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Co-creating socio-technical scenarios for net-zero emission pathways: Comparison of five national case studies

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ABSTRACT

The extent to which modelled future pathways support effective policymaking for sustainability transitions has been questioned for a long time, with one major issue being the insufficient integration with the perspectives of policymakers and other stakeholders. One proposal to address this issue has been to set up facilitative dialogues with stakeholders to extend model-based pathways to socio-technical scenarios. This paper presents the results of a first series of such co-creation workshops, where stakeholders discussed bottlenecks for model-based decarbonisation pathways and ways to overcome these bottlenecks through tailored policy mixes. The workshops took place in five countries: Brazil, Canada, Greece, Germany, and the UK, each with a specific sector focus. In all five workshops, it became clear that substantial tensions exist between the "ideal" modelled decarbonisation pathways and the real-world situation on the ground. Also, adverse political framework conditions, uncertainty of future policies and resistance of powerful actors were emphasised as overarching bottlenecks in most workshops. At the same time, in several instances stakeholders pointed out important aspects of transformative trajectories that are not covered by the models. Some challenges and solutions stand out in all countries in spite of the strong diversity of contexts: allocation of capital towards massive investments into low-carbon solutions; infrastructure development for generation and transport of hydrogen, capture and use of CO_2 as well as electricity grid and storage adapted to renewable energy solutions; stakeholder and citizen dialogues, where agreement is reached on cornerstones of long-term decarbonisation trajectories; and demand-side measures complementing investments into low-carbon processes.

Introduction

Scenarios based on quantitative techno-economic modelling, for example using integrated assessment models (IAMs), energy-economic models, and sectoral models, are common tools supporting scientific advice to policymakers in energy and climate policy (cf. [1]). However, the extent to which modelled future pathways effectively support policymaking for sustainability transitions depends on several factors and has long been questioned (see, e.g., [2,3]). A major issue lies in the insufficient integration of perspectives of policymakers and other stakeholders in the modelling process [4,5]. It has been argued that IAMs are biased towards goal-seeking smooth pathways, thereby neglecting multiple uncertainties, challenges, and disruptions faced by decision makers on the ground, highlighting the need to incorporate non-IAM pathways including qualitative storytelling into climate policy advice [6].

Techno-economic models particularly struggle to capture real-world complexity that affect the timing and scale of new technologies deployment. They often apply a linear notion of market diffusion [7], thereby only depicting sections of the complex empirical reality of how innovations manifest in different socio-technical contexts [8], also referred to as generalisation [9]. Critically, aspects of societal embedding of technologies and subsequent repercussions cannot be captured by such models. At the same time, qualitative empirical studies in the

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context of Science and Technology Studies (STS) often provide in-depth accounts of the contemporary interaction of societal and technological change for specific case studies but provide little insight into quantified future trajectories and implications for key policy targets such as carbon emissions. Similarly, stakeholder-based creative transition scenario processes [10–12] are able to recognise a wider range of change factors including disruptive seeds of change but lack interfaces with quantitative pathways. A first step to overcome these issues is to involve stakeholders in the design of the modelled pathways by discussing with them key assumptions and outputs to be generated, possibly in an iterative way, i.e. adapting the modelled pathways based on stakeholder feedback about intermediate results [13]. Even after such a process, however, there will remain tensions between the model results and observable real-world trajectories due to aspects not covered by the models and the potentially radical transitions needed, which can only be addressed from a socio-technical perspective going beyond the modelled pathways [14].

Several authors have therefore proposed conceptual frameworks for bridging between qualitative and quantitative approaches, with one of the most prominent being the notion of "socio-technical scenarios" [8,15], which could be developed in a dialogue process between modellers and stakeholders [14]. Ideally, such a process is implemented in a co-creation process with stakeholders and provides signposts for a transformative policy mix [16], which provides a more holistic view on the required system transformations than recommendations that are based on modelling alone [17]. In particular, transformative policy mixes, which cover not only a policy instrument mix but also corresponding policy strategy and processes [18], comprise systemic instruments and new flexible and inclusive governance structures in addition to classical push and pull measures, thereby addressing not only market failures but also system failures as well as societal exnovation and experimentation [16]. Until now, however, the conceptual framework by Geels et al. [14] has only been applied to the transformation of the electricity sector and without participation of stakeholders.

In this paper, we close this gap by proposing an operationalisation of this conceptual framework in a co-creation process with stakeholders, which we then validate through its application in five case studies covering a broad spectrum of sectoral transformations. This comparative assessment of the framework in different contexts allows us to draw best-practice insights for complementing model-based results with stakeholder input when developing zero-emission pathways. At the same time, the case studies yield novel insights on bottlenecks and tensions in these pathways for specific sectors and contexts.

Our case studies stem from a recent research process comprising extensive modelling of climate change mitigation pathways on various geographical scales. The modelling already involved stakeholder interactions to set the research questions and validate model assumptions (as described in detail in [13,19,20]). To go beyond techno-economic considerations, this was complemented by in-depth qualitative socio-technical analyses capturing the real-life context of deep decarbonisation pathways in several countries with a focus on specific sectors. For five of these countries with particularly relevant transitions (see Section 2.1), namely Brazil, Canada, Greece, Germany, and the UK, we set up a dialogue process with stakeholders based on the approach suggested by Geels et al. [14]. In each dialogue, we co-created socio-technical transition narratives complementing the modelled pathways and derived insights for transformative policy mixes. We draw from these empirical cases to investigate which transition bottlenecks stand out across countries and sectors and which elements of policy mixes are considered particularly relevant in the context of these bottlenecks. We compare the results across the cases and assess the experience from the stakeholder process, both content-wise and with regard to the co-creation process.

The article is structured as follows: In Section 2, we describe the methodology applied to co-create the transformative policy mixes, including case study selection, the framework for structuring transition bottlenecks, and a description of the workshop setup. In Section 3, we document the five national case studies in detail, summarising the content and results of the stakeholder workshops. In Section 4 we discuss similarities and differences between the five case studies and in Section 5 we draw conclusions on the process and future steps.

Methodology

The approach combined two key elements, socio-technical analyses and stakeholder dialogues, used to extend quantitative techno-economic scenarios by qualitative socio-technical transition narratives. First, socio-technical analyses of the national sectors were examined to identify potential conflicts between model-generated future pathways promoting the desired transitions and current socioeconomic contexts, forming first hypotheses on transition bottlenecks (cf. [14]). Secondly, interactive workshops with a broad range of stakeholders were undertaken within five countries. The aim of these workshops was to validate and amend the bottleneck hypotheses and to outline potential policy mixes for different phases of the transformation (cf. [16]). These findings were then synthesised to socio-technical scenarios exploring how to realise the modelled pathways. The results of all national dialogues were then evaluated across countries to identify similarities and differences. The general approach is outlined in Fig. 1. In the following, we describe the case study selection, the structuring of transition bottlenecks and the workshop setup in more detail.

Case study selection

The choice of countries for the case studies (Greece, Germany, United Kingdom, Brazil, and Canada) enables a comparison between European countries with similarly-developed countries outside Europe. In each country, we focused on a specific sector (cf. Table 1).

From a sectoral perspective, the link between model-based scenarios and socio-technical systems in the power sector has already been explored (see, e.g., [14,15]), and we build on this by focussing one case study on this sector, namely the one for Greece, which is of particular relevance here due to the required phase-out of lignite mining (cf. [21]). The other case studies focus on some of the so-called hard-to-decarbonise sectors, namely the energy-intensive industries and the transport sector, which have been studied less in regard to the link between model-based scenarios and socio-technical systems (cf. [8,22–24]). To enable a meaningful comparison of case studies, we have chosen two case studies for each of these sectors. For the transport sector, we consider Brazil and Canada due to their large travel distances and the domestic relevance of the oil sector (cf. [25,26]). For the energy-intensive industries, we focus on Germany and the United Kingdom (UK), where historically the role of industry is particularly

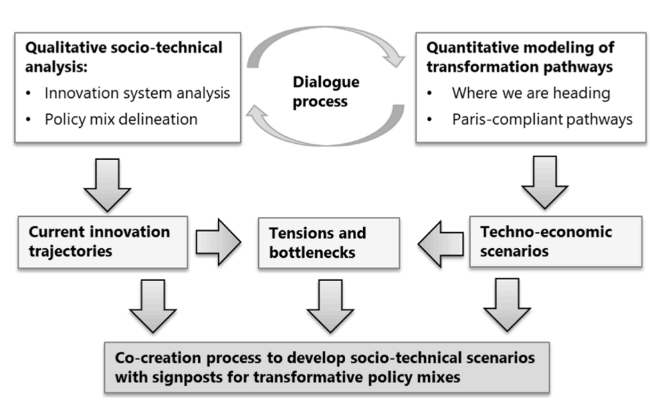

Fig. 1. Overview of the approach to generate socio-technical scenarios with transformative policy mixes.

