as congestion, space consumption and induced CO_2 emissions from expansion of road construction and maintenance. In addition, moving to zero-emission electric mobility requires full fleet conversion and decarbonisation of global power systems within the same time frame, an objective only few nations are expected to meet by 2050. Most scenarios do not yet triangulate between energy ("Energiewende") and mobility system ("Verkehrswende") transformation and the interface between these deserves further research and analysis.

Recent studies have indicated significant systemic decarbonisation potential can be achieved by the coupling of renewable power and electric mobility systems at the local level. Integrating electric mobility as a component of a future renewable energy system appears to be a promising policy vector [70]. To attain maximum decarbonisation impact, however, fuel substitution strategies will need to be integrated with distributed smart grids, energy-efficient urban infrastructures and energy storage systems (i.e. not be solely focused on the electrification of existing fleets and modes).

Modal Shift and Mobility Services

Reducing the share of travel by individual low-ridership combustion engine vehicles can lead to significant reductions in CO_2 emissions. This involves a reduction of use of personal-use and low-occupancy vehicles by promoting the use of more energy-efficient modes such as conventional mass transit (bus, tram, light rail), other shared-ride solutions, as well as cycling and walking. Across a number of European cities daily travel modes have recently shifted away from the automobile and towards public transport or active travel (e.g. London-12%, Berlin-8% from 1998 to 2013, [71]) and individual motorization is a minority mode share in a range of global cities [72]. These are positive trends for decarbonisation.

Conventional car-sharing or short-term rental in principle do not significantly reduce vehicle kilometres travelled and as such do not constitute modal shift. They may have the potential to decrease the overall amount of vehicles required and can potentially enable more efficient first/last mile access to mass transit systems thereby contributing to modal shift. However, even when highly integrated with public transport, a recent study in Germany has indicated conversion to ubiquitous car-sharing would achieve reductions of only 4% of total German transport CO_2 emissions [61]. Better results could be expected from ride-sharing and mass transit services which can significantly increase the number of passenger per vehicle and consequently reduce overall vehicle kilometres travelled.

With regard to new mobility services—as for instance on-demand individual mobility as a stand-alone service innovation for point-to-point transport—early evidence thus indicates these do not necessarily contribute to significant transport decarbonisation. While a reduction in motorisation rates may be achieved with some potential benefit for urban space reclamation, fossil car-based individual mobility services do not in principle reduce vehicle kilometres or related CO_2 emissions. Whether or not new mobility services can avoid or replicate some redundant traffic flows (by avoiding parking spot search traffic or by increasing the number of vehicles in constant circulation seeking riders) remains to be empirically examined and validated at scale and under real-world conditions.

Automation and Vehicle Efficiency

With stable or increasing demand for mobility, automated vehicles will only reduce emissions and energy consumption if they are zero-emission and sustainable from a full system perspective. A priori, automation does not represent a meaningful decarbonisation lever as it does not fundamentally reduce or substitute primary energy used per passenger or vehicle kilometre. While incremental emissions reduction may be achievable through an increase in fuel and circulatory—or traffic—efficiency resulting in an incremental reduction of fuel use and of vehicle kilometres travelled, any meaningful emission reduction could only be achieved by deploying fuel substitution including electrification, as the primary lever. Whether automation is a necessary condition for electrification has not yet been convincingly established. A focus solely on automation could engender complex and expensive vehicles requiring significant investments into public and private digital infrastructure and thus create barriers to rapid fleet decarbonisation and fuel substitution. It may, however, ease the integration of electric fleets with renewable smart grid and charging infrastructure and thus can potentially make a positive indirect contribution to fuel substitution.

Automation also does not in principle contribute to meaningful emissions reduction through vehicle efficiency unless fundamental proportions—i.e. volume, weight, speed—of vehicles become more resource and spatially efficient [73]. A more effective lever in this regard is vehicle miniaturisation. The development of personal electric vehicles capable of blending with low speed active travel in cities and providing first/last miles individual mobility integrated with mass transit, should allow for a significant reductions of emissions from individual mobility. As with electrification, however, automation is not prima facie a necessary condition of miniaturisation or a fundamental decarbonisation lever of vehicle efficiency.

