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Towards Integrating Social Dynamics into Climate Economic Scenarios

Literature Review

Simon Barth

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Simon Barth, Research Unit Sustainability & Global Change
University of Hamburg, Germany

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Kontakt:

WiSo-Forschungslabor
Von-Melle-Park 5
20146 Hamburg
E-Mail: experiments@wiso.uni-hamburg.de
Web: http://www.wiso.uni-hamburg.de/forschung/forschungslabor/home/

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Simon Barth

University of Hamburg, Germany

Research Unit Sustainability & Global Change

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Abstract

Climate policy options are usually elaborated scientifically by Integrated Assessment Models that combine the economic system, the energy system and the climate system in one comprehensive framework. Most of them follow a neo-classical economic paradigm and calculate cost-efficient technological transformation pathways of the energy system. Critique has grown that the real-world problem is more complex especially with regard to the dynamics reigning in human societies. These should be considered in the models in order to derive effective policy recommendations. This literature review presents and structures a list of publications making first steps into this direction, either by delivering promising methodological suggestions, by reporting evidence on social dynamics or by presenting first model integrations. By this, the paper illuminates the scientific challenge of integrating social dynamics into climate economic scenarios and builds a knowledge basis for future research endeavors.

Keywords

Climate economics, social dynamics, energy transitions, integrated assessment

Table of Contents

List of Figures

1 Introduction

Anthropogenic climate change caused by greenhouse gas emissions from the combustion of fossil fuels and land use changes poses a major threat to the welfare and security of the human civilization in the 21st century (IPCC, 2014). Traditionally, the problem is elaborated scientifically by so-called Integrated Assessment Models (IAMs) that combine the economic system, the energy system and the climate system in one comprehensive framework. The first of its kind, the DICE model, was developed by Nordhaus in the early 90s (Nordhaus, 1992, 1993) and won him the Nobel Memorial Prize in Economic Sciences in 2018. Nowadays, a vast number of IAMs exist with varying depth and resolution of the modelled sectors. Most of them run a neo-classical economic growth engine at their core that maximizes an intertemporal welfare function under climate constraints. This translates then into cost-efficient technological transformation pathways of the energy system. The models have been compared and challenged in several intercomparison projects and subsequent publications, e.g. RECIPE model intercomparison (Luderer et al., 2012), which has finally emerged in a broad synthesis within the 5th Assessment Report of the Intergovernmental Panel on Climate Change Working Group III. The report states a robust finding of only 0.06 % loss of annual consumption growth in economic scenarios that reach a temperature stabilization goal of 2°C by 2100 with respect to a 1.6-3 % annual consumption growth reference case (IPCC, 2014).

Hence, IAMs based on neo-classical economics claim a dominant role in informing policy makers. But critique has emerged and grown that these models treat the problem too narrow and that the real-world problem is more complex especially with regard to the mechanisms and dynamics reigning in human societies. Therefore, many scientists call for improved models or at least for acknowledging the insights from other disciplines foremost social sciences by policy makers (Beckage et al., 2020; Carrico, Vandenbergh, Stern, & Dietz, 2015; Farmer, Hepburn, Mealy, & Teytelboym, 2015; Li, Trutnevyte, & Strachan, 2015; Müller-Hansen et al., 2017; Revesz et al., 2014; Sovacool, 2014a, 2014b; Stern, 2016; Stern, Stiglitz, & Taylor, 2021; Victor, 2015). Prominent social scientist Benjamin Sovacool working on energy transitions states: “To be successful, technologies must not only get built, but get built into society”

(Sovacool, 2009). Li and Strachan (2017) suggest that cost-efficient technology pathways stemming from optimization analyses should be understood as techno-economic maxima in the solution space of transformation pathways towards a climate stabilization goal. Going beyond technological change and market design instruments and exploring effects and levers of changing behavior, lifestyles, institutions and culture on energy demand and carbon emissions might open up the solution space.

That there is indeed much need for understanding energy transitions from a more holistic view than strict cost-efficiency in order to understand the system evolution better and to propose and implement effective policy is revealed by two empirical studies. Trutnevyte (2016) investigated the UK electricity system transition between 1990 and 2014 in an ex-post modelling analysis. She finds deviations of the real world evolution in comparison with the optimal solution from 9 % up to 23 % depending on various assumptions regarding technology, cost, demand and discount rate. The second empirical finding refers to UK's Green Deal program that started in early 2013. The policy scheme aimed at increasing energy efficiency in private homes by providing financing schemes for various efficiency measures that could be undertaken with positive net costs. After a disastrous low penetration rate the Green Deal program was abruptly ended in 2015 with no replacement policy in place. In hindsight, scientific analysis concluded that the policy design did not account for key behavioral factors of consumers (Marchand, Koh, & Morris, 2015).

Hence, there are many empirical and theoretical indications that energy transitions need to be understood from a holistic perspective on human societies and their dynamics in order to derive effective policy recommendations. This literature review tries to collect and present a broad but by no means complete number of scientific publications that make first steps into this direction, either by delivering promising methodological and conceptual suggestions, by reporting evidence on relevant societal dynamics or by presenting first model integrations.

2 Methodological Strategies and Conceptual Frameworks

The scientific endeavor of integrating processes of social dynamics into quantitative models of climate economic scenarios poses questions and provokes debates of epistemic nature which in consequence divide scientific approaches to the problem. While many social scientists even claim that there will never be a full integration in quantitative modelling of social processes due to fundamental differences in science philosophical approaches in the involved disciplines (Castree et al., 2014; Geels, Berkhout, & van Vuuren, 2016; Olsson, Jerneck, Thoren, Persson, & O'Byrne, 2015), several (especially natural) scientists advocate the idea of a comprehensive, quantitative earth system model that includes human societies and their dynamics (Donges et al., 2017; Palmer & Smith, 2014; Scheffran, 2016; Schellnhuber, Crutzen, Clark, & Hunt, 2005).

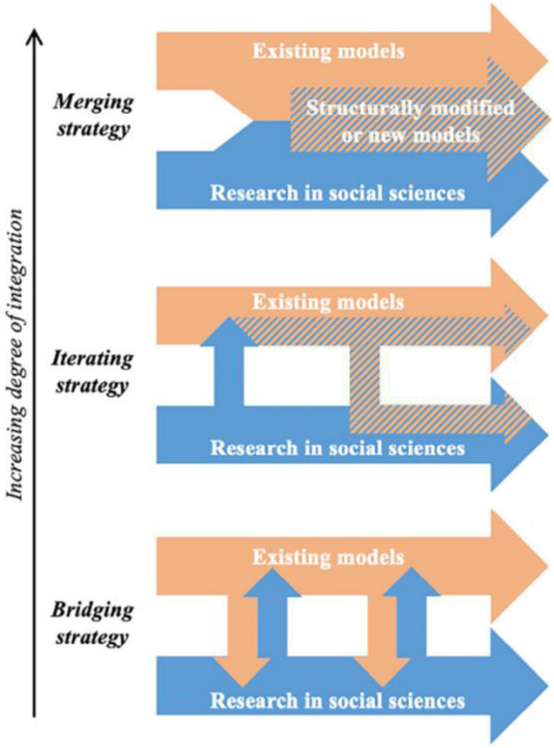

Figure 1: Illustration of the three different degrees of integrating social dynamics into existing IAMs. Adopted from Trutnevyte et al. (2019)

Trutnevyte et al. (2019) acknowledge huge challenges in fully integrating social science insights into quantitative modelling efforts of climate change but advocate for scientific experiments at all levels of integration. They propose three depths of integration levels in increasing order: bridging, iterating and merging (see Figure 1).

