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Model-Stakeholder Interactions for a Sustainable Mobility Transition

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Abstract The complexity of sustainability transitions calls for transdisciplinary dialogue processes among different stakeholder groups. When policy options are discussed with decision-makers, scientists often support them with the help of quantitative outputs provided by simulation models. As could be observed in the climate policy process within the European Union, the choice and design of the model, which produced the respective outputs, are seldomly questioned. With the increasing complexity of models in times of big data and high-performance computing, making the model and its parameters transparent and integrating them into stakeholder dialogues is essential for successful and democratic decision-making processes. Furthermore, such integration allows for the discussion of a broader variety of pathways or scenarios supplied by models. The combination of digital technologies and large computing capacity has led to a new methodological frontier through the possibility of interactive visualization of pathways, hence increasing efficiency and impact of stakeholder dialogues in decision-making processes. By describing such a process in light of a mobility transition towards sustainability, we show how an agent-based model can be used in stakeholder discussions among decision-makers.

1 Introduction: The Sustainable Mobility Transition

The major challenges of achieving a transition to sustainability – meaning a development that balances environmental, societal and economic priorities – have inspired scientists to overcome disciplinary and methodological boundaries. Sustainability science (Bettencourt and Kaur 2011; Clark and Dickson 2003; Kates et al 2001; Komiyama and Takeuchi 2006) at the forefront has striven to incorporate inter- and transdisciplinary approaches as well as to develop a balance of research and action (Matson et al 2016). On a theoretical level, sustainability science has operated within Elinor Ostrom's socio-ecological systems framework (Ostrom 2009). The latter was designed as an interdisciplinary tool, combining social and ecological sciences, and explicitly takes into account relationships in complex, multi-level systems.[1] In practice, sustainability science has expanded the focus of the SES framework in several ways: Firstly, by its solution-orientation, which leads to the integration of societal actors that have an interest or are impacted by a certain event, decision or transformation, namely stakeholders, into the research process. Such co-creation (Cornell et al 2013; Lang et al 2012)[2] leads to the inclusion of other kinds of knowledge such as target or transformation knowledge (see Partelow (2016) on a comprehensive assessment of the coevolution

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[1] Fischer et al (2015) describe SES as "complex adaptive systems characterized by feedbacks across multiple interlinked scales". Multi-level systems are characterized by a shared authority across several levels of government (Hooghe et al 2001).

[2] The methodological terms for integration of stakeholders are manifold, from action research (Action Research Manifesto 2011) over use inspired-research (see Clark 2007; Arnold 2008) to stakeholder involvement (Mielke et al 2017).

of SES and sustainability science). Secondly, there has been an effort to better understand the systems dynamics and interactions in SES, essentially addressing "why some SESs are sustainable whereas others collapse" (Ostrom 2009, p. 420). This effort has led to establishment of the field of sustainability transitions (Frantzeskaki and Loorbach 2010; Markard et al 2012; Van den Bergh et al 2011) which deals with "the issue of how to promote and govern (...) a fundamental transformation towards more sustainable modes of production and consumption" (Markard et al 2012, p. 955).

Specifically, the multi-level perspective on socio-technical transitions by Geels and Schot (2007) is a valuable structure to analyze model-stakeholder-interactions in the context of a transition to sustainable mobility. Here, the success of technological innovation which happens in *niches* (on the micro-level) depends on changes in the institutional, regulatory and normative environment shaped by the respective community (*regime*; the meso-level). Both are embedded in a *socio-technical landscape* beyond the scope of the regime actors (the macro-level). The behavior of users and institutional structures changes with a new technology, while an infrastructure environment is created and new business models and products emerge (Markard et al 2012).

Based on this reasoning, we develop a model-stakeholder methodology to study sustainability transitions[3] in the mobility sector. The latter is currently undergoing a transition due to e.g. new technologies, digitalization and corporate scandals. The sector is characterized by high levels of greenhouse gas emissions and a large-scale heterogenous network of agents with multi-dimensional mobility preferences, including not only time of travel or availability of a technology, but also convenience or status. Thus, achieving a transformation in such a sector requires solutions that rely on a combination of technical and societal factors (for definitions and frameworks concerning low-carbon mobility transitions, see e.g. Köhler et al 2009; Geels 2012; Geels et al 2011). To contribute to such solutions, this paper develops a research process based on the development of an agent-based mobility model, accounting for the large network and the multi-dimensional preferences in the transport sector mentioned above, within a series of stakeholder interactions, allowing for a better understanding and acceptance of the transition and its effects by users (Harris et al 2015).

A special focus here lies on the transdisciplinary element of this approach, since the complexity of sustainability transitions calls for dialogue processes among different stakeholder groups (Mielke et al 2016). Especially when involving decision-makers, the normative dimension including individual and collective responsibilities needs to be stressed (Tàbara et al 2017). The use of an agent-based model – the Mobility Transition Model (MoTMo) – in dialogues allows to discuss scenario-based narratives with stakeholders along the dimensions of technology, market and regulation, incorporating e.g. infrastructure, business models and prices. MoTMo connects the behavioral micro-scale with the economic and technical macro-scale and contains a synthetic population. Thus, it can be an important tool to analyze the behavior of social systems (Dum and Johnson 2017). By designing an iterative research process that allows for feedback between modelers and stakeholders, and where a broad range of scenarios[4] is provided to decision-makers in deliberative discussions (Mielke et al 2016), plausible scenario-based narratives shall be co-created.