On-demand mobility for individual vehicular point-to-point travel, automated or not, does not appear to offer meaningful decarbonisation potential as it would not in principle and without deploying other levers contribute to significant modal shift, fuel substitution or vehicle efficiency.

A key question to be analysed is thus whether a required "densification" and "electrification" of transport should proceed from the simple conversion of existing motor vehicle systems or from the differentiation of integrated mass transportation systems—both arterial and capillary—offering significant reductions in vehicle kilometres by providing shared mobility at scale and individual first/last mile mobility on demand.

Land-Use Management and Zero-Emissions Mass Transit Systems

The insights from the scenarios analysed suggest strongly that a key lever for successful and deep decarbonisation of transport will be the expansion of zero-emissions mass transit systems and their integration with first/last mile personal electric mobility and active travel. Given demographic and urbanisation trends, spatially and carbon-efficient high through-put public transport has the potential leverage to provide sustainable transport capacity to meet this rising demand. Global scenarios currently offer little intelligence on this core lever which should be a central focus of transport policy. Enabling core mass transportation systems can provide the backbone for integrating decarbonised new mobility services, and energy systems and contribute to sustainable transit-oriented urban development.

Efficient mass and public transport has historically and successfully enabled urban agglomeration and continues to underpin mobility systems in leading global cities such Singapore, Hong Kong, Zurich, Amsterdam, Berlin, London, Barcelona, Paris, Tokyo and New York. Whether automation of individual mobility services can provide an alternative solution to mass transit, in particular in cities with low public transport infrastructure remains to be established. Automation and/or on-demand provision of private vehicular services, however, in principle do not address the energetic and spatial inefficiency of low-occupancy individual motorisation or attendant infrastructure emissions and unsustainable land-use.

While automation, in particular of mass and ride-share transit, has great potential, it does not a priori provide a strategic decarbonisation lever for urban mobility, which will have an increasingly dominant share of global transport emissions. Empirical evidence will yet need to be obtained to evaluate and validate automation and individual mobility services as a decarbonisation strategy. They can strongly support a shift to transport decarbonisation, or further lock in unsustainable travel behaviour and infrastructure design.

In this respect, Mobility-as-a-service and automation strategies should be examined for their balanced contribution to significant modal shift, ubiquitous fuel substitution and sustainable land-use and demand management.

Closing the Gap Between Research Paradigms and New Data Collection Tools

Understanding and differentiating the systemic carbon mitigation performance of emerging and integrated new transport and mobility systems will be fundamental in identifying successful and sustainable transformation paths and to inform long-range policy design. This is a complex and challenging task requiring analytical insights and empirical evidence from across disparate disciplines and domains, relating to complex interactions between technology development, service innovation, user behaviour and preferences, infrastructure and urban design, spatial and economic efficiency and environmental performance.

The comparison of scenario studies reveals a gap between scientific communities. Different paradigms have not been well integrated. Assessing potential new pathways of transport decarbonisation requires a systemic view of the evolving transport transformation across different domains such as energy, transport, ecology, urban design, logistics and dynamic human behaviour. Integrating these multidisciplinary insights will have to build on a critical analysis of transport decarbonisation policy strategies to date and will require policy analysis and decision support systems that can assess and evaluate multidimensional and integrated transport transformation pathways.

Given the combined scenario outlooks discussed above, future policy design will need to focus on optimising the systemic resource efficiency of global transport systems rather than pursuing mono-dimensional levers such as carbon-pricing, fuel efficiency or substitution which only deliver partial success in decarbonisation or suffer self-defeating externalities. A more balanced policy mix is required to account for the real-world complexity of global transport systems and the inter-dependencies of urban form, energy sufficiency and human and ecological quality of life.