Bridging corresponds to a science work program where quantitative modelers and social scientists more or less work in parallel and only come together to discuss outcomes or shared concepts. Following this strategy, IAMs would first provide cost-efficient technological scenarios. These scenarios are then confronted with feedback from social science insights in order to identify socially impossible transformation characteristics. With this feedback the socially feasible transformation pathways might be identified or new model runs can be executed with revised input assumptions (Geels et al., 2016; Turnheim et al., 2015). Iterating describes an approach that is employed in the idea of shared socio-economic pathways (SSPs) (Bauer et al., 2017). Social scientists develop broad narratives of potential socio-economic futures including population dynamics, economic growth, urbanization, political circumstances etc. that are subsequently quantified and incorporated as exogenous parameter inputs by modelers. The merging strategy is based on the idea that at least to some degree social processes can be dynamically and quantitatively captured by models. This would require intensive cooperation of social scientists and modelers and result in structurally modifying existing models or constructing entirely new modelling concepts. (Trutnevyte et al., 2019)

While these three different options describe methodological strategies for integrating social dynamics into climate economic models, scholars have also taken on the challenge to develop meta-theoretical frameworks which try to stake out the problem from a content perspective. Two major publications are authored by Cherp, Vinichenko, Jewell, Brutschin, and Sovacool (2018) and Grubb, Hourcade, and Neuhoff (2015). Cherp et al. (2018) argue that the three factors, economic development, technological innovation and policy changes are key in shaping energy transitions. These factors can only be integrated by combining several academic perspectives and disciplines, namely *techno-economic* represented by energy system analysis and neo-classical economic thought (this refers to the current IAMs), *socio-technical* with roots in sociology of technology (STS) and evolutionary economics and lastly, *political* represented by political sciences. According to the authors, techno-economic IAMs are especially limited in representing innovation dynamics of new technologies and dynamics of policy making. Two factors that are arguably governed by what can be described as social dynamics and are highly relevant for understanding energy transitions. This is shared by another early publication arguing that energy transitions are a process of technological innovation that can be facilitated or impeded by social factors (Jacobsson & Johnson, 2000). Based on these considerations Cherp et al. (2018) then lay out an analytical framework that allows to analyze national energy transitions. It is inspired and guided by Elinor Ostrom's framework approach where she calls for identifying and organizing relevant variables into "nested conceptual maps" in order to understand complex systems consisting of various subsystems (Ostrom, 2005, 2007, 2009). In the second paper, Grubb et al. (2015) observe that there is large divide between the sustainability transition and innovation systems literature and the neoclassical IAM community using these telling words: "it almost seems as though processes of social and technological change and transformation exist on a different planet from that which spawned the dominant branches of mainstream economic thought and modelling". The authors argue that this failure in integrating and acknowledging the different theoretical approaches in their distinct domains explain and cause to a certain degree the up-to-date failure of delivering adequate and effective policy. They identify three domains of theory in economics that are relevant for energy transitions and that respectively, derive equally important but different policy implications: behavioral economics, neoclassical economics and evolutionary economics. While neoclassical economics study markets and prices usually under the assumption of perfectly rational decision-makers, behavioral economics deliver insights on behaviors and decisions of individuals that fall short with regard to economic efficiency such as bounded rationality (Simon, 1955, 1959) or herding (Banerjee, 1992). Evolutionary economics in the tradition of Schumpeter's "creative destruction" (Schumpeter, 1934) cover theories of innovation dynamics and systems that are often characterized by non-linear and feedback dynamics between industry and consumer preferences. While the second domain (neoclassical economics) treat first and third domain processes often as "market failures", Grubb et al. (2015) insist for acknowledging them as socio-economic processes that need to be understood in their own right rather than being seen as errors to fix. They further argue that the dynamics of energy transitions are governed by decisions on multiple levels such as short-sighted individual consumers and their directly facing companies, investment and procurement decision-makers in early/middle supply-chain companies and long-term strategic decision-makers in public authorities or multinational business organizations. This takes into account adaptive, disaggregated and robust decision-making as well as collective responses to changing environments and management policies (Lempert, Scheffran, & Sprinz, 2009; Scheffran, 2008). Therefore, different types of policies are needed to address the respective decision level in order to change course. A similar result is revealed by an extensive review of mechanisms that are not covered by IAMs but are expected to play an important role in climate policy by Staub-Kaminski, Zimmer, Jakob, and Marschinski (2014). They determine three distinct clusters of "obstacles" for the implementation of least-cost climate policy namely demand-side obstacles linked to governments and institutions (political economy etc.), supply-side obstacles which cover households and firms (individual behavior etc.) and market distortions (imperfect innovation markets etc.).

While delivering important insights on which societal processes, dynamics and academic theories might play a role in energy transitions and how they are conceptually interrelated, these meta-theoretical frameworks are not capable of delivering concrete and quantitative entry points for modelling. However, the Potsdam Institute for Climate Impact Research's copan:CORE project developed a vision for so-called "World-Earth models" that integrate not only the climate system (biophysical taxon) and the economic system (socio-metabolic taxon) but also human societies (socio-cultural taxon) as an explicitly modelled part. Their illustration of this modelling vision gives a vivid overview of what the overall idea is (see Figure 2) (Donges, Heitzig, et al., 2018). They argue that since the Anthropocene arose in the late 18th century (Crutzen, 2002), the dynamics of the earth system are fundamentally governed by two forces: the biogeochemical processes of the planet and the processes of human societies, in particular their economies and cultures. Hence, in order to derive relevant insights on pathways and policies that lead into a safe-operating space for humanity within the planetary system (Rockström et al., 2009), science needs to develop holistic, quantitative models which in particular endogenize socio-cultural processes.