Table 1
Overview of stakeholder workshops.

Country	Sector focus	Workshop date	Place	Number of participants
Brazil	Transportation	May 2nd, 2022	Online	14
Canada	Transportation	May 9th, 2022	Online	20
Greece	Electricity	June 30th, 2022	Athens, Greece	45
Germany	Energy-intensive industries	July 8th, 2022	Berlin, Germany	17
United Kingdom	Energy-intensive industries	October 7th, 2022	London (hybrid), UK	28

important (cf. [27]). The resulting variety of countries and sectors is particularly useful to address the broad range of systemic innovation processes required in climate change mitigation, in order to showcase the multiple obstacles and barriers to an archetypical market diffusion of innovations as described by Rogers [7] in different socio-technical contexts.

Framework for transition bottlenecks

We classified transition bottlenecks in the system-wide manifestation of innovations—as reflected in the tensions between desired transformation pathways and the current innovation trajectories—to enable their discussion in co-creation processes with stakeholders. We identified relevant types of bottlenecks (cf. [16]) to a linear diffusion of innovations, as shown in techno-economic models, and related characteristics of transitions (cf. [28]), by evaluating the innovation system and transition analyses (cf. [21,25–27]). Based on the evaluation of these analyses and the set of bottlenecks described by Rogge et al. [16] and Geels et al. [14], we distinguished six types of bottlenecks, referring to different kinds of feasibility and impacts, see Table 2 for details and examples.

These six types of bottlenecks mainly follow the dimensions of the well-established STEEP (social, technological, economic, environmental, and political) concept (cf. [29]) but include an additional distinction between economic feasibility and economic impacts. The reference to feasibility and impacts is meant to facilitate stakeholder input in the identification of bottlenecks, as they often use these terms to express their concerns.

Table 2
Types and examples of transition bottlenecks based on [14,16,21,25–27].

Type	Transition bottlenecks	Examples
Social feasibility	• lack of acceptance by important groups • deviation from societal trends and norms • required behavioural changes	• opposition to new infrastructure • historical role of fossil industries • changes in mobility patterns
Political feasibility	• established power structures • limitations of current political system • deviation from political targets + strategies	• vested interests of incumbents • vertical power split • economic growth objective
Technological feasibility	• transformation of physical infrastructures • required technological maturity of certain technologies not yet available	• decentralisation of electricity grids • immaturity of carbon capture and storage (CCS) technologies
Economic feasibility	• mobilising needed investments • need of importing certain goods • deviation from current market trends	• lack of venture capital • availability of hydrogen imports • ban of cars w/ combustion engines
socio-economic impacts	• labour impacts • price increases deemed unacceptable • required changes of standards and skills	• job losses in fossil sectors • higher costs for green products • skills to build low-carbon housings
Socio-ecological impacts	• additional uses of land and other natural resources deemed unacceptable • impacts harmful to the environment	• lack of land for food production • impact of offshore windplants on marine ecosystems

Workshop design and setup

Fig. 2 provides an overview of the workshop methodology we used to co-create transformative policy mixes in each of the five case studies.

The objective of the workshops was twofold: first, to identify bottlenecks in reaching a desired transformation of the system under consideration, by comparing transformation pathways based on quantitative modelling with a corresponding innovation system analysis; and, second, to describe overarching signposts for the future governance of the transformation, which we coin as transformative policy mix signposts, on how to overcome these bottlenecks and thus foster the desired transformation.

Accordingly, two main inputs for the co-creation process were taken from *pre-workshop processes*: first, a set of model-based transformation pathways and, second, the corresponding innovation system analysis for the selected focus country and sector. The techno-economic modelling covered at least two transformation pathways, namely a reference pathway describing where the system under consideration is currently heading (given current policy measures and/or stated objectives) and at least one pathway describing how compliance with the Paris Agreement mitigation objectives (cf. [30])—predominantly interpreted as a net-zero GHG emissions target by or around mid-century —could be achieved. In some instances, several variants to reach net-zero emissions were modelled to allow for a comparison of potential bottlenecks between the variants, which can be helpful to address different stakeholder concerns. The innovation system analysis characterised the most relevant dimensions of the system to be transformed, in particular the stage of transformation, the geographical conditions, actor constellations and power structures, infrastructures (physical, knowledge, financial), and the role of regulation and socio-cultural factors (cf. [28]).

During the *workshop preparation*, we developed an indicative list of potential bottlenecks based on an analysis of potential tensions between the model-based pathways with the current trajectory of the innovation system, also considering additional literature where available. The second important step of the workshop preparation was to involve stakeholders covering the most relevant actor groups. Based on the scientific literature [31–33], we defined stakeholders as "people, groups, or institutions affected by (either negatively or positively), or able to affect, measures to overcome the bottlenecks in the decarbonisation trajectories." This was specified in line with the categorisation of bottlenecks outlined above; therefore, we identified affected and influencing groups with respect to social, technological, economic, and ecological aspects of the transition for each case study individually. Workshop participants were selected to achieve a balanced coverage of the most relevant affected and influential stakeholder groups while paying attention to diversity with respect to gender, age and other relevant factors such as geographical location, which is crucial in some of the countries covered. In all cases, invited stakeholders included representatives of relevant industries from different stages of the respective value chain, policy makers from relevant domains such as industrial and climate policy, mediators such as sector associations or

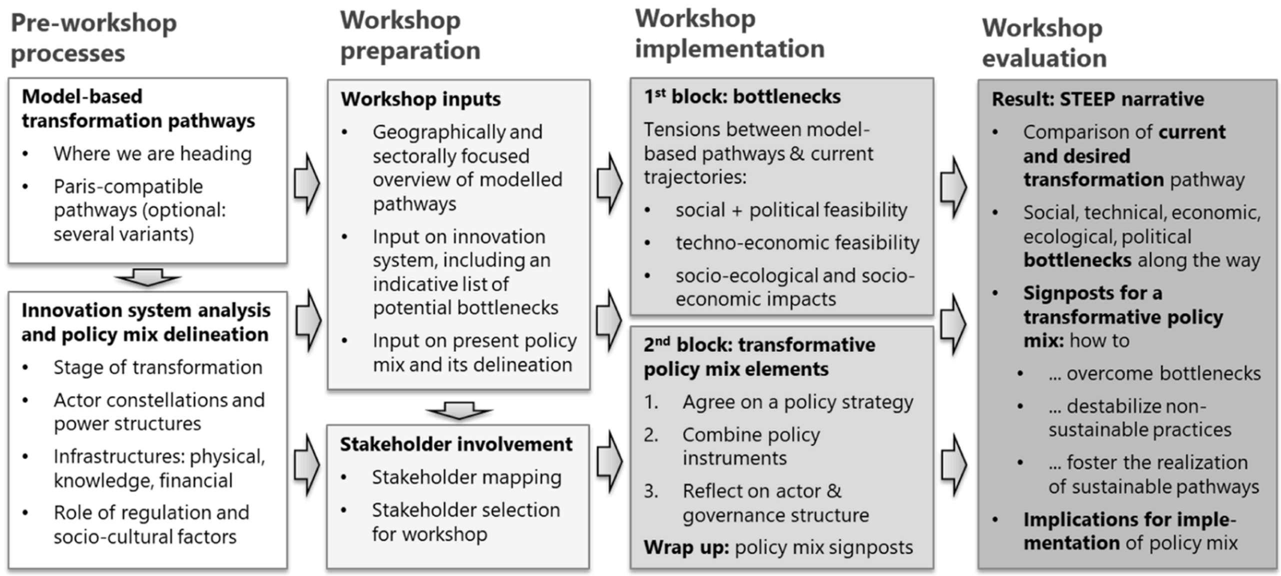

Fig. 2. Overview of the methodology for co-creating transformative policy mixes.

cluster managers, researchers with deep expertise on the key transition aspects and Civil Society Organisations (CSOs) active in the respective transformation domain. These groups were roughly represented equally but in spite of strong efforts from the project team to mobilise CSOs, they were somewhat underrepresented. At the same time, some of the invited researchers were closely associated with social movements and to some extent able to bring in the CSO perspective.