As a priority, transport decarbonisation policy research and development should aim to establish robust policy analysis tools that can integrate the emerging wealth of data from across the scenario domains. This should provide a rigorous basis from which to evaluate and model more sustainable pathways for future mobility systems and to inform public deliberation on transport futures.

However, global transport policy analysis suffers acutely from a lack of reliable and comparable international open data at both the micro and macro level as well as from a lack of multidisciplinary pooling of evidence. New data collection tools can provide real-time empirical data on the movement of people and goods across space and time. These tools enable a much wider range of mobility and transport data to be collated at the individual and spatial level allowing for more precise modelling of the potential impacts of transport policy levers as they interact in real time and space. Integrating this data with existing scenario intelligence should provide for a more balanced configuration of global transport decarbonisation policy. The development of open data research infrastructure to inform public decision-making on sustainable transport pathways should be a core element of a sustainable transport policy agenda.

A collaborative international effort is needed to assimilate and verify the empirical evidence of sustainable transport innovation at the local and regional level and to develop evidence-based global policy strategies for truly intelligent mobility.

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Appendix

See Tables 2, 3, 4 and 5.

Table 2 BAU scenarios used in Fig. 3

#	Source	Scenario
1	IEA [8]	BAU—IEA 2002
2	IEA [9]	BAU—IEA 2004
3	WBCSD [10, 12]	BAU 1—WBCSD 2004
4	WBCSD [10, 12]	BAU 2—WBCSD 2004
5	WBCSD [10, 12]	BAU (IEA 2004)
6	IEA [17]	BAU—IEA 2006
7	IPCC (2007)	WBCSD (2004)
8	WEC [21]	BAU 1—WEC 2007
9	WEC [21]	BAU 2—WEC 2007
10	EC [23]	BAU—EC 2007
11	Meyer et al. [24]	Gompertz constant technology
12	IEA [26]	BAU
13	IEA [30]	BAU
14	McKinsey [34]	No-action scenario
15	IEA [36]	BAU
16	IEA [42]	Current policy scenario
19	Girod et al. [48]	TIMER
20	Girod et al. [48]	GCAM
21	Girod et al. [48]	POLES
22	Girod et al. [48]	GET
23	Girod et al. [48]	IEA
24	IEA [1]	BAU—IEA 2015

Table 3 Policy scenarios used in Fig. 4

#	Source	Scenario
1	IEA [8]	Alternative policy scenario
2	IEA [9]	Alternative policy scenario
3	WBCSD [10]	Diesels potential
4	WBCSD [10]	Hybrids potential
5	WBCSD [10]	Fuel cells (H_2 from NG) potential
6	WBCSD [10]	Advanced biofuels potential
7	WBCSD [10]	Combined technologies scenario
8	WBCSD [10]	Fuel cells (zero-carbon hydrogen) potential
9	WBCSD [10]	Advanced biofuels (also in heavy trucks) potential
10	WBCSD [12]	Pathways 2050
11	WBCSD [12]	Pathways 2025
12	IEA [17]	Alternative policies scenario
13	WEC [21]	BTL 25% in 2050
14	WEC [21]	Diesel 50% in 2050
15	WEC [21]	BTL 25% and diesel 50% in 2050

(continued)

Table 3 (continued)

#	Source	Scenario
16	WEC [21]	Cellulosic 25% in 2050
17	WEC [21]	Hybrid 50%
18	WEC [21]	Cellulosic 25% and hybrid 50% in 2050
19	WEC [21]	FCV 25% in 2050
20	WEC [21]	Pass km reduction 30% in 2050
21	EC [23]	Carbon case
22	EC [23]	H_2 case
23	IEA [26]	Alternative policy scenario
24	IEA [30]	550 policy scenarios
25	IEA [36]	450 policy scenarios
26	McKinsey [34]	Biofuels
27	McKinsey [34]	Traffic flow
28	McKinsey [34]	Driving behaviour
29	McKinsey [34]	Distance driven
30	McKinsey [34]	Optimised ICEs
31	McKinsey [34]	Mixed technology
32	McKinsey [34]	Hybrid + electric
33	IEA [36]	450 policy scenario
34	IEA [42]	New policy scenario
35	IEA (2011)	450 scenario
36	Girod et al. [48]	TIMER
37	Girod et al. [48]	GCAM
38	Girod et al. [48]	POLES
39	Girod et al. [48]	GET
40	IEA [1]	New policies scenario
41	IEA [1]	450 scenario