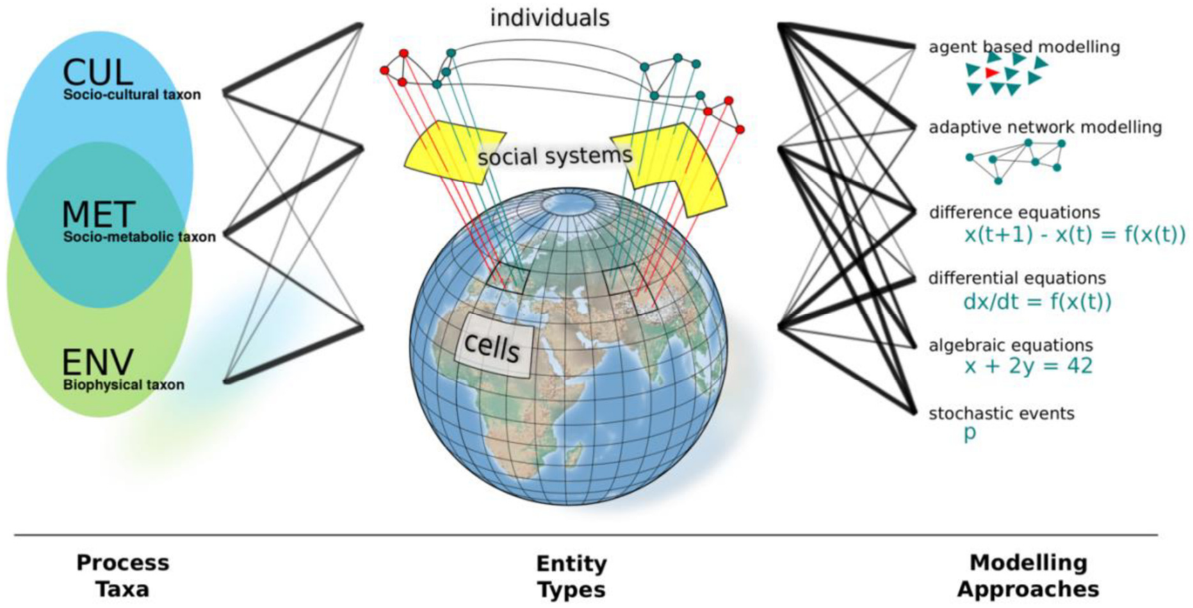

Figure 2: Illustration of "World-Earth models" that integrate not only the climate and the economic system but also the social system as an explicitly modelled part. Adapted from Donges, Heitzig, et al. (2018)

copan:CORE offers an open source modelling framework calling for cooperation among scientist from different groups to contribute on this Herculean task. In the paper by Donges, Heitzig, et al. (2018), a simple (dummy) World Earth model is presented that incorporates besides a representation of the global carbon cycle and the economic system some dynamics of social systems that are relevant for the integrated environmental dynamics. It is assumed that global society's individuals express an opinion variable regarding environmental awareness/friendliness which is continuously updated due to randomly occurring environmental impacts. Furthermore, individuals' opinions are influenced by others through social learning processes. A feedback loop from this opinion formation in society to affecting carbon emissions is implemented by every four year election events that might induce climate policy instruments if large enough fractions of society express environmental friendly opinions. Figure 3 illustrates the graphs of the performed model runs. While the results must be regarded as exploratory in nature without meaningful quantitative relevance, they show how such socially enhanced quantitative model outcomes might look like. Another paper in preprint lays out further ideas on a modelling taxonomy for these World Earth models and what potential interactions of the three different taxons (biophysical, socio-metabolic, socio-cultural) might be (Donges, Lucht, et al., 2018).

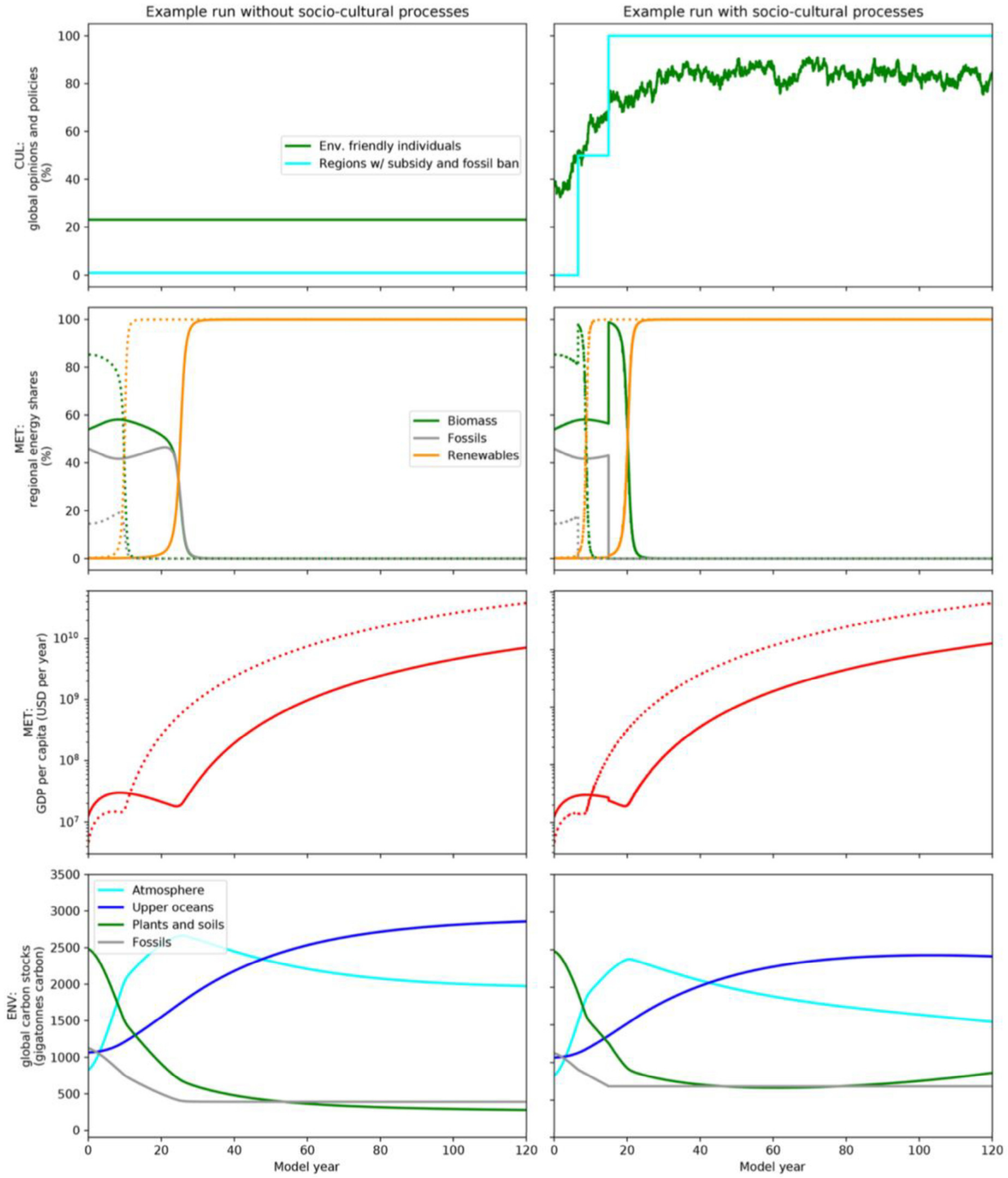

Figure 3: Results from a dummy World Earth model including socio-cultural processes with regard to social learning, environmental awareness and voting on climate policy. Adapted from Donges, Heitzig, et al. (2018)

While Donges, Heitzig, et al. (2018) start directly with the holistic and maximum vision of World Earth models that in principle aims at integrating all relevant processes within the planetary system, the previously mentioned paper by Staub-Kaminski et al. (2014)

call for starting from IAMs and enhance them towards their identified three areas of obstacles. This endeavor would then lead to what they name "Integrated Policy Assessment Models". They mention the PRIDE model presented by Kalkuhl, Edenhofer, and Lessmann (2012) as a precursor of this endeavor or at least as a first step in the right direction. The model going by the name "Policy and Regulatory Instruments in a Decentralized Economy" is constituted by utility maximizing households, profit-maximizing businesses in several sectors relevant for climate-energy policy questions, a carbon-budget bank issuing emission allowances and a government that has several policy options at its disposal such as taxes, subsidies or feed-in-tariffs. Furthermore, market failure dynamics such as innovation spillovers or discount rate mark-ups due to e.g. insecure property rights or risk premiums in certain sectors are included. Consequently, the model allows to study optimal government behavior in the face of a climate constrained and by several market failures distorted economy (Kalkuhl, Edenhofer, & Lessmann, 2013). More information on the PRIDE model can be found here:

https://www.pik-potsdam.de/en/institute/departments/transformation-pathways/models/pride/pride-policy-and-regulatory-instruments-in-a-decentralized-economy .