Thus, our work can contribute to the stakeholder-model nexus in a threefold way: Firstly, it can serve as a methodological guideline for scientists striving to integrate ABMs and stakeholder dialogues by providing a framework for such interactions. This includes a distinction of dimensions of model parameters into those which can be influenced by stake-

[3] Mercure et al (2016) define sustainability transitions as involving "a highly non-linear, self-reinforcing process with lock-ins that drive expectations, propelled by choices of and adoption by diverse agents with different perspectives and incomes".

[4] By the term scenario we refer to a possible future pathway generated by a computer model.

holders (*action*) and others that describe exogenous *events* which occur without influence, as well as those that are primarily *value-based* and those which are mainly *technological*. Secondly, it can contribute to the effective use of new tools, e.g. for visualization, and data in stakeholder involvement. Thirdly, it can enhance the literature on socio-technical sustainability transitions, with a special focus on future mobility.

2 Narratives and Scenarios

Narratives lie at the core of transitions in society[5]. A well-known example is the Diesel-motor, once invented to decentralize industry. Diesel generators allowed small-scale production, as opposed to the dominant large steam engines, and were associated with modernity and progress. Today, our perception of the Diesel is shaped by the recent scandals in the automotive industry and the idea of it being a dirty and harmful technology that should be banned from cities. In both cases, the narratives are closely linked to the cultural identity of the time.

Narratives are crucial for collective identity, the latter of which Brown (2006) defines as a "discursive construct". For narratives to be effective in fostering transformative (collective) action, Pahl-Wostl et al (2008) define three key elements: they should firstly "support and resonate with aspirations, ideals and desires", secondly be "engaging and empowering" and thirdly "resonate with moral authority". They can be defined as "simple stories that describe a problem, lay out its consequences and suggest (simple) solutions" (Hermwille 2016). A *transformative* narrative should be telling "a positive story, by articulating a vision of 'where we want to go'" and at the same time offering "solutions for attaining this vision" (Autonomous University of Barcelona et al 2018). Chabay (2015) stresses the need for substantive collaboration between science, art, technology and humanities to create and reflect on narratives for sustainability.

In the policy context, Roe (1989) advocates for assessing complex and controversial policy issues, where information is difficult to validate, with narrative policy analysis, concluding it could alleviate uncertainty. Today, decision-makers are often confronted with scenarios, that, with their visionary elements, are closely linked to narratives (Miller et al 2015; Moss 2011). Kemp-Benedict (2004) and Schmid and Knopf (2012) see scenarios as narratives with a quantitative (model) basis, linking both worlds. We instead argue that ***plausible narratives*** should be based on scenarios stemming from models, making them ***visionary stories about the future* with a *quantitative core***. A **scenario-based narrative** as the authors here define it should have the following components:

I. A scenario from a model, answering the question: Where could we go and how do we get there?
II. A surrounding story of a possible future pathway, answering the question: Where do we want to go and how do we get there?

The methodology defined here in Section 3 shall lead, through the model-stakeholder feedback, to different *possible* scenario-based narratives in a first step. As a second step, these different pathways shall be evaluated in terms of plausibility (Wiek et al 2013) to lead to *plausible* scenario-based narratives. This approach is intended to achieve two goals simultaneously: to create a new kind of scientific knowledge as well as to broaden the decision-making space of stakeholders, meaning the number of possible pathways available when discussing a transition.

[5] Schapp (2012) goes as far as describing all processes in society as based on stories in which people are more or less entangled. Geertz (1973) expands on Gilbert Rye's distinction of "thin" and "thick" descriptions when analyzing behavior in the context of cultural settings, arguing that research in this field is more interpretive than observational.

2.1 The Model-Stakeholder-Nexus

The use of scenarios has become frequent in stakeholder dialogues concerning complex sustainability challenges (see e.g. Van Notten et al 2003; Miller et al 2015). On the one hand, model outputs are often simply presented to stakeholders who are expected to use them in decision-making processes without making the construction and assumptions on parameters and inputs of the model transparent (Rosen and Guenther 2015).[6] On the other hand, many social scientists who work with narratives are reluctant to use numbers or computations, arguing they lead to a confusion of stakeholders (Shaw and Corner 2017). To create transparency and use model outputs as an enhancement of a dialogue, researchers in sustainability science have increasingly tried to integrate stakeholders more actively into the model world. While Czaika and Selin (2017) let participants use a model to produce output, the companion modeling approach of Ètienne (2013) goes as far as letting stakeholders build the models in collaboration with the researchers.