Table 4 GHG emissions—BAU scenarios (# corresponds to number in Table 2)

#	GHG emissions per year (Mto)									
	1971	1990	2000	2010	2015	2020	2025	2030	2040	2050
1	2320		4814	6010		7449		9024		
2	2351		4914	5977		7375		8739		
3			6370	7640		9200		10,580	12,200	14,350
4			4760	5680		6820		7750	8900	10,300
5			5370				6963			
6		3875	5306		6630			8402		
7	2375	4300	5400	6400		7700		9000	10,400	11,870
8			5850	6850		8250		9250	10,650	12,300

(continued)

Table 4 (continued)

#	GHG emissions per year (Mto)									
	1971	1990	2000	2010	2015	2020	2025	2030	2040	2050
9			5900	6900		8300		9400	10,800	12,450
10		3982	5056	5461		6206		6815		7263
11			2085	2920		4193		5991	8127	10,576
12		3950			6524			8293		
13		4390	5370		7292	7796	8249	8680		
14				3324	3604	3910	4248	4712		
15		4574				7733		9332		
16						7398		8617		
19		4000	5000	5400		6400		7800	9400	12,000
20		4000	5000	5700		6700		7700	8700	9600
21			5000	5800		7000		8200	9000	9300
22		4300	5200	6500		8000		9700	11,900	14,000
23			4900	5800		7100		9300	11,900	14,600
24		4604		7441		8263		9553	10,942	

Table 5 GHG emissions—policy scenarios (# corresponds to number in Table 3)

#	GHG emissions per year (Mto)								
	1990	2000	2010	2015	2020	2025	2030	2040	2050
1			5914		7032		8179		
2			5846		6893		7792		
3		4760	5680		6600		7300	8100	9400
4		4760	5680		6450		6900	7500	8500
5		4760	5680		6500		7200	7700	8200
6		4760	5680		6200		6350	6000	5250
7		4760	5680		6150		6000	5500	4970
8		4760	5680		6300		6200	5750	4950
9		4760	5680		6150		6000	5200	3400
10		5370							4778
11		5370				6926			
12	3875	5289		6265			7336		
13		5850	6820		7850		8700	9720	10,950
14		5850	6850		8200		9200	10,500	12,000
15		5850	6850		7900		8700	9640	10,790
16		5900	6900	4650	7600		8200	9000	9800
17		5900	6950	4600	8250		9250	10,350	11,900
18		5900	6950	4700	7550		8200	8850	9700
19		5850	6850		8050		9050	10,270	11,750

(continued)

Table 5 (continued)

#	GHG emissions per year (Mto)							
	1990	2000	2010	2015	2020	2025	2030	2040	2050
20		6000	7650		9000		10,200	11,600	13,500
21	3982	5056	5439		5861		6184		5850
22	3982	4487	4787		5741		6528		5660
23				6188			7102		
24					7720		8190		
25							7800		
26			3301	3378	3595	3987	4315		
27			3297	3333	3513	3865	4212		
28			3270	3270	3432	3743	4162		
29			3252	3239	3378	3707	4086		
30			3252	3108	2919	2784	2730		
31			3239	3077	2842	2671	2527		
32			3230	3050	2847	2608	2410		
33					7066		7688		
34	4393			6911	7262	7633	8089		
35					6962		6841		
36			5577		6331		7375	7550	8180
37					6000		6216	6391	6234
38					6869		7209	7301	7145
39					7697		8243	7798	6442
40					8150	8558	8898	9660	
41					7969		7789	7107	

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