Another conceptual starting point for the model coupling of social dynamics and climate economic scenarios stems from the framework of "shared socio-economic pathways" (SSPs). IAM builders need to include assumptions on various societal parameters and their development trajectories over time in order to give models a relevant real-world calibration. Societal parameters in this respect are for example population growth, economic growth, globalization dynamics, environmental awareness, technological change and innovation dynamics or global institutional strength. They are estimated and then exogenously included into the IAM. The IAM community has defined five distinct SSPs ranging from "Sustainability" (SSP1) over "Middle-of-the-Road" (SSP3) to "Fossil-fueled Development" (SSP5) (Bauer et al., 2017). Social dynamics enhanced climate policy models would now aim for dynamically endogenizing these parameters.

One completely different, heavily practice oriented and very pragmatic approach trying to acknowledge the relevance of social dynamics in the plausibility of climate economic scenarios is presented by Schmid and Knopf (2012). During consecutive dialogues, relevant stakeholders for the energy transition towards decarbonization are confronted with model inputs and model outputs from a standard optimizing IAM. The received feedback from the stakeholders is then used to further refine the model scenarios as well as to select the scenarios that might be feasible with regard to societal requirements.

3 Agency and Intervention Points

One of the most relevant questions if one thinks about representing social dynamics in climate economic models might be the topic of where agency on the relevant decisions lies and automatically as a consequence, what are relevant intervention points. In the techno-economic (neoclassical) world of Integrated Assessment Models agency is almost exclusively assumed to lie in the hands of policy makers. And the policies employed by the policy makers appear as external, exogenous and costless, normative targets rather than being product of a dynamic political process (Cherp et al., 2018; Staub-Kaminski et al., 2014). According to the fully rational decision maker paradigm prevalent in the current models, each of the myriad decisions made on investment or consumption by companies and consumers are the result of a cost-minimizing decision process in order to fulfill static (exogenous) preferences. Thus, decisions other than the imposed policy might be seen as a passive outcome of the existing market, technology and preference setting. Consequently, in techno-economic IAMs agency and the intervention point is concentrated on the chosen policies which aim at changing the market setting by prices, technology standards, subsidies or bans (Trutnevyte et al., 2019). The necessary change of the myriad decisions on all levels in the economy in order to move the system towards climate stabilization goals is then the automatic result of the cost-minimizing process in each individual confronted with a changed, exogenous economic landscape.

Both, meta-theoretical frameworks described in the introduction by Cherp et al. (2018) and Staub-Kaminski et al. (2014) make clear that various empirical evidence on different effects exists which prove this assumption to be limited, especially with regard to individual consumption decision (behavioral economics), innovation dynamics (evolutionary economics) and dynamics of policy making. This in turn means that there are many more levels of decision making that exert agency on transformation pathways of the energy system and consequently, many more intervention points.

First of all, it is helpful to provide a meaningful definition of agency. Following Pattberg and Stripple (2008), human agency describes the capacity of individuals or collective actors to change the course of action or the result of processes. With respect to the Earth system, Dellas, Pattberg, and Betsill (2011) understand human agency as the capacity of reacting to earth system transformations and to produce changes of action which shape natural processes in the biogeochemical sphere of the planet. This capacity eventually emerges as “governance of the Earth system”. However, this agency can hardly be understood as one atomistic decision making entity which acts and decides like a global dictator but is rather characterized by complex social, economic and natural dynamics moving up from local to global scale, through uncountable economic, social and political institutions and organizations and so on. Governance involves multi-agent and multi-level decision-making that combines top-down approaches of institutions on global targets for emission reductions and bottom-up approaches of local agents such as citizens, consumers, and companies taking actions according to their interests. Global and local levels can potentially lead to conflict but also bridge micro-macro interactions across the meso level (Lempert et al., 2009). Academics in the Earth system analysis have proposed descriptions of these cumulated human processes, e.g. Schellnhuber (1999). He introduces the idea of a “global subject” that emerges from the collective actions of a self-conscious humanity. It manifests itself in global agreements on human rights, trade regulations or environmental protection agreements. However, it is clear that this global subject is still highly abstract in nature and only rarely appears to exert real agency so far.

Otto, Wiedermann, et al. (2020) published an important analysis on the subject of human agency in the Anthropocene. From reviewing extensive literature in the social sciences they identify several layers of agency that are relevant for governing Earth system processes. Figure 4 illustrates four different dimensions of agency spanning a system of coordinates which builds an ordering system for relevant social phenomena. Concepts by Lister (2003) and Coulthard (2012) draw the x-axis ranging from everyday agency to strategic and political agency. The former describes the daily decision-making “around how to make the ends meet” while the latter is related to long-term planning and strategies including the capacity to affect the political and wider sphere. Hence, the x-axis might be understood as the weight of decisions on which agency is exerted. The range of the y-axis stems from work by Bandura (2006) who differentiated between individual agency and collective agency. Obviously, this refers to the number of people that need to be coordinated in order to gain agency on the respective decisions ranging from one person (individual) to large groups up to globally organized bodies (e.g. G8/20, UN, international corporations).

Now, several social phenomena can be assigned into this systemization according to their characteristics. For example, consumer choices and preferences are an expression of everyday agency (low-weight decisions, short term etc.) and individual agency since they are influenced mostly by single persons or small groups (e.g. family). Voting in a democratic election assigns agency on high weight and long-term decisions (strategic and political agency) to each individual citizen. Social movements are a type of strategic and political agency that requires a high level of coordination among a large group of people (collective agency). Like this, the long list of social phenomena described in the social science literature can be classified.