In the discourse on climate policy, computable general equilibrium models such as GEM-E3 or integrated assessment models have been widely used. When it comes to modeling sustainability challenges, agent-based models have become more common in recent years (Bonabeau 2002; Filatova et al 2013). We want to point out two important reasons for this development: On the one hand, such models, which describe a system from the perspective of autonomous decision-making entities that interact repeatedly (Epstein and Axtell 1996), can address a broad(er) view on societal challenges. The latter call for an integration of people's behavior with the ecosystem they live in (Folke et al 2016). This is especially relevant for sustainability transitions of socio-technical systems which show various feedback loops between user behavior, technology development and regulation. Here, ABMs can describe e.g. rebound effects, where well-intended measures and products lead to problematic outcomes. On the other hand, the increase of data availability and computing power have enabled researchers to create more realistic agent-based models and synthetic populations[7]. In our field of inquiry – the sustainable mobility transition – these models and frameworks have become increasingly popular (Köhler et al 2009).

However, the development and use of such models remains a major challenge for scientists and stakeholders. Since these behavioral models are inherently rich in the use of assumptions, the output that is presented to stakeholders can never consist only of absolute "numeric" results, but has to be put in perspective by e.g. embedding them in a narrative. The modelers, in turn, need stakeholder interaction to increase validity of their behavioral assumptions and to create output that is useful for stakeholders. Thus, both scientists and stakeholders require new skills and methodologies to process these behavioral modeling concepts. This includes testing a wide range of hypotheses and beliefs concerning future developments, but also the interactive discussion of results to develop computationally enhanced narratives and policy recommendations.

3 Computation Modeling Approach – MoTMo

The agent-based model MoTMo used here (Mobility Transition Model) simulates the future development of the private mobility sector in a socio-technical context. The following section provides a brief overview of the model structure and capabilities. The description is focused on the parts that are important for the stakeholder involvement process.

[6] For a criticism of the most influential model used for the evaluation of climate policy measures in the EU, see Schütze et al (2017).

[7] E.g. for the purpose of modeling the behavior of early adopters in a statistically accurate way, populations of millions of agents are required.

3.1 Model Structure

The model is implemented as an agent-based model (ABM) of many interacting agents, i.e. individuals, of different types. The system evolves in discrete time steps and covers the time period from 2005 to 2035. A synthetic population of Germany reproduces the relevant population characteristics like household structure and statistical distributions of age, gender, income and mobility demand together with interdependencies. A network of grid locations maps the spatial dimension. Agents are structured in households implemented as utility-optimizing decision makers. A social network is created based on spatial proximity and similarity of agents. Agents share information and experiences via the social network and therefore form a social learning network that adapts to environmental changes and technical innovation. Thus, this model structure allows for behavioral change, socio-technical feedback effects (e.g. rebound-effects) and the spread of innovation and social norms.

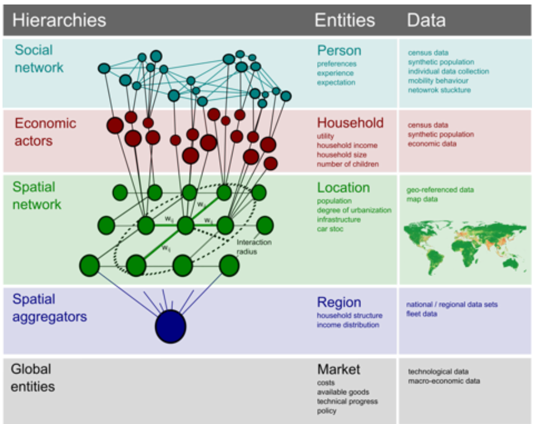

Fig. 1 Illustration of the hierarchical model structure including entity types and possible data inputs.

3.1.1 Agent-based View and Scope of Information

To represent the evolution of social norms and diffusion of innovation, agents have only a limited scope of information that they can access, thus having to act under uncertainty. The agents' actions are implemented from an agent's perspective (e.g. "I collect all available information about the mobility choices of my friends and decide if I want to change"). Consequences of different actions can only be estimated based on past experiences or information communicated within the social network.

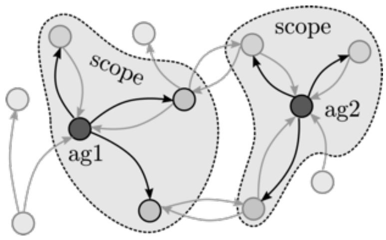

Fig. 2 Conceptual illustration of the information scope of each agent.

We distinguish between action agents and passive entities (e.g. grid cells or states) that are important for aggregation and statistical analysis (e.g. the total CO_2-emissions within a region). Locations form a regular spatial grid and are connected with other locations within a defined interaction radius. A household is characterized by its income, location, and the composition of people living in it (household type). That means, all households are connected to their respective location and to all persons living in them (see Figure 1). The household coordinates the decisions for all persons such that the overall utility of the household is maximized.