The *workshop implementation* comprised two building blocks. In the first block, we presented the modelled pathways, including findings on their socio-economic impacts such as required investments, GDP changes and labour impacts when available, and the tentative list of bottlenecks to the stakeholders, using our classification of bottlenecks (see Section 2.2) and distinguishing between general bottlenecks for a deep decarbonisation pathway and specific bottlenecks related to the focus sector. Participants were then invited to amend the list of bottlenecks—e.g., by proposing additional ones or discarding and modifying some of the suggestions. Participants were next asked to assess the importance of tackling each bottleneck to reach the climate goals, either through an online voting tool, as in the case of Canada (Fig. 3), or though voting dots in the workshops with no virtual interaction.

The highest ranked bottlenecks were discussed in breakout groups in more depth. First, participants were asked to specify the bottlenecks and then invited to propose elements of a transformative policy mix that could overcome the bottleneck. Results of the discussion were captured on sticky notes (either virtual or physical) as illustrated in Fig. 4 for the case of Brazil. After presentation of the breakout groups' results, the workshops closed with a final round of comments and feedback. Results

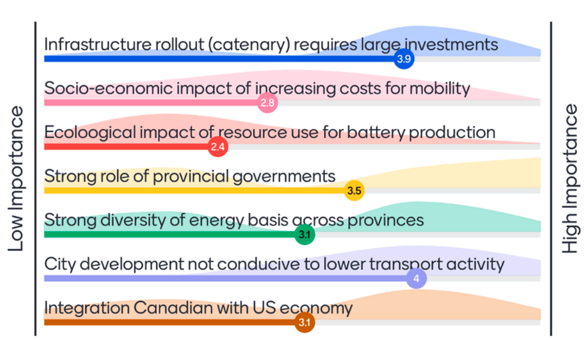

Fig. 3. Example for voting on bottlenecks (Canada).

were documented and shared with the participants for further commenting. Based on the insights provided by participants at each workshop, we developed a plausible narrative of how to achieve the desired transformation (see the supplementary information).

Results

In the following, we present the main outcomes of each of the five national co-creation workshops that were carried out according to the concept outlined above. We present our results on a country-by-country basis, first highlighting key features of the mitigation scenarios as produced by the modelling analysis, then summarising the most important bottlenecks followed by a description of the key elements of a potential transformative policy mix that arose from the workshop discussions. Details on the scenario assumptions, the models used and the outcomes of the workshops are provided in the Supplementary Information.

Brazil

The workshop in Brazil addressed net-zero emissions pathways for the Brazilian energy system as well as a sectoral zoom-in on the transport sector. Participants included government officials, researchers and representatives of the automotive sector roughly equally represented but unfortunately none of the invited CSO representatives was able to participate. The modelled Paris-compliant mitigation pathway achieved net-zero GHG emissions before 2055, implying strong efforts across all sectors of the economy. In particular, the use of fossil fuels was reduced by roughly one fourth (see Fig. 5) compared to a business-as-usual development (CurPol_EI) and the remaining use of fossil fuels was compensated by increasing the carbon sequestration via natural sinks and CCS to 350 million tonnes per annum. The sectoral zoom- in the transport sector showed an expansion of electric mobility to a share of 15 % and of biofuels to 80 % in 2050.

The results of the voting process for the importance of bottlenecks are presented in the supplementary information. Based on this assessment, three themes of bottlenecks were identified as particularly relevant for the overall transformation with a focus on the transport sector: (1) issues around resistance of powerful actors; (2) the prices of batteries and access to credits; and (3) the cost of mobility and diesel sensitivity.

In the discussion of the financing-related bottlenecks, it was emphasised that inequality and poverty—and subsequent lack of funds on individual and municipality levels—need to be considered for any

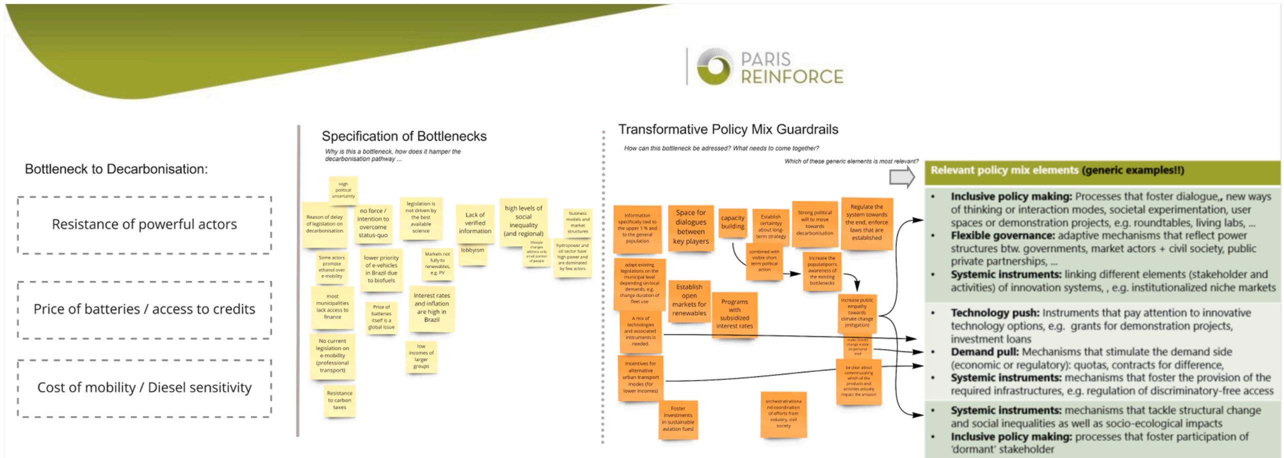

Fig. 4. Setup for the discussion in breakout groups (Brazil).

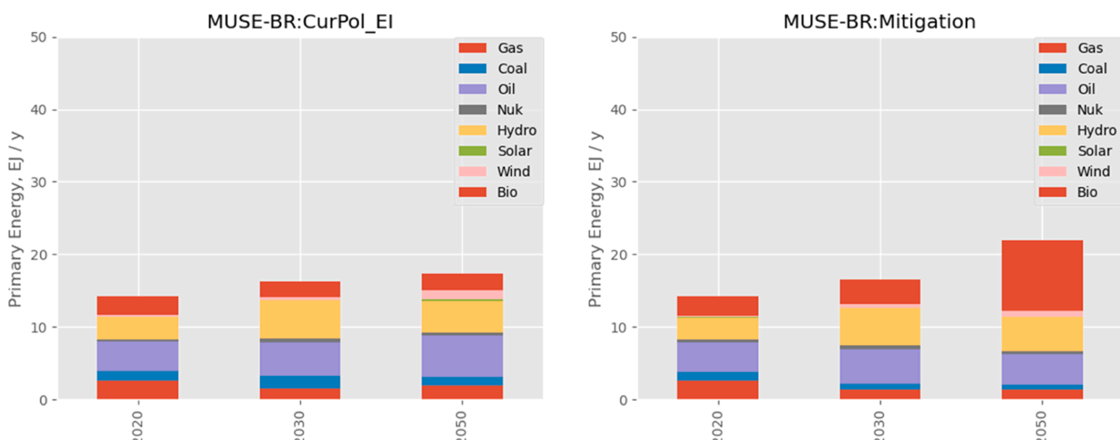

Fig. 5. The primary energy supply in the Mitigation Scenario compared to a Current Policies Scenario for Brazil (Source: [20]).

effective climate policy strategy, especially in the context of rising interest rates and inflation at the time when the workshop was carried out. Participants stressed that the focus of e-mobility efforts in Brazil needs to be on collective use (public transport, shared vehicle fleets) rather than pushing for increasing private car ownership. Issues hampering progress include the difficulty to access credits but also the lack of functioning business models. While the currently high prices for batteries contribute to the financing issues, it was noted that this is a global rather than specifically a domestic problem.