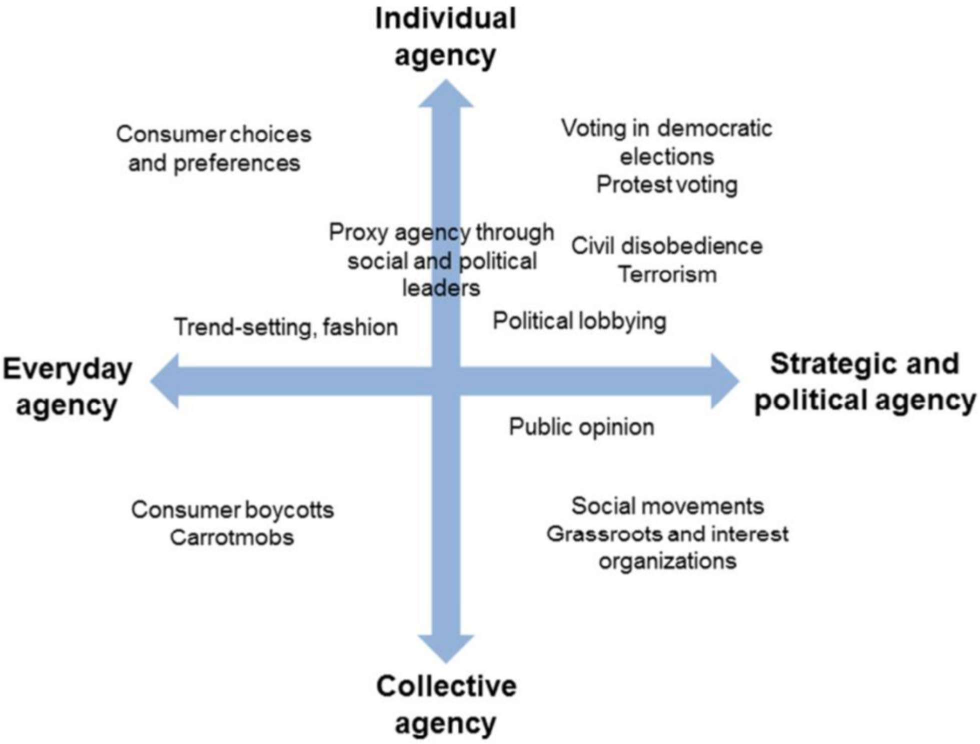

Figure 4: Representation of several agency dimensions in human systems. Adopted from Otto, Wiedermann, et al. (2020)

Moving forward from these insights on different levels of agency which also correspond to intervention points, Otto, Wiedermann, et al. (2020) make several suggestions on how these plural agency levers might be picked up by IAM efforts. First, they argue that the different agency levels are related to different layers of social structure. Following Williamson (1998), three main layers are identified: 1. Institutional which is further differentiated in informal rules (norms, religion, culture etc.) and formal rules (constitutions, judiciary etc.). 2. Organizational (governance structures, networks, organizations) 3. Technosphere (infrastructure, technology). Then, they further argue that these different layers are not distributed equally among people and thus, agency is not distributed equally. The authors suggest (instead of the usually used Marxian or Weberian class theories) the introduction of the socio-metabolic profile as a proxy for levels of agency (Martinez-Alier, 2009). Regarding these heterogeneities and social linkages, Otto, Wiedermann, et al. (2020) claim that models need to introduce different types of agents with different goals, opinions and preferences. Furthermore, the agents need to be organized in networks that represent the various and heterogeneous linkages and influences. Relevant, existing modelling concepts are suggested to be the voter model (Clifford & Sudbury, 1973; Holley & Liggett, 1975), the Axelrod model (Axelrod, 1997), the VIABLE model (Bendor & Scheffran, 2019) or network models (Costa, Rodrigues, Travieso, & Villas Boas, 2007).

A paper by Otto, Donges, et al. (2020) makes a significant contribution to identify some social dynamical processes that can be expected to be relevant for the global transformation towards a sustainable human system. It is a matter of facts that reaching a 1.5 °C temperature goal as outlined in the Paris agreement demands net-zero emissions around 2050 which implies unprecedented reduction rates in fossil fuel consumption and other economic processes. Therefore, the authors focus on so-called social tipping dynamics or elements. These subsystems are characterized by the possibility that small changes or intended interventions in the system parameters can trigger enormous (non-linear) transformations in the subsystem and the wider system through positive feedback mechanisms. Social tipping elements usually manifest themselves in spreading processes in complex social networks of behaviors, opinions, knowledge, technologies and social norms. By conducting expert interviews and an extensive literature review. Otto, Donges, et al. (2020) reveal a list of six social system elements that satisfy the outlined requirements. 1. The energy production and storage system. Intervention measurements are subsidy programs that terminate subsidies for fossil fuels on the one hand and increase subsidies for fossil-free technologies on the other hand as well as the construction of decentralized energy systems. 2. Human settlements could be developed to carbon-neutral cities. 3. Financial markets start divesting massively from fossil fuels. 4. Norms and value system. Human societies might become aware of the immoral character of fossil fuels. 5. The education system could trigger a wide-spread awareness of the climate change issue through climate education and engagement. 6. Information feedback by declaring carbon emission footprints on consumption products. Similar suggestions are made by Farmer et al. (2019) who use the term “sensitive intervention points” with more or less the exact same meaning. They name three examples of intervention points that cause these non-linear feedback effects. First, new regulations for financial disclosure of companies and firms with regard to climate risks. Second, support for low-carbon energy technologies would non-linearly amplify deployment due to positive feedback effects arising from learning/experience curves. Third, political mobilization for ambitious climate policy might be accelerating fast if a large but silent majority of support is triggered by committed political entrepreneurs. In order to understand, predict and trigger these type of non-linear system dynamics, the authors call for fine-grained complex system models of the economy and technological change that are coupled with models of opinion dynamics and of financial and legal systems. A similar call is made in Farmer et al. (2015) who identify two model paradigms that have the potential to fulfil the mentioned requirements: dynamic stochastic general equilibrium (DSGE) models or agent-based models (ABM) (Czupryna, Franzke, Hokamp, & Scheffran, 2020; Weber, Barth, & Hasselmann, 2005).

A very tangible case for an intervention point for climate policy other than price and technology options is provided by a study by Dietz, Gardner, Gilligan, Stern, and Vandenbergh (2009). They investigate the potential for emission reductions due to behavioral changes in US households. Identifying 17 household action types in 5 behaviorally distinct categories offers the potential of a total of 7.4 % reduction of US nationwide emissions without or little decrease in household well-being. This includes for example upgrade of heating and cooling equipment after its useful life, maintaining equipment in order to elongate its lifetime, decrease laundry temperatures or eliminating stand-by electricity consumption. The most effective levers for triggering change in these areas combine mass-media messages, household- and behavior-specific information and communication through social networks and communities. There are numerous other studies providing information on this topic e.g. Carrico et al. (2015), Abrahamse, Steg, Vlek, and Rothengatter (2005), Abroms and Maibach (2008).

As outlined in aforementioned conceptual papers on agency and intervention points, gaining support for climate policies or in other words determining the dynamics of political mobilization is an important part. Lamb and Minx (2020) provide an empirical analysis on political economy constraints that hinder or challenge the implementation of climate policy. They identify several factors that show consistent correlations with the absent of necessary climate policy stringency: fossil fuel extraction activities, supply-side coal dependency, a lack of democratic norms, exposure to corruption, a lack of public climate awareness, and low levels of social trust. By employing cluster analysis they are able to differentiate 5 types of countries that share characteristics with regard to these factors and build distinct “architectures of constraints”. These are (1) oil & gas states, (2) fragile states, (3) coal-development states, (4) fractured democracies and (5) wealthy OECD. Based on their data, they see strong co-dependencies across these factors which leads to the conclusion that they might be mutually reinforcing and highly resistant to intervention. Quoting the authors opens up again the fundamental necessity of understanding social (and here in particular political) dynamics in Integrated Assessment modelling: “It is important to have a clear-eyed view of these political economic challenges. If one cannot simply mobilize political will and technocratic skill to advance climate policy – because these ingredients are purposefully absent – then what are realistic intervention points?”. One particular idea of climate policy making that deals with constraints of political support and policy implementation is described by policy sequencing (Meckling, Kelsey, Biber, & Zysman, 2015; Meckling, Sterner, & Wagner, 2017; Pahle et al., 2018). This idea proposes based on historical evidence for example in Germany that green industrial policy is an expedient entrance into climate policy action. While being considered a less-optimal/efficient solution by economists, green industrial policy might be easier to be implemented by governments since it does not penalize polluters but support some industries and therefore, causes less opposition. The subsidized and consequently, growing green industries start to employ more and more workers and build itself an increasing lobbying force that could allow the implementation of more efficient and stringent climate policy instruments such as carbon prizing later. This type of positive feedback loops within political dynamics is a good example for social mechanisms that might be incorporated in more holistic “Integrated Policy Assessment Models”.