Agents are part of a heterogeneous synthetically generated population, which differs in age, gender, mobility patterns and personal priorities (see section below). The priorities represent the importance of four components and how strongly they contribute to the utility function. Furthermore, persons interact with other members of their household in the decision-making process and share experiences in their social network. Thus, persons are connected to their household and to other persons (their social network outside of their household). Within the simulation, agents develop expectations (expected utilities) about the available mobility modes, including those, which are only communicated by members of their social network. These expectations are used in a twofold way: First, by comparing their own experience about a mobility mode with the other agents' experience in the social network where the agent can approximate the similarity to the others and therefore approximate the reliability of the information. Second, by considering the experience from the network and the reliability of the persons, each agent can evaluate new alternative mobility modes and imitate the most promising ones.

3.1.2 Mobility Modes

The model currently distinguishes five different mobility modes: "fossil" (high-emission) cars, "electric" (low-emission) cars, "public" (public transport), "shared" (shared mobility) and "none" (non-motorized). The mobility modes currently differ in two properties (emissions and total cost of ownership/use) and the functions that represent the convenience of each mobility type. The convenience is implemented as a function of the population density in each location and the current technical progress. Furthermore, different modes offer different degrees of innovativeness to resemble the roles of innovators, early adopters, early and late majority as well as laggards from classical innovation approaches (Rogers and Shoemaker 1971).

3.1.3 Mobility Memes

A meme can be seen as the corresponding concept to a biological gene in the social context that contains a set of information. In MoTMo, a mobility meme **d** (MoMeme, see Figure 3) is a set of information that contains the current mobility decisions of a person. Each person aims to identify a MoMeme $\mathbf{d}_{opt}$ that maximizes the individual and the household utility.

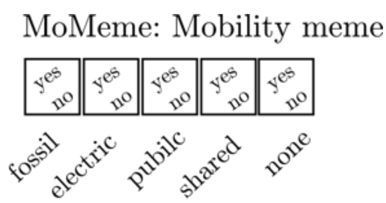

Fig. 3 Illustration of a mobility meme for five different modes.

3.1.4 Utility Evaluation

The actual utility is a function that consists of four components that correspond with the consequences $\mathbf{x}$ (see Section 3.2.1) of the mobility choice. The consequences are weighed by the person's priorities $\mathbf{p}$. The Cobb-Douglas utility function has the following form:

$$U(\mathbf{x}) = \prod_{\mathbf{i=1}}^{\mathbf{n}} \mathbf{x_i^{p_i}}$$

3.2 Building Blocks

In contrast to describing MoTMo as a temporal sequence of code, this section describes the most important building blocks which illustrate the main concepts in MoTMo.

3.2.1 Consequences

Each mobility decision of an agent produces different consequences which represent the satisfaction with the mobility mode related to the priorities and are normalized between 0 (non-fulfilled) and 1 (fully satisfying). The vector of consequences $\mathbf{x}$ consists of the entries convenience (x_1), ecology (x_2), remaining budget (x_3) and innovativeness (x_4).

The consequence “convenience” (x_1) measures the overall convenience that a mobility mode provides. It depends on the current (technological) state (e.g., range, travel speed) and the related infrastructure (e.g. charging stations) in the surroundings. For more detail, see the example below. The consequence “ecology” (x_2) relates to the CO_2-emissions produced by the mobility mode. The emissions of each mobility mode depend on technological progress at the time of purchase. The consequence “remaining budget” (x_3) is the money that is saved by low-cost options and can be spent for other amenities. Expenses of all persons in the household are summed up, and the sum is used to compute the remaining share of money. The consequence “innovation” (x_4) exemplifies how much the agent feels like using a new innovative technology and is, thus, related to the degree of technical progress.

The total ownership cost (TOC) or the use of a service for all mobility modes are changing with the technological progress at the time of purchase, which is a function of sectoral growth rates. According to “Wright's law”, the technical progress is proportional to overall production numbers of a good.

Example: Convenience
Modeling the convenience of different mobility modes requires making assumptions, e.g. based on expert judgment. Comparing model output under different assumptions helps to create an understanding of mechanisms in the system and its dynamics. A useful and simple approach is to model the convenience at a given technological state as dependent on population density, and if necessary later with more specific interactions such as actual infrastructure development. Figure 4 shows how one single functional form is currently used to express various assumptions for the convenience that people experience when using a certain mobility mode. Two states are defined to account for the technical progress of each technology. The “init” state represents the technological state at the start of the simulation, whereas the “final” state represents the technical limit that can possibly be reached in the future. For both states, the modeler defines minimum and maximum of the convenience function, the population density for which the highest function value is reached and the width (spread) of the function for the two states. Depending on the market share, the function transforms within the simulation from the “init” state towards the “final” state.

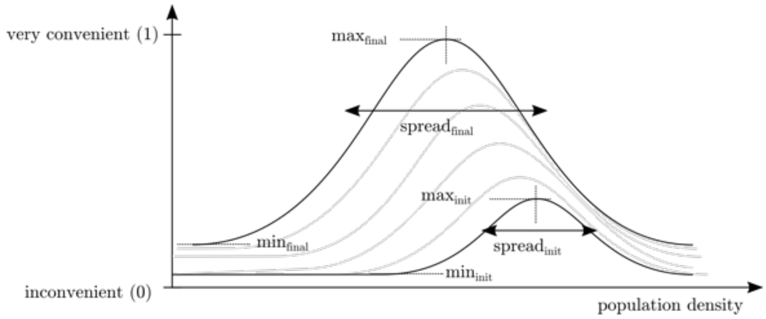

Fig. 4 Schematic illustration of the convenience function including all parameters.