With respect to resistance of powerful actors in incumbent industries such as oil, gas, and hydropower, it was pointed out that legislation was not always driven by the best available science but instead was prone to influence from various lobby groups. Consequently, there was too little momentum to overcome the status quo and delay of important legislation on decarbonisation and in particular e-mobility. In addition, it was pointed out that some actors push for ethanol and biofuels rather than e-mobility solutions. In general, there was a feeling that especially the wealthy part of the population did not care too much about sustainable lifestyle choices, even if they agreed with abstract sustainability targets. Furthermore, participants stressed that too little verified information on climate change and mitigation options was available to the public.

As key elements of a possible policy mix to support the transformation several elements were discussed, including

- bespoke awareness-raising to increase public empathy towards climate change,
- longer-term planning,
- target-orientated coordination of efforts between industry, civil society, and government in dedicated spaces for dialogue,
- strict and science-based regulation, and finally creation of open markets for renewables.

It was emphasised, however, that none of these measures on its own is a silver bullet, so effective policies will need to focus on the complex interplay of developments.

Canada

The workshop addressed net-zero emission pathways for the Canadian energy system and zoomed-in on the decarbonisation of the transport sector. Participants included government representatives, researchers and CSOs in roughly equal numbers. Industry representatives were invited but unavailable. The modelled Paris-compliant mitigation pathway achieved net-zero GHG emissions by 2050. This pathway included strong efforts across all sectors of the economy. In particular, the use of fossil fuels had to be reduced substantially compared to a business-as-usual development and the remaining use of fossil fuels was compensated by increasing the carbon sequestration via CCS to 150 Mt CO_2eq in 2050. Key elements in the transport sector were the decarbonisation of freight transport via electrification and biofuels and the reduction of the final energy use of fossil fuels by 25% compared to a business-as-usual development (see Fig. 6).

In the interactive part of the workshop, a number of important bottlenecks to decarbonisation were highlighted as shown in the

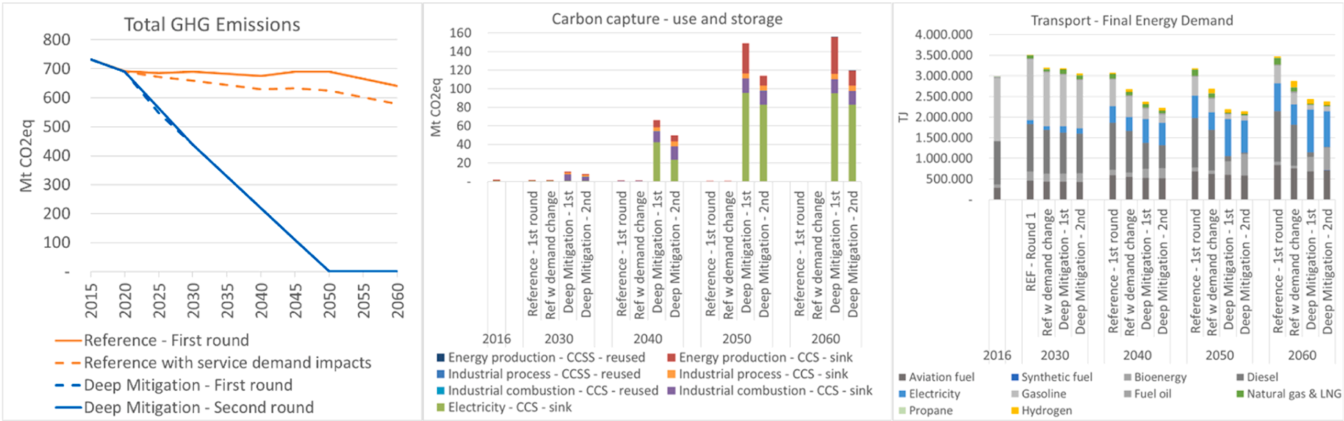

Fig. 6. The net-zero GHG scenario for Canada in comparison to reference scenarios (Source: [19]).

supplementary information. The highest ranked in terms of importance were CCS-related uncertainties, lack of options for decarbonisation of freight, and urban planning failures.

With regard to the substantial uncertainties around CCS technologies, stakeholders highlighted that implementation of CCS was surrounded by considerable unknowns, including the future cost reduction prospects of CCS, considering the persistent high costs and the lack of confidence in the CO_2 capture and storage potential. Stakeholders emphasised that the lack of a clear taxonomy for acceptable CCS performance criteria as well as that regulatory barriers had slowed capital allocation. Furthermore, it was pointed out that the geographical separation between capture sites and storage sites could also prove a hindrance to successful project deployment. Questions over longevity of policies and carbon price volatility were also thought to hamper long-term investment, while the lack of legitimacy of CCS especially in connection with enhanced oil recovery and tax rebates for the oil industry was highlighted. There were fears that CCS might divert attention from transformative changes away from a fossil fuel-based economy and the reduction of overall energy consumption. Accordingly, key elements of the transformative policy mix were:

- a clear taxonomy and roadmap generating trust in truly effective decarbonisation technologies and guiding capital allocation;
- a strong regulatory framework including clear property rights surrounding captured and stored CO_2.

Regarding decarbonisation of freight transport, stakeholders pointed to the lack of roadmaps for modal shifts and the need for thorough analysis of alternative technologies for high-duty vehicles (HDVs) and rail transport. With regard to urban planning, stakeholders emphasised that current municipal plans were not all aligned with climate goals and the role of local governments in achievement of transport decarbonisation was unclear. Accordingly, urban planning was largely not conducive to lower and decarbonised transport activity. Attempts to curb urban sprawl and increase density of cities were scarce. Accordingly, participants highlighted the following as key for a successful transformative policy mix:

- long-term planning and robust measures towards a just transition that focused equally on innovation and exnovation;
- targeted support to transitioning of the workforce from the oil and gas sector within the affected regions;
- differentiated modelling on a regional or even local level as an enabler for such tailored strategies;
- intergovernmental coordination of efforts to decarbonise;
- tax schemes to govern the use of roads.

Across all these themes, governance issues resulting from multi-scalar structures were emphasised as a key challenge to effective decarbonisation pathways and, from a scientific perspective, so was the need to advance models by building bridges to advocacy and socio-technical analysis communities to better incorporate also social and behavioural changes.

Greece

The workshop addressed modelling of net-zero emission pathways for the Greek electricity system. A majority of participants stemmed from academia covering various aspects of energy system research. Another major group was from industry including energy companies, system operators and energy consultants. Policymakers and CSOs were also represented albeit in much smaller numbers than the other two groups. The modelled mitigation pathway achieved net-zero GHG emissions of the electricity system by 2035. This pathway included strong efforts across all sectors of the economy including large efficiency gains and reduction of energy demand. Moreover, it comprised a penetration with 100 % renewables and smooth phase-out of natural gas (cf. Fig. 7).

Stakeholders complemented the first tentative list of bottlenecks with further aspects and singled out especially pertinent issues through a voting process (cf the supplementary information). In the small group discussions participants elaborated on the highest voted bottlenecks and discussed possible policy approaches to overcoming them.

The following key issues were highlighted. The adaptation of the grid to decentralised zero-carbon electricity poses major challenges. Grid operators face high uncertainties and hesitate to invest. This is aggravated by a lack of mature and affordable solutions for energy storage and slow digitalisation. Moreover, widespread opposition to expansion of renewable energy and especially wind power has already slowed down the ramp-up. Often legitimate concerns around nature conservation and energy costs are amplified by actors with vested interests. Finally, stakeholders saw the danger that high investment into liquefied natural gas (LNG) infrastructure would cause a lock-in into fossil-based electricity generation.