3.1 Social norms & Social Learning

There are two types of social processes that might represent relevant intervention points and that have experienced some special traction in social modelling efforts with regard to the climate problem and hence, deserve elaboration in more detail. These are social norms on the one hand and social learning on the other, though, both are closely related and often treated hand in hand in the existing publications.

Social norms are usually defined as “learned behavioral standards shared and enforced by a community” (Chudek & Henrich, 2011). The dynamics of emerging social norms are described by a dual-inheritance theory that sees pro-social behavior, e.g. norms, as the result of co-evolutionary processes of culture and genes (Chudek & Henrich, 2011; Davis, Hennes, & Raymond, 2018). According to Davis et al. (2018) norms are culturally inherited modes of behavior, while the motivation for following and enforcing norms is genetically enshrined. The process of transmittance of social norms horizontally and vertically through generations is called social learning. Social psychological science usually distinguishes two types of social norms: descriptive norms and injunctive norms (see Figure 5).

While descriptive norms are related to the perception of behavior that is typically *performed* and can be explained by people following heuristics in a self-interested way, injunctive norms refer to the perception of what behavior is typically *approved/disapproved* according to the moral standards of a group (Cialdini, 2003). Clearly, with regard to pro-sustainable behavior both types of social norms play an important role whether it is impeding descriptive norms due to prevalent car use in cities (Creutzig et al., 2020) or the supporting role of injunctive norms with regard to less-meat dietary changes in Western countries (Sanchez-Sabate & Sabaté, 2019).

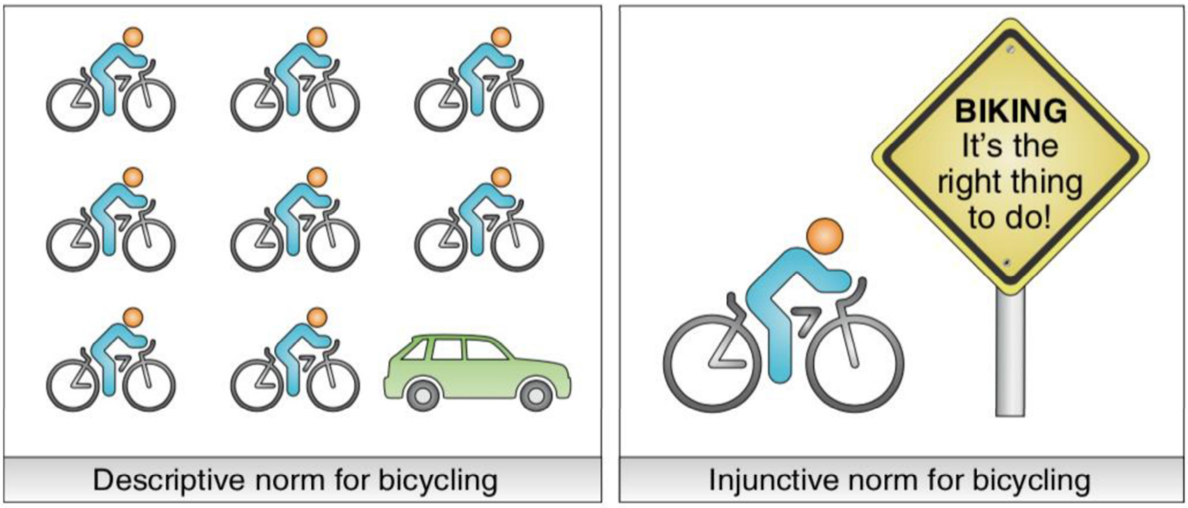

Figure 5: Illustration of descriptive and injunctive norms using bicycling as example. Adopted from Davis et al. (2018)

Looking at characteristics of intervention points regarding social norms, Davis et al. (2018) argue that it is highly relevant to understand the complex dynamics of instrumental and intrinsic motivations that give rise to social norms. Instrumental motivation for normative behavior arises due to incentives or penalties while intrinsic motivation is induced by one's own perception to do the "right" thing. Countless empirical studies on the success of policy-norm interventions draw a very unclear picture. Sometimes external incentives cause intrinsic motivation to be crowded out, sometimes they are successful in internalizing social norms that then prevail even after the incentives are expired (Davis et al., 2018). Therefore, also other scholars repeatedly called for initiatives to better understand this policy-behavior-norm nexus (Kinzig et al., 2013). Usually, policy interventions aiming at inducing behavior change through social norms are either in the area of incentives/punishments or education (Allcott, 2011; Nyborg et al., 2016). However, due to the uncertain and complex feedback or boomerang mechanisms that are involved in the dynamics of social norms, Davis et al. (2018) argue for more diverse experiments and emphasize the important role of opportunities for social learning in order to support the emergence of wide-spread norm change. They mention the opportunity for governments to open up space for so-called "model communities" where a small group of people can, while protected from the norm sanctions from the wider society, develop new modes of behavior and social norms that might then diffuse into the mainstream (Bicchieri, 2016). Another interesting mechanism that might make social norm interventions successful is reported by Blondeel, Colgan, and Van de Graaf (2019) who studied intensively two norm campaigns by environmental NGOs and other activist groups on subsidy reform of fossil fuel consumption and financial divestment from fossil fuel activity. They find more success in the campaigns when the goal is linked to or reframed as to solve other goals of policy makers, in particular economic ones such as fiscal stability.

A global and political perspective on the issue of social norms is investigated by Green (2018a). He coins the term anti-fossil fuel norms as a global moral imperative and social consensus that might emerge similarly to other global norms such as the condemnation of nuclear weapon testing, slavery or waging aggressive war. All of these practices were once and often for much of human history the regularity and are now seen as morally wrong by the majority of the population. Green (2018a) sees the establishment of a global anti-fossil fuel norm as a prerequisite for a political landscape that is able to introduce stringent climate policies. In another article, he then argues further that bans on fossil fuels are an effective measure of countries already in favor of ambitious climate mitigation goals to signal the morally wrongness of unlimitedly burning of fossil fuels (Green, 2018b). This clear statement would impose high social costs on all states that do not conform with this moral obligation. In Green (2018b)'s view, it is this transparency of bans on fossil fuels that justify their propagation, because other more economically efficient climate policy measures such as carbon prizing are silent to the moral quality of fossil fuels. This is an illustrative example of how taking into account mechanisms of social dynamics might lead to significantly different policy implications compared to those derived from current Integrated Assessment Models.