Figure 5 exemplarily shows the assumed development considering various influence factors. For example, for fossil and electric vehicles (EV), the convenience is assumed to decrease with increasing population density since parking in cities becomes difficult, travel speed decreases and traffic conditions become more challenging. The convenience for EVs is additionally decreasing for low population densities, since we assume missing charging infrastructure and longer travel distances for which the range limitations of electric cars matter more. In contrast, the convenience of public transport, car sharing and non-motorized mobility increases with the population density, however for different reasons. Main factors are shorter travel distances, better infrastructure and better public transport scheduling. The peak values, minima and maxima, are calibrated on existing data from 2005 to 2017 so that the model matches the past development.

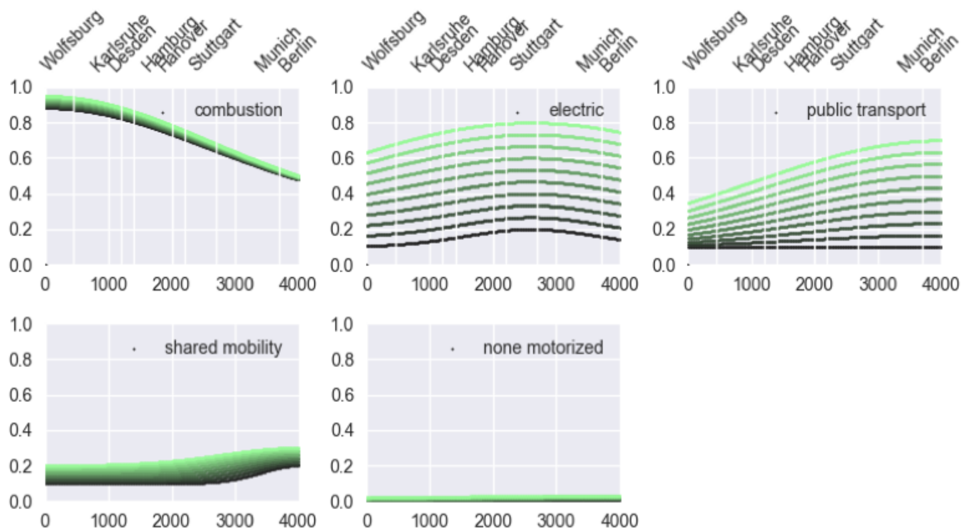

Fig. 5 Assumptions about the convenience of mobility type over population density and the development with technical change (black to green).

The definition of the shapes of the convenience functions will allow stakeholders to represent different technological developments that they believe to be most plausible.

3.2.2 Social Evolution

Social evolution is used to model how innovation and expectations about new technologies spread within social networks. We currently employ basic mechanisms that are transferred from evolutionary algorithms for optimization problems. Within the social network of each agent, many different mobility memes are exchanged together with an expected utility. In addition, each person is weighted by other persons through a reliability measure that accounts for the usefulness of the recently provided information (meme + utility). For each meme, the expected utility and reliability are multiplied and normalized to compute a selection probability. Based on this probability, a defined number of memes are selected as candidates for potentially improving the person's utility. The list of all candidate mobility memes of all persons is used to create all possible combinations for each household (see Figure 6). In an optimization step, the combination with the highest utility for the household is identified. In case a combination is accepted, all persons in the household take action to obtain the new mobility mode.

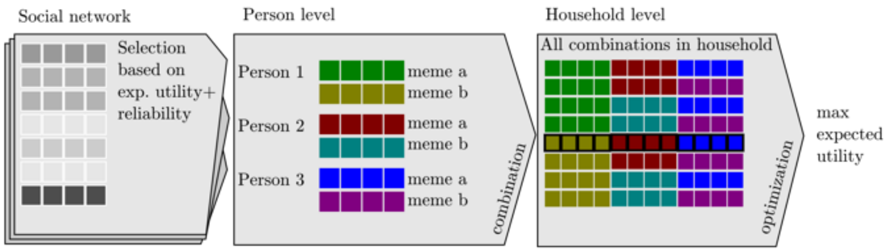

Fig. 6 Illustration of the different parts that resemble the evolution of memes in the social context. In later stages, not only imitation processes, but also other components like mutation and crossover of mixed strategies can be implemented for the evolution of memes.

Overall, the framework allows for the evolution of social behavior that adapts to changing environmental and technical forcing. By weighting, the social network can change so that more useful interactions between agents are strengthened and sources of unreliable information are reduced. The local scope and a social network structure dependent on similarity allows for different niches for certain socio-technical transitions.

4 Research Design

By discussing input parameters, model outputs and assumptions about future developments within a broader context of the mobility transition in an iterative process, we establish narratives for an urban sustainable future. The development of these narratives will take place in a "decision theater", an interactive environment where groups of stakeholders can directly visualize potential consequences of their choices.