The proposed policy mix elements comprised early education about climate change and renewable energy alongside the active generation of positive narratives about renewables that could achieve a much-needed change of mentality. In addition, community-based business models that give back to communities, such as energy cooperatives, are expected to enhance buy-in; this ties to the wider issue of climate democracy—i.e., including citizens in decision-making and communicating reasons for decisions in a transparent manner. In addition, environmental impact assessment and sustainable forest management should accompany each project along with strategies for dismantling, recycling, and restoration

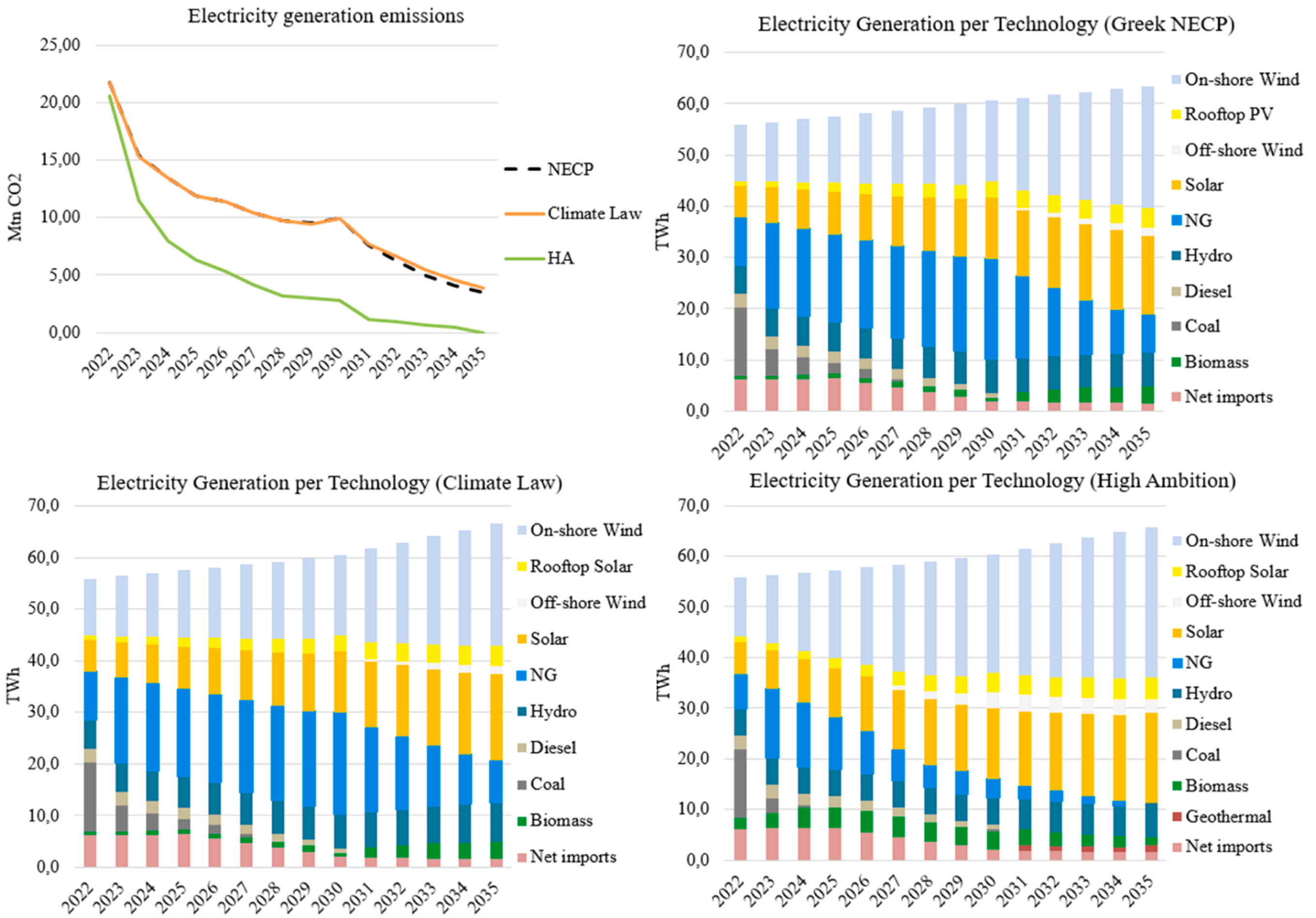

Fig. 7. Three scenarios for decarbonisation of the Greek electricity sector, HA = High Ambition Scenario (Source: [34]).

resulting in sensitive placing of renewable energy projects.

To overcome the challenges around grid development, stakeholders proposed promoting integrated regional smart (micro-)grid solutions that use the grid and its devices as storage and energy could be transferred and stored across communities. The already ongoing legal activities should be complemented by massive research and development investment into integrated demand and storage solutions. Most importantly there is an urgent need for power-sector system changes, mainly orienting towards market and institutional design in order to reduce uncertainty to unlock also private financing sources and to mobilise demand side responses from through market-based incentives.

Germany

The workshop in Germany addressed net-zero emission pathways for the European energy system. The sectoral zoom-in was on the German industry sector. Participants included government representatives, researchers and CSOs in roughly equal numbers. Industry representatives signed up for the event but unfortunately were not able to participate in the end. The modelled mitigation pathway achieved net-zero GHG emissions by 2050 with industry emissions reduced by 94%. This pathway comprised ambitious resource and energy efficiency measures across all sectors. In addition, the energy-intensive industries such as the steel and the cement sector invoked radical process substitutions. In

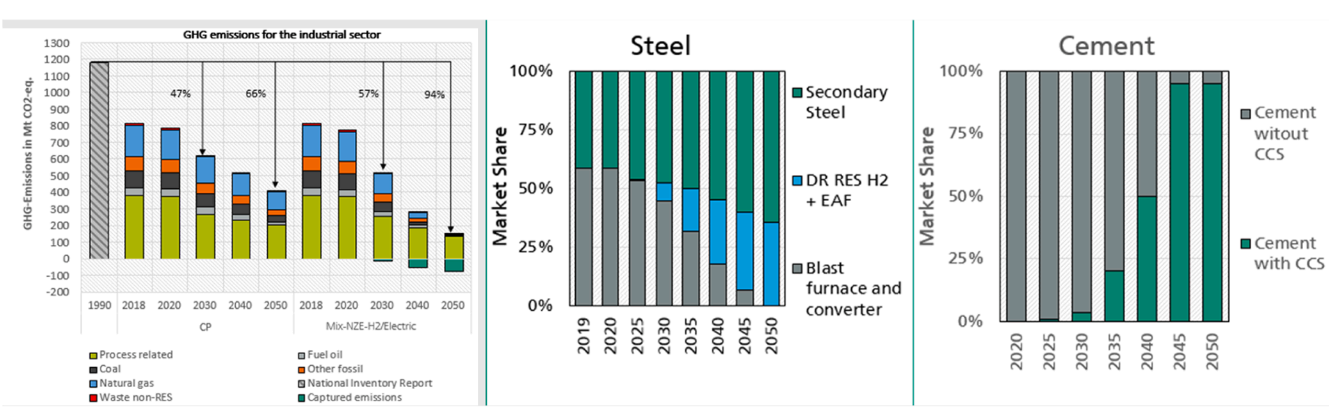

Fig. 8. The net-zero emissions scenarios for German industry in comparison to a reference based on current policies (Source: [35]).

particular, primary steel production switched from the blast furnace route to the direct reduction route fuelled by renewable hydrogen completely. Moreover, all new and existing cement plants were equipped with carbon capture technologies during the same period (see Fig. 8). In addition, socio-economic impacts of the scenarios were presented, showing that industrial employment would decrease until 2030 but increase beyond today's levels afterwards.

The results of the stakeholder voting on the importance of bottlenecks are shown in the supplementary information. As a result, the following bottlenecks were singled out as particularly relevant:

- Infrastructure-related bottlenecks: uncertainty around availability of hydrogen and renewable electricity; infrastructure expansion for hydrogen and CO_2; and uncertain political framework conditions
- Demand-side-related bottlenecks: certification of green steel/cement; markets for green steel/cement; and customer-related barriers (norms, competences, etc.)