Despite the obvious complexity of representing dynamics of social norms and social learning in quantitative modelling efforts, there are several noteworthy approaches in the literature. Schleussner, Donges, Engemann, and Levermann (2016) suggest a complex, adaptive network model that simulates the co-evolution of individual behavior and the social network structure regarding smoking behavior. Smoking behavior is an intensively studied area with regard to social dynamics, social learning and norms which provides a comprehensive basis for empirical data and testing modelling approaches (Christakis & Fowler, 2008; Nyborg & Rege, 2003). The endogenously modelled binary variable smoking/non-smoking behavior is determined by both individual disposition and the social influence/learning from social interactions. The latter is modulated by the social network characteristics which are endogenously determined in the model as well. Social influence dynamics are modelled following an Ising-type approach which was described by Kohring (1996). The individual disposition is understood as culturally transmitted norms, values, knowledge or slowly changing collective contexts and exogenously determined. Hence, the model allows to investigate dynamics of individual behavior change and the interdependent restructuring of the social network by imposing gradually changing norms. During this exogenously forced societal transition, the model observes reduction of smoking numbers, but more importantly resolves the dynamics of increasingly clustered groups of smokers who increasingly preferred to stay within this group. This result is in congruence with the empirical finding and hence, the authors argue that these type of models might be used for understanding and forecasting other areas of socially determined behavior such as pro-environmental behavior (Schleussner et al., 2016).

Several publications that try to couple the social system and the natural system and explicitly model social dynamics have emerged around the Theory of Planned Behavior by Ajzen (1991). This theory represents a dominant paradigm in psychology explaining human behavior and its change and is often referred to by the social sciences work around climate change and pro-environmental behavior (Engels, 2016). According to the theory, people's behavior is determined by their intentions regarding this behavior and more importantly, the intentions towards a certain behavior are governed by the person's attitude about the behavior, the perceived behavioral control a person feels about executing the behavior and the perceived social norm that society has developed towards the behavior. These functional relations are illustrated in Figure 6 which is the full model visualization of a coupled climate social model (CSM) developed by Beckage et al. (2018).

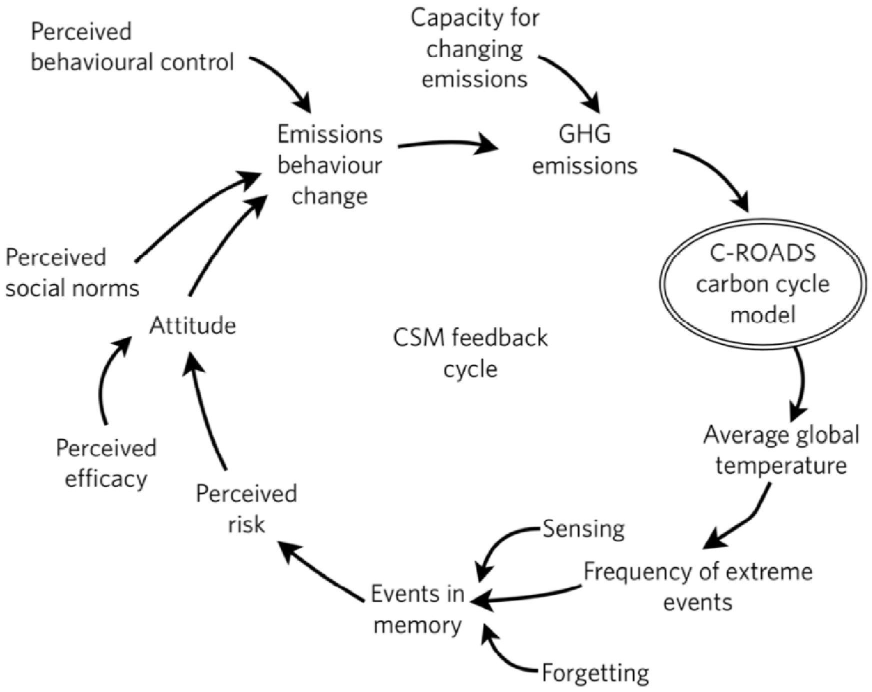

Figure 6: Illustration of the effect and feedback mechanisms in Ajzen's Theory of Planned Behavior coupled to a simple climate model. Adopted from Beckage et al. (2018)

They embed the attitude variable in a feedback cycle from the climate model which generates a frequency of extreme weather events linked to changing GHG emissions. The number of extreme events is further processed by an individual’s memory that senses them but also forgets them over time and by the perceived risk that arises from these extreme events. Due to missing empirical information on parameters and concrete functional relations, the authors test a wide range of parameter values and several functional forms, altogether close to 800,000 simulation runs. Hence, the results are only explorative by nature but show that the temperature uncertainty arising from the social reaction to climate change is on the same level (2.8 °C) as the uncertainty from the physical processes (3.5°C). An analogous modelling endeavor was performed by Eker, Reese, and Obersteiner (2019) in the area of food consumption and dietary change.

A further step in the area of coupled socio-climate models that incorporate social norms and learning is provided by Bury, Bauch, and Anand (2019). While the previous presented two publications treat social norms and learning as exogenously imposed parameters, they try to develop a mathematical representation for these dynamics. The population is divided into mitigators and non-mitigators. For each behavioral category, the model calculates a utility function that includes costs for mitigating behavior, costs from a carbon tax for non-mitigators, costs from climate damages and a non-monetary cost parameter that arises from social norms and depends on the fraction of mitigators/non-mitigators, respectively. From this, each individual calculates a behavioral strategy that is more favorable for him. Behavioral change from mitigator to non-mitigator and vice versa is due to a certain probability which is proportional to the utility difference and further influenced by a social learning parameter that is proportional to the number of mitigators in the population due to a social contact logic. What follows is a net rate of behavior change from mitigators to non-mitigators or vice versa that is mainly determined by a carbon tax, the social learning rate and the effect of social norms. While the social learning rate offers a positive feedback loop towards mitigating behavior, social norms impose a two-sided effect. If social norms are strong, they represent a strong impediment for newly emerging mitigating behavior but on the other hand, can act as a stabilizer if mitigating behavior is established. As in the previous publications, the main problem is caused by missing empirical information on the parameter values for social processes. Still, the approach by Bury et al. (2019) shows how concrete social processes can be mathematically formalized and integrated into models of the earth system.

4 Demand-side Mitigation Options

One major shortcoming of the above presented explicit modelling efforts of social processes in climate mitigation models lies in the question how does a mitigation attitude and behavior translate into concrete GHG reduction decisions. The models just assume for a growing fraction of mitigators in the population a certain amount of GHG reduction without resolving what the changed production or consumption behaviors are. Besides others, one relevant entry point that provides a valuable linkage here might be the area of demand-side mitigation options. Demand-side mitigation represents in itself an under-investigated area of climate change solutions (Creutzig et al., 2018). While the early Integrated Assessment models considered the assessment of climate mitigation almost exclusively as a supply-side problem by looking at a generic consumption good that is produced requiring a certain amount of energy which can be provided by an increasing amount of renewable energies instead of fossil fuels through technological change or supply-side investments in energy efficiency (Edenhofer, Bauer, & Kriegler, 2005; Nordhaus, 1992), more recent model developments at least offer some exogenous parameters that can mimic demand changes as mitigation options especially in the food sector (Popp, Lotze-Campen, & Bodirsky, 2010).