Observing the reactions of the model based on a change of inputs and, thus, gaining insight on the model, will enhance transparency. Moreover, scientists can change their primary role as information providers for policy makers to a co-design approach (Moser 2016) that aims at exploring future pathways with stakeholders. The focus on the mobility transition in Germany serves as an example of intermodal, electric and digital mobility concepts. The model, which is a consumer ABM extended by macro-scale technical change and infrastructure development, investigates the diffusion of innovative technologies in social networks. Through the inclusion of individual preferences such as environmental and consumer attitudes as well as financial constraints, agents learn and alter their decisions concerning different mobility modes.

4.1 Model-Stakeholder Interactions

The aim of our interactive methodology is to combine model and narrative with a feedback between modeling work and stakeholder dialogues as described in Figure 7. Theoretical **reflection** will help to refine and extend our agent-based model MoTMo, construct scenario-based narratives and interpret our stakeholder dialogues. MoTMo will provide **input scenarios** as a quantitative element of the **narratives** of possible futures of low-carbon mobility.

The scenario-based narratives, including the underlying model assumptions, will be discussed in **dialogues** to gain different types of knowledge from stakeholders from all parts of society, e.g. scientists, policy-makers, non-governmental decision-makers as well as entrepreneurs. The guiding research questions will be: 1. Where could we be? (referring to the scenario) and 2. Where do we want to be? (referring to the narrative). The goal is to reach plausible results, leading to the selection of different possible future narratives.

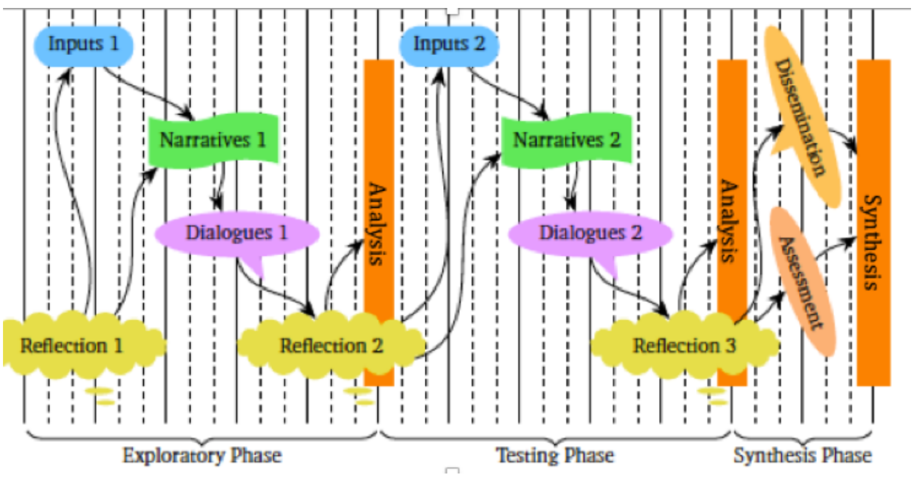

Fig. 7 A research process of model-stakeholder interactions.

We adhere to the concept of science-based stakeholder dialogues presented by Welp et al (2006), defined as a "structured communicative process of linking scientists with selected actors that are relevant for the research problem at hand". Thus, stakeholders are actively engaged in the research process instead of being merely treated as objects of scientific research. Through the use of focus groups, they will be able to provide input for the research design as well as evaluate and modify the resulting narratives (Kasemir et al 2003). This allows actors to develop ownership of the results and to communicate their constraints (Welp et al 2006).

The iterated process will have three phases: An exploratory phase where research on a test region is conducted by establishing a network of relevant stakeholders, finding controversial topics and political goals concerning mobility. This way, ideas for possible scenarios and narratives are generated. The preliminary results from the dialogues are then evaluated in the analysis phase to refine the guiding hypothesis, improve the model, the narratives, and the stakeholder dialogue design. The testing phase repeats the process and the second analysis phase specifies key results. In the synthesis phase, all co-created knowledge will be used to disseminate and assess the data, creating plausible scenario-based narratives for sustainable mobility in Germany as a synthesis.

Table 1 specifies the different steps of the research process:

Exploratory Phase	Reflection 1	– describe the current mobility situation in the respective area and the projects that are being planned (regional assessment) – analyze the stakeholder network
	Inputs 1	– create scenarios based on reflection (model output) – identify parameters for the model discussion
	Narratives 1	– prepare a scenario-based narrative to be discussed with stakeholders
	Dialogues 1	– discuss scenario-based narratives, model parameters and further topics with stakeholders in line with the dimension cube established in reflection 1 (market, technology, regulation)
	Analysis 1	– transcribe and analyze results – feed them back into the model scenarios and the narratives
Testing Phase	Repeat the process	
Synthesis Phase	Synthesis	– develop plausible scenario-based narratives based on iterated model-stakeholder dialogues

Table 1 The model-stakeholder research process

4.2 Visualization

A key element of the mixed methodology that combines quantitative and qualitative elements is visualization (Bagnoli 2009; Nind and Vinha 2016). By using digital tools, we want to make numbers, spatial structures and complex relationships more accessible to stakeholders. With this approach, we relate to three desired effects of visualization defined in the companion modeling approach (Ètienne 2013), aiming for: creation of knowledge; help in interacting with others; and a creation of a forum for discussions between participants. Thus, we choose visualization through diagrams and maps as well as real-time simulations on multiple screens. After a brief introduction of our work, stakeholders will be able to analyze different concepts and parameters of the model, based on the choice of scenario. Stakeholders can then alter the parameters and see their influence on the output. After a "playing" period, stakeholders have to fill in their choices in a survey. The results will be used to then alter our scenario-based test narrative by incorporating stakeholders' knowledge.