With regard to the infrastructure-related bottlenecks, the uncertainty around availability of hydrogen and renewable electricity was perceived as critical. In particular, the potential lack of truly additional renewable electricity increased the uncertainty about future supply with green hydrogen. This was seen to be worsened by a lack of resources (e.g., rare earths) and capacities to build electrolysers producing the desired green hydrogen. Other kinds of low-carbon hydrogen such as blue hydrogen were expected to face limitations with regard to public acceptance. The use of renewable electricity for direct electrification of industry processes was considered of highest priority here, while clear rules for the production of green hydrogen were to be enforced. Moreover, the participants saw a trade-off between the expansion of the electricity grid and building a hydrogen network. In turn, the uncertainty about the desired volumes of CO_2 capture and its further usage was perceived too high for rolling out a full-fledged infrastructure immediately. Finally, participants suggested to avoid political uncertainty about the extent of industry decarbonisation, as this might lead to cost increases or skill shortages with regard to the more difficult processes. According to the participants, these bottlenecks were calling for:

- increasing the support for the expansion of renewable electricity production and grids even more,
- harmonisation between hydrogen production and renewable energy production, including clear rules for the production of green hydrogen,
- requirements for a transition from blue to green hydrogen,
- a support scheme for establishing a hydrogen backbone network,
- developing a vision for circular CO_2 flows and a management strategy before rolling out infrastructure,
- an early push for initial CCUS projects and the development of a regulatory framework,
- a clear political agenda for complete decarbonisation of industry and
- early development of the required skills and competences.

With regard to the demand-side-related bottlenecks, stakeholders highlighted that the continued free allocation of emission allowances under the EU Emission Trading System did not provide a sufficient incentive for energy-intensive industries to seriously explore low-carbon alternatives, such as new processes and recycling solutions. There was too little research into such alternatives and the risk that production could be transferred to other countries instead. In addition, participants stressed the long time for reforming norms and standards to accommodate new materials as important barriers. This added to the lack of clear definitions of both green steel and cement. Finally, the willingness of customers to pay a premium for green products was considered far from certain, while information for customers remained scarce. Measures that were discussed to overcome the demand-side-related bottlenecks included:

- green public procurement initiatives,
- reduction in material consumption through innovative building solutions,
- electrification of construction sites,
- fostering of exchange of pioneering construction projects,
- strategies for upscaling from local projects, information campaigns for builders and architects as well as corporate sustainability departments,
- research and innovation in support to low-carbon solutions such as recycling in construction and alternative construction materials,
- scrap export could be reduced to increase the amount of scrap available for recycling, and scrap quality could be improved with better sorting—e.g., via a digital product pass.

In turn, participants stressed that in the long term, however, the carbon price would need to become the main regulating mechanism.

United Kingdom

The workshop addressed modelling of net-zero emission pathways for the European energy system as well as a sectoral zoom-in on the UK industry sector. Participants included government representatives, researchers, industry representatives and CSOs in roughly equal numbers. The modelled pathways for the European energy system that were used to stimulate discussions in the workshop achieved net-zero GHG emissions before 2050 (cf. [36]). This pathway included strong efforts across all sectors of the economy, including the energy-intensive industries such as the steel and the cement sector. In addition to ambitious resource and energy efficiency measures, this comprised the electrification of substantial shares of boilers, furnaces, and machinery, the use of hydrogen in boilers and machinery, as well as the mitigation of residual emissions of boilers, furnaces, and process emissions by CCS within 30 years (see Fig. 9). In addition, findings on socio-economic impacts of the decarbonisation of the European and UK economy were presented, showing that major GDP losses would only occur in case key mitigation technologies would not become mature sufficiently fast.

In the interactive session, participants amended the proposed list of bottlenecks and selected the most pressing ones through an online polling (see the supplementary information).

A first issue was *Infrastructure Expansion* with concerns about the cost-effectiveness of technologies, the uncertainty on the optimal industrial decarbonisation route and subsequent financing risks, the lack of cross-sectoral coordination, possible underestimation of electricity demand for the sector, regional inequalities in hydrogen access resulting in socio-economic shifts within the country. Secondly bottlenecks were associated with *financing, investment cycles, and energy prices*. Stakeholders pointed out that there exists no financial structure to make net-zero investments bankable, since investors tend to avoid deals with no track-record. Thirdly stakeholders perceived a severe lack of *skills, competencies and manufacturing capability to manage the unprecedented upscaling of technologies required for the transition.*

As the key element of a policy mix stakeholders stressed the urgent need for a long-term net-zero industrial strategy and long-term government investment cycles to provide a stable environment for investments in innovative technologies, infrastructures and the required skilling and national capacity building by fostering more trust and confidence amongst investors. To achieve this, it was deemed necessary to build cross-party consensus through various stakeholder interactions.

Regarding infrastructure expansion, Industrial clusters were seen positively as a way to overcome discussed bottlenecks, and so was the prospect of using the existing gas infrastructure for hydrogen. The discussions also highlighted the value of a hybrid policy approach to design the hydrogen infrastructure strategy, by consulting with regional stakeholders about supply and demand needs and by exploiting existing networks/clusters. With respect to *financing* stakeholders demanded simplicity and certainty in policy support e.g. through standards for

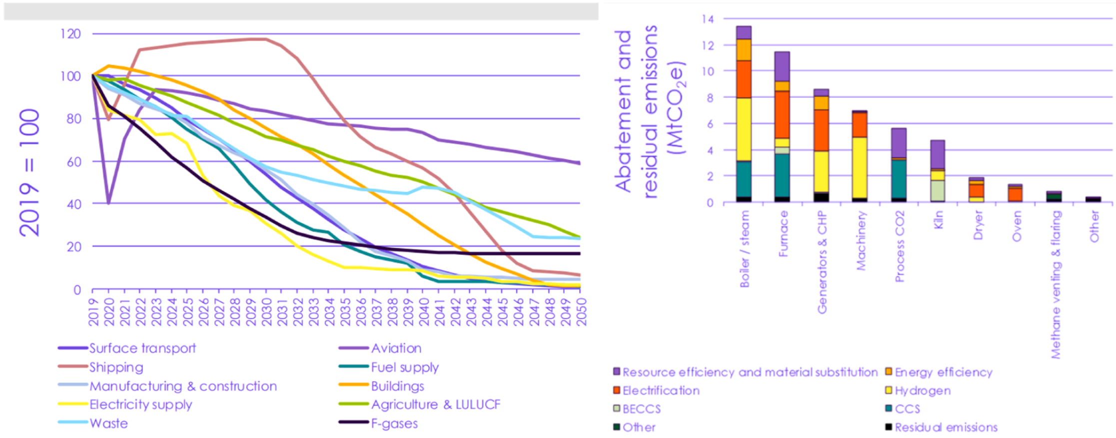

Fig. 9. UK Energy and Climate Transition CCC Balanced Net Zero Pathway (Source: [36]).

financial investment and targeted subsidies. Secondly, they highlighted strong demand-pull policies to support companies in selling green products at premium cost such as contracts for difference and public procurement measures.

Suggested policy mix elements for building technology upscaling capacity included support to highly innovative technologies via establishing national research centres, sorting out UK access to European flagship research programmes, to improve international cooperation, and to secure long-term local access to vital raw materials and energy. With respect to the required skills and engineering expertise, it was considered important to identify skill needs, to improve cooperation between SMEs and universities, to give value to technical trainings and improve their quality, to learn from other countries' best practices, and to strengthen industrial councils on skilling.

Discussion

In this section, we discuss similarities and differences in the stakeholders' assessment of the transition bottlenecks and the proposed solutions to overcome these.

Comparison across countries and sectors

In all five workshops, it became clear that substantial tensions exist between the "idealised" modelled decarbonisation pathways and the real-world situation on the ground, in line with similar previous findings (cf. [37]). In particular, several stakeholders expressed major concerns about the realisability of some of the solutions that figure prominently in the models, such as large-scale CCS application in the case of Canada, major upscaling of e-mobility in Brazil, and fast adoption of low-carbon processes in some energy-intensive industries in the UK and Germany. At the same time, in several instances stakeholders pointed out important aspects of transformative trajectories that are not covered by the models. Examples are "energy democracy" in Greece, reduction of transport activity in Canada, alternative building materials in Germany, higher waste use in the UK, and nature-based solutions in Brazil.