5 Scenario-based narratives

We aim for a two-step process. In a first round of workshops, we want to discuss parameters and their influence on the model output with stakeholders engaged in the field of mobility, namely decision-makers, mobility service companies (bike, car, public transport), energy companies, unions, chamber of crafts, mobility industry companies and scientists. 6-8 participants would discuss the parameters and, linked to these, their *priorities and expectations* concerning the future of mobility. The topical focus shall include infrastructure development, the integration of renewables and mobility via digital technologies and the future of the transforming industries around mobility. These results shall flow back into the model, offering the unique opportunity of aligning stakeholder information needs with model development. We will derive narratives from these workshop results, which will help to prepare the second round of dialogues in a "decision theater". Then, in a second step, stakeholders shall be able to alter model assumptions in the form of parameters, namely "play" with them to achieve different outputs that are visualized for them. On the basis of these outputs, we want to achieve more plausible mobility narratives.

5.1 Narratives for Sustainable Mobility

The development of the narratives is based on three dimensions in the model – *market, policy and technology* [8]. These dimensions resonate with the theory of socio-technical transitions (see Section 1). In a first step, they are broken down to three topics that can **a)** be utilized in the model and **b)** are important in the public debate (Schmid and Knopf 2012). The timeframe is until 2035, the scale is national (Germany). Figure 8 shows these dimensions in a **"decision cube"** and shows the Business-As-Usual narrative (BAU) that is explained in the following section.

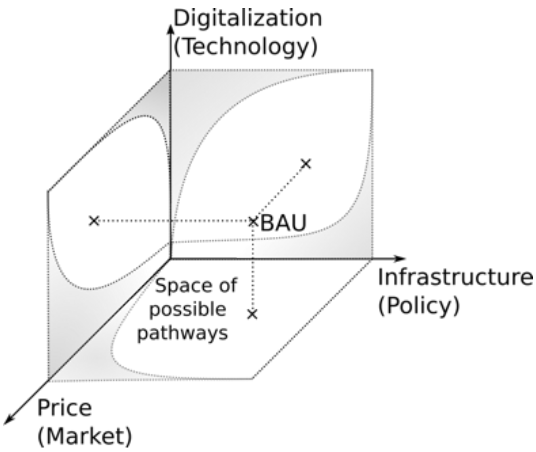

Fig. 8 Dimensions for scenario-based narratives in a "Decision Cube".

To allow for an interactive discussion with stakeholders, the model has to be adapted to parameter changes in real time, or stakeholders have to access a database of model variations and corresponding outputs. Examples are:

Infrastructure. Variation: Number of charging stations over time, convenience of EVs. Output: Distribution of charging stations and EVs that change with infrastructure investment.

Prices. Variation: Stakeholder assumptions concerning global EV sales that lead to different technological progress rates and prices. Output: Effects on amount and distribution of EVs.

Digitalization. Variation: Convenience and emissions of EVs and car sharing, innovation capacity of agents, feedback-mechanisms. Output: emission reduction due to digitalization in the energy and automotive sector, changes in the electricity mix, development of fossil

[8] Geels sees the following dimensions policy, "technology, user practices, science, cultural meaning, textbfinfrastructure and industry" as part of the socio-technical regime concept (Geels 2014, p. 25).

Expansion of charging stations (CS)	Action	Event
technological	number of CS	price of CS
value-based	location of CS	governmental support of CS

Table 2 Exemplary distinction of model variants and parameters

mobility niches (e.g., rebound effects), potential of new mobility modes, development of public transport networks.

This framework includes a distinction of model parameters (see Table 4) into those which can be influenced by stakeholders (*action*) and others that describe exogenous *events* which occur without influence, as well as those that are primarily *value-based* and those which are mainly *technological*. Certain parameters can be more successfully discussed with technical experts, while others are prone to be assessed by decision-makers.

The “decision cube” leads to the following first round narratives for a sustainable mobility in Germany. They are based on MoTMo scenarios; the latter correspond to points in the cube, see, e.g., the BAU scenario represented in Figure 9.

a) Business as Usual (BAU)

Infrastructure: The expansion of charging infrastructure for EVs continues in a linear way, but remains uncoordinated (see Figure 9). A network of superchargers is slowly built along highways. Until 2035, the lack of infrastructure, among other reasons, leads to Germany missing its target of 6 million electric cars. Intermodal mobility is realized through pilot projects.