Bottlenecks related to the economic feasibility were considered as particularly important by stakeholders across almost all cases. In Greece and Brazil, stakeholders highlighted bottlenecks related to social feasibility in the context of domestic social inequalities. Bottlenecks related to political feasibility were rated of high importance by stakeholders in both transportation-focused case studies as well as in the German case. In Canada, Greece, and the UK, stakeholders raised particular concerns with regard to technological feasibility. In the industry-focused cases, bottlenecks related to socio-economic impacts were rated as particularly relevant by stakeholders, while their importance was considered relatively low in the other case studies. Socio-ecological impacts received particular attention by stakeholders only in the Greek case focused on the electricity sector. The bottlenecks considered most relevant by the stakeholders are summarised in Table 3 for all national case studies.

With regard to these bottlenecks, some signposts for transformative

Table 3
Overview of key bottlenecks across the five national case studies.

Country	Sector	Bottlenecks considered most relevant by stakeholders	Types of bottlenecks
Brazil	Transportation	(1) Issues around resistance of powerful actors, (2) price of batteries, access to credits, (3) cost of mobility, diesel sensitivity.	Political feasibility Economic feasibility Social feasibility
Canada	Transportation	(1) uncertainties around CCS technologies, (2) decarbonisation of freight transport, (3) urban planning not suitable for mobility shift Crosscutting: governance issues resulting from multi-scalar structures	Technological feasibility Economic feasibility Political feasibility
Greece	Electricity sector	(1) high costs of grid adaptation to RES and access to finance, (2) issues with RES (esp. wind power) expansion: opposition, ecosystem impact & land-use constraints, (3) potential lock-in due to high investment into LNG infrastructure, (4) energy storage maturity	Economic feasibility Social feasibility Technological feasibility Socio-ecological impacts
Germany	Energy-intensive industries	(1) Infrastructure-related bottlenecks: Uncertainty around availability of hydrogen and RES and political framework conditions, (2) demand-side-related bottlenecks: certification and markets for green steel/ cement, customer related barriers (norms, competences)	Political feasibility Economic feasibility Socio-economic impacts
UK	Energy-intensive industries	(1) financing, investment cycles, and energy prices, (2) unprecedented upscaling of technologies and required skilling, (3) infrastructure expansion	Economic feasibility Technological feasibility Socio-economic impacts

policy mixes stand out in all countries despite the strong diversity of contexts:

- Economic feasibility: Allocation of capital towards massive investments into low-carbon solutions is seen as critical by stakeholders, amongst others for green chemicals in the UK, low-carbon building materials in Germany, energy storage and grid technologies in Greece, credible CCS projects in Canada, and battery technology in Brazil. This requires removal of uncertainty through clear long-term strategies. As an example, in Canada the development of a taxonomy with clear performance criteria for low-carbon technologies and in particular CCS was seen as a key lever for allocating capital into green investment and thereby accelerating the low-carbon transformation. Another example is the reference to standards for financial investment through certified Climate Bonds highlighted by UK participants. Especially in the two workshops focussing on industry (Germany and the UK) but also for the case of the electricity grid (Greece), the importance of capturing windows of opportunity from investments cycles was stressed. In Greece, participants stressed the potential role of energy cooperatives as a highly distributed financing model that could at the same time achieve buy-in into the energy transition. These findings resonate with the calls for creating positive feedback loops to sustain transitions [38] and even accelerate them [39].
- Economic and technological feasibility: Infrastructure development was the second critical factor highlighted in all workshops. The most prominent infrastructures discussed were for generation and transport of hydrogen (the UK and Germany), capture and use of CO_2 (Canada, the UK, and Germany), and electricity grid and storage adapted to renewable energy solutions (Greece, Brazil, the UK, and Germany). Repeatedly, it was emphasised that the fast ramp-up of these infrastructures is the precondition for net-zero trajectories to take off, e.g., for companies to confidently invest in hydrogen-based technologies. Most stakeholders agreed that the infrastructure development requires dedicated policy support, showing the important role of systemic instruments in transformative policy mixes (cf. [16]).
- All types of transition bottlenecks: Stakeholder and citizen dialogues, where agreement is reached on cornerstones of long-term decarbonisation trajectories, were seen as a key element of all proposed transformative policy mixes and subsequently feature prominently in all our “transition narratives”. Many participants saw such processes as the only basis for creating the certainty required for the investment mentioned above. As an example, in Brazil, participants in both groups stressed the urgent need for a long-term transformative strategy building across the different sectors together with all stakeholders. In a similar vein, participants in Canada and the UK saw dialogue processes as the key means for achieving agreement on green investment criteria. In Germany, Brazil, Canada, and most of all in Greece, the importance of involving also ordinary citizens into such processes was stressed, with Greek participants spearheading the notion of “energy democracy” to achieve widespread buy-in into the rollout of renewable energy. This underlines the role of new flexible and inclusive governance structures in transformative policy mixes (cf. [16]), though stakeholders engaging in co-creation processes might be biased towards such governance structures to a certain extent.
- Socio-economic feasibility and impacts: Demand-side measures were stressed in all workshops as an important aspect of the decarbonisation policy mix. There was wide agreement that investing into low-carbon processes alone could never achieve the required reductions in emissions without changing the patterns of using energy and carbon-based products. Examples are the emphasis on urban planning to reduce transport in Canada, the focus on green building regulation and norms and green public procurement strategies in Germany, as well as the request for carbon contracts for difference in the UK and Germany. In Brazil, participants highlighted consumer attitudes as a lever for generating demand for low-carbon products. This provides evidence that transformative policy mixes need to combine technology push with demand pull measures (cf. [16]).

In the following, we take a closer look at the two pairs of workshops with the same sectoral focus and compare the electricity case study for Greece with the existing literature.

Comparison of transport sector decarbonisation in Brazil and Canada

The socio-technical context of the transition to net-zero GHG emissions in Brazil and Canada is quite different due to the different geographical and socio-economic conditions, as seen by comparing the socio-technical analyses for both countries (cf. [25,26]). Nonetheless, the fossil fuel industries play a strong role in both countries, which has implications with regard to labour markets and national income streams. The bottlenecks considered most important in the Brazil and Canada workshops were rather different. For Brazil, there was a strong focus on bottlenecks related to social and political feasibility as well as socio-economic and socio-ecological impacts. Still, technological and economic feasibility were also a concern to a certain extent, though less prominent. The particular emphasis of socio-ecological impacts was due to the particular role of the rainforest and corresponding land-use-related issues. The high importance of socio-economic issues and political feasibility highlighted the strong welfare spread within the Brazilian population. In turn, the focus of the considered bottlenecks in Canada was strongly linked to political feasibility with regard to the federal governance system and to social and technological feasibility of large-scale CCS applications as one part of the Canadian mitigation pathway.

Nevertheless, in both workshops, an integrative stakeholder process was an important part of the transformative policy mix. Our in-depth comparative assessment, however, shows that this was mostly about regional alignment in Canada, while it was more about societal groups with different socio-economic backgrounds in Brazil, though a strengthening of the role of municipalities was also important here. This suggests that such participative processes should be tailored to the individual needs. Regarding the transport sector, much emphasis was placed on a reduction of transport through appropriate urban planning as well as behavioural changes in Canada. This confirms conclusions on the transport sector transition by Köhler et al. [23]. In Brazil, in turn, it was emphasised that any transport transformation policy had to take into account the impacts on citizens with low income and focus on collective rather than individual transport. Overall, the difference between the domestic bottlenecks considered most important in Brazil and Canada was so large that the proposed solutions also differ substantially and are hard to compare.