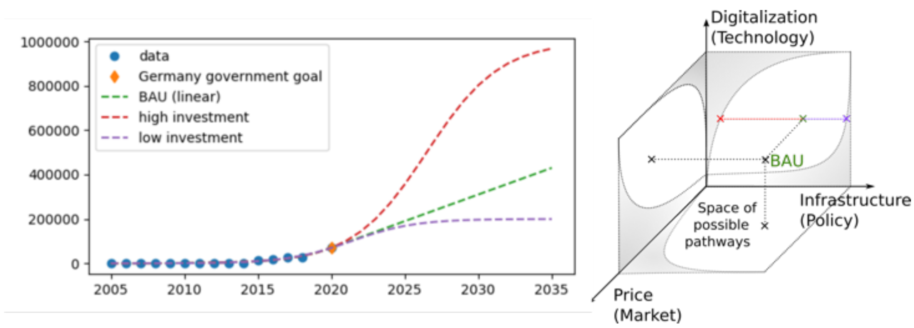

Fig. 9 Scenarios for the expansion of charging infrastructure in Germany as a starting point for a discussion of policy measures.

Prices: The global prices are slowly reduced due to technical progress of cars and batteries in China and the EU (see Figure 10). This allows for a higher diffusion of EVs, but does not push other technologies out of the market. The range of electric cars improves to 400 km per charging.

Digitalization: Digital mobility applications for carsharing and ride-hailing[9] take up 15% of the mobility mix, which is further composed of 60% motorized private transport, 5% public transport, 15% bikes and 5% of people walking. Some businesses offer services for smart charging and vehicle2grid, leading to a slightly higher share of renewables in the transport sector.

9 For the ambivalent effects of ride-hailing in terms of reduction of CO2 or traffic, see (Clewlow and Mishra 2017).

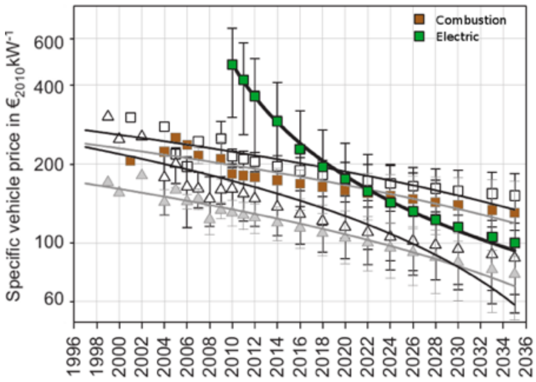

Fig. 10 Pathways of global prices for electric and combustion cars (Weiss et al 2012).

b) Smart Green/Electric Mobility

Infrastructure: Charging infrastructure for e-mobility is massively expanded in pilot regions (Rhine-Ruhr, Hamburg, Munich and Berlin), leading to 10 million EVs in Germany by 2035. The country is integrated into a European network of superchargers along the highways. The share of renewables in the mobility sector reaches 45%. All urban centers supply the infrastructure for intermodality, allowing new business models and companies to emerge.

Prices: The global prices of EVs decrease rapidly due to technical progress of cars and batteries in China and the EU. This allows for a high diffusion of EVs and pushes other technologies out of the market.

Digitalization: Digital applications such as carsharing und ride-hailing alter the mobility mix. Prices are low since these companies partly use autonomous cars. Motorized private transport is reduced to 20%, digital mobility modes are used by 45% of the people due to their high flexibility and low prices. Public transport is reduced to 5%, while 25% of people use bikes and 5% travel by foot. Intermodal mobility is supported massively by the government. Due to the establishment of a smart transmission and distribution power grid, renewables power up to 350.000 EVs. This electricity would have been lost because of curtailment of renewables in the BAU-scenario due to a lack of flexibility and sector integration.

c) Brown/Fossil Mobility

Infrastructure: Motorized private transport remains the main mode. The car industry focuses on more efficient combustion engines, the low wages in the transport and logistics sector lead to an increase of goods being transported on the road. Electric mobility does not succeed on a broad scale, instead, several technologies such as hydrogen and gas compete in a niche market. Investments in charging infrastructure for e-mobility are reduced. In 2035, there are 1,5 million EVs on the road in Germany, manly in urban centers. The share of renewables in the mobility sector remains at ten percent.

Prices: The US and Germany succeed in keeping up their combustion car industries. EVs remain expensive and due to accidents and low mileage are considered inconvenient by many users.

Digitalization: Automatic cars are used to increase convenience on the road while leading to more traffic and congestion. Motorized private transport remains high (70%), digital technologies are used by 10% of the people while public transport, bikes and walking each remain at 5%.

6 Conclusions

To tackle the complex sustainability challenges of our times, scientists have to find new ways to bridge the gap between the real world and the scientific realm. Often, models are used to give decision makers numerical results. We argue that in times of big data and increasing global interconnectedness, a new methodology that combines model work and stakeholder involvement is needed. We propose a framework that allows decision makers to understand and use the model that produces results, and to integrate their choices into the model development and thus, to broaden their knowledge space and decision space beyond simple numbers. By using an agent-based model for the mobility sector in stakeholder dialogues with interactive tools, we show that such a methodology can create meaningful plausible narratives based on scenarios that can be influential in society and politics.

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