Comparison of industry sector decarbonisation in Germany and the UK

The underlying socio-technical analyses used as input to the workshops and our overall research process had revealed relatively different starting points for the transformation to begin with [27]. On the one hand, this was linked to Germany being part of the EU and having a strong industry, while the UK is striving for an autonomous pathway after the Brexit and experiencing a shift from industry to the service sector. On the other hand, German innovation trajectories were focused more on using hydrogen than on using CCS, while it was the other way round for the UK. In general, there was a strong focus on bottlenecks related to technological and economic feasibility as well as socio-economic impacts in both workshops. Nevertheless, social feasibility showed up with regard to acceptance issues, in particular in the German workshop, and political feasibility was considered important in the UK workshop due to uncertainty about continued support by the UK government. Socio-ecological impacts were less of a concern in both workshops. While CCS constituted the more prominent decarbonisation option in the UK, the associated bottlenecks were rated higher by the German stakeholders, mainly due to the issues in public acceptance. In both workshops, infrastructure expansion was considered one of the key bottlenecks. This applied to all kinds of energy infrastructure, in particular to electricity grids, hydrogen, and CO_2 networks. An important element of this bottleneck was the large uncertainty about the demand and the production of hydrogen and electricity. The issue of skill gaps was mentioned in both countries but received substantially more attention in the UK workshop. In total, the bottlenecks align between the two cases but also go beyond the problems concerning lock-ins of energy-intensive industries found by Wesseling et al. [40].

For both countries, clarity about the long-term pathway for energy-intensive industries was seen as an important signpost for the transformation, with an integrative stakeholder process to determine it being a key element of the transformative policy mix. For the UK, there was more emphasis on financing issues and government-driven support, although these were relevant in the Germany workshop too. For Germany, the focus was more on long-term market-based financing and less on support schemes, which may result from the higher uncertainty about the government support expressed by the UK workshop participants—this came in at a time of continuous change of governmental synthesis of 2022. Moreover, it is noteworthy that while the presented modelling results featured a roll-out of hydrogen-based direct reduction plants for the steel sector in both Germany and the UK, this was not taken up by stakeholders in the UK workshop, probably because there was much less attention to this technology in the UK at the time than in Germany. Overall, the suggested solutions overlap substantially, but also differ to a non-negligible extent, being aware of the different domestic challenges and bottlenecks.

Comparison of the findings for electricity sector decarbonisation in Greece with similar results from the literature

Although the lack of a similar analysis as with the Greek power sector case study, either for the power sector in a different geographical region or for the decarbonisation of a different sector within the Greek context, does not allow us to perform a comparative analysis, we rely on stakeholder engagement and desk research exercises in the literature for that same purpose.

Most notably, Kleanthis et al. [41] engaged with stakeholders in Greece to identify critical issues of the energy transition, highlighting some similar aspects with our analysis, albeit without prioritising them. In particular, an aspect raised by Kleanthis et al. [41] was around the importance of electricity storage and interconnections with neighbouring countries. On top of these results, our analysis indicated that the high costs for grid adaptation are the most upvoted bottleneck, with concerns over the maturity of storage technologies, while the need for enhancement of interconnections to increase reliability and solutions for the non-interconnected islands appeared in the discussion but received less votes. Additionally, Kleanthis et al. [41]raised the issues of people living near RES installations reacting negatively on such projects, the fear of carbon lock-ins, the timeline of the coal and natural gas phase-out, the access to finance (debt and finance issues were also identified by Alamanos et al. [42] in a more targeted stakeholder engagement setup on the water-land-food-energy nexus), and the expected job losses (also noted by Pavloudakis et al. [43]; focusing mostly on Western Macedonia). Our analysis also highlighted these aspects and additionally provided a ranking of these bottlenecks co-created signposts for a policy mix aiming to navigate them based on inter alia achieving a net zero electricity system as early as possible with a high level of decentralisation, engage citizens with community-based activities and invest on research and development for storage technologies (see Supplementary information Greece).

Within the electricity generation but focusing on the German and UK sectors, Rogge et al. [16] and Geels et al. [14], respectively, identified transition bottlenecks to accompany quantitative modelling results. Their desk research identified many similar bottlenecks as in our study, namely social resistance, concerns over the rapid expansion of technologies, employment, as well as inconsistencies of grid expansion with current trajectories. On top of these similarities, our co-created stakeholder-based approach differed from such desk research efforts, by elaborating on contemporary context-specific issues. Notably, the occurrence of public resistance to onshore wind projects has been framed in the two studies as a possibility, while our stakeholders, with their "ground" knowledge, stressed that this is an issue of importance that is already happening. Additionally, while a desk reject approach could hint at regime lock-ins, our analysis highlighted such issues in more detail, especially around the concern for lock-ins as a result of high investments in LNG infrastructure, a bottleneck that is quite recent as a result of the energy crisis, and therefore much more difficult to identify in the literature.

Conclusions and outlook

Facilitative dialogues with stakeholders have been proposed to integrate modelled future pathways with the perspectives of policy makers and support effective policy making through socio-technical scenarios. Here, we have presented the results of five such co-creation exercises in different sectoral and national contexts, where stakeholders discussed bottlenecks for the feasibility of model-based decarbonisation pathways and ways to overcome these bottlenecks through tailored policy mixes, namely in Germany, Greece, the UK, Brazil, and Canada. The outcome of such a process is not a detailed description of a policy mix, but rather provides overarching signposts for the future governance of the transformation, which we have therefore coined as policy mix signposts.

In all cases, we were able to develop transition narratives out of the workshop results. In some cases, where the results of the policy mix discussion were relatively advanced, such as in the case of Greece, this was more straight forward than in others, such as in Brazil, where due to time restrictions the focus in the workshop was more on the bottlenecks than on possible solutions. Some challenges and solutions stood out in all countries despite the strong diversity of contexts, namely:

- allocation of capital towards massive investments into low-carbon solutions;
- infrastructure development for generation and transport of hydrogen, capture and use of CO_2, and electricity grid and storage adapted to renewable energy solutions;
- stakeholder and citizen dialogues, where agreement is reached on cornerstones of long-term decarbonisation trajectories;
- demand-side measures complementing investments into low-carbon processes.

The results highlight areas of conflict between "idealised" modelled pathways and the real-world decarbonisation situation on the ground, feasibility aspects that are not covered by the models, as well as common or diverging challenges and solutions for each context. We expect that even in cases where stakeholders did not converge on desirable pathways and supporting policy mixes, the process can provide valuable insights for decision makers into where to expect tensions and resistance and where there will be need for additional interventions. Also, we reckon that, for the stakeholders themselves, uncovering divergence of their strategies with policy expectations or other stakeholders' interests may well be a valuable outcome, which may eventually lead to strategy revisions.

To function as facilitators of change in the respective countries, the developed policy narratives now need to be validated, enriched, and amended by the stakeholders themselves. This process reaches beyond the scope of this study but can and should be pursued in the future. Future research could consider in more detail how outlining the signposts of a transformative policy mix may inform the design and implementation of concrete policy instruments. Such a process will not only need a mandate for the implementation but also require including stakeholders with conflicting interest, in order to foster a broader acceptance of its outcomes.

From a methodological perspective, in all five workshops, the stakeholders immediately related to the concept of bottlenecks and complemented the suggested list with additional bottlenecks, which were often in line with the near-, medium-, and long-term forces that cannot easily be captured in IAMs, as highlighted by Gambhir et al. [6]. In particular, aspects of the just transition were prominent but also geopolitical aspects like technology availability and cultural changes were brought up. Oftenmingle lively debates emerged from this workshop phase. Also, the voting was much appreciated with hardly any dropouts. Comparability could have been improved by using the same scheme for the voting in physical and online workshops. On the other hand, the physical voting by dots provided an opportunity for participants to exchange arguments for the voting and mingle in different configurations. In the second phase, transformative policy mixes were developed in all cases, albeit in some instances somewhat superficially due to the time restrictions. More time would have been required to push the notion of an integrated policy mix in contrast to just listing different measures.

The approach we presented here can be seen as an add-on to a modelling exercise to extend techno-economic pathways to socio-economic scenarios. As discussed in the introduction, the integration of stakeholders in the design of the techno-economic pathways is an equally important approach to overcome the limitations of past modelling exercises. Within the PARIS REINFORCE project, both approaches have been applied to produce scenarios better aligned with stakeholder views but in a separate manner, i.e. with different stakeholders involved and without a full integration of both approaches. We expect that combining both approaches in an integrated way may lead to outcomes even more streamlined with stakeholder views. However, this will also require an even higher level of engagement by the stakeholders. It will be worthwhile to explore this in future research.

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

Only limited data was used. All the data is available in the supplementary information.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rset.2023.100064.

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