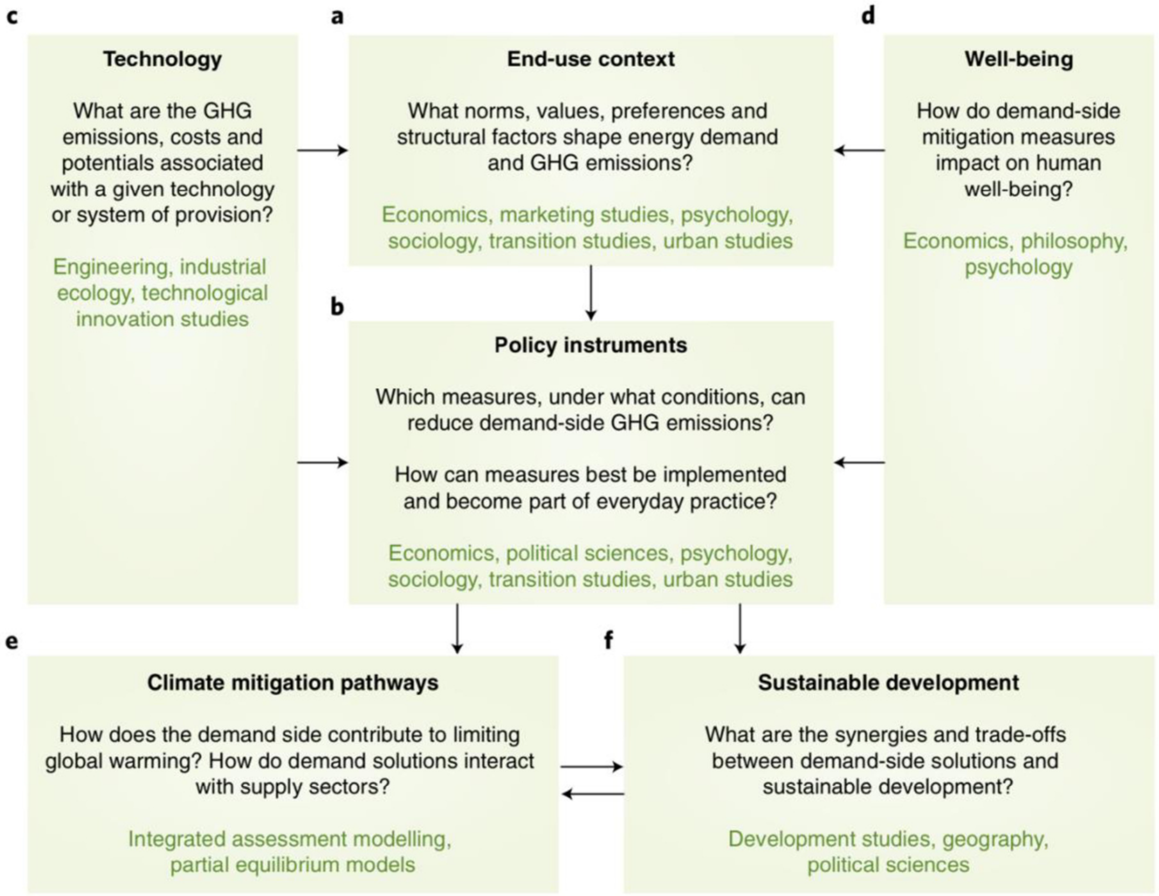

Figure 7: Relevant research questions and scientific disciplines for a research agenda on demand-side climate mitigation options. Adopted from Creutzig et al. (2018).

Still, the area of demand-side mitigation options is highly under-explored and under-represented in research and modelling efforts, especially when looking at the existing potential for emission reductions (Creutzig et al., 2016). Therefore, Creutzig et al. (2018) call for a transdisciplinary research initiative that explores demand-side mitigation options by identifying relevant options in the first place, investigate their mitigation potential, design policy measures and assessing their impact on human well-being (see Figure 7). Creutzig et al. (2016) make a comprehensive contribution in collecting a list of relevant demand-side mitigation options and their potential for reducing GHG emissions in the sectors of transport, buildings and agriculture/land use. For example, behavioral and infrastructure interventions in cities have the potential to reduce GHG emissions from urban passenger transport by 20-50 % until 2050 (Creutzig, 2016).

Overall, most demand-side mitigation options rest upon the assumption that human preferences are prone to changes. This is in fundamental opposition to the standard economic assumption that preferences are fixed and that choices on consumption or demand patterns are only governed by changes in the households budget or changing prices of the available goods (Mattauch & Hepburn, 2016). However, many scholars argue and much empirical evidence is established that preferences are highly influenced by cultural transmission which happens through the social process of learning (Bowles, 1998). An often named and empirically intensively studied issue with regard to endogenous preference formation is the people's preference for modes of transport in correspondence to the built environment or infrastructure. Even people moving from an area with good public transport to a city with car-dependent transport infrastructure export their mobility habits in favor of public transport (Cao, Mokhtarian, & Handy, 2007; Weinberger & Goetzke, 2010, 2011). This has serious consequences for the assessment of climate mitigation options as is comprehensively outlined by Mattauch and Hepburn (2016). They investigate the special case of climate policy interventions itself having an effect on people's preferences but the consequences hold true for all the other influences on preferences such as changing social norms, social learning, cultural evolution etcetera. Taking the mobility infrastructure example: if a climate policy measure consists of rebuilding a cities mobility system away from gasoline-fueled individually owned cars towards cycling infrastructure and public transport, cost-effectiveness analysis within the current IAM paradigm (fixed preferences) would account for the opportunity costs that arise from people's decreased fulfilment in the preference of driving one's own car. However, if one acknowledges that preferences change with the mobility environment, the opportunity costs are reduced or even vanish. Consequently, policy assessment assuming fixed preferences would systemically over-estimate the utility costs of the respective policy measure and as a consequence suggest higher carbon prices than actually needed. It must be added, that the preference change might also occur in the opposite direction maybe by citizens who feel patronized by the political measures and develop strong opposition against the new system. However, it must also be mentioned that in the endogenous preference paradigm any decision on the infrastructure including the decision on leaving it as it is, plays on the preferences. This discussion on paternalism in nudging theory from behavioral economics is intensively debated (Sunstein, 2015). Clearly, understanding processes of preference formation and influences from various factors is exactly the type of social dynamics that must be understood by targeted models in order to do justice to their significance in assessing climate mitigation options.

Hence, making preferences and consequently demand-side mitigation options an endogenous variable might provide a practical linkage point for models of social processes (e.g. opinion formation, cultural evolution, social learning, social norms etc.) to the current Integrated Assessment Models. The conceptual linkages might look like this: an alternative intervention action such as an information campaign or norm entrepreneurs shape values, norms and consequently preferences of the wider population for example in dietary options (less meat), more cycling in cities, wooden homes instead of cement or choosing local vacation options over ones requiring long distance flights. These changes in preferences would then feed back into the macroeconomic dynamics of the neoclassical IAM.

There are some efforts in the IAM community to start representing demand-side mitigation options in transformation scenarios that are in accordance with a 2 °C or even 1.5 °C climate target. van Sluisveld, Martínez, Daioglou, and van Vuuren (2016) present a study that considers exogenous lifestyle changes especially in the buildings and transport sector and investigates the consequences for the overall transformation pathway. They utilize the integrated assessment model IMAGE which provides relatively granulated resolution in energy demand processes. This allows for concrete adjustments in the model parameters in correspondence to certain lifestyle or behavior changes. This goes down to measures such as temperature change in space heating, reducing household dimensions, reduction of shower duration, switching off standby in electronic appliances, reduced vehicle use and mode shift to public transport and several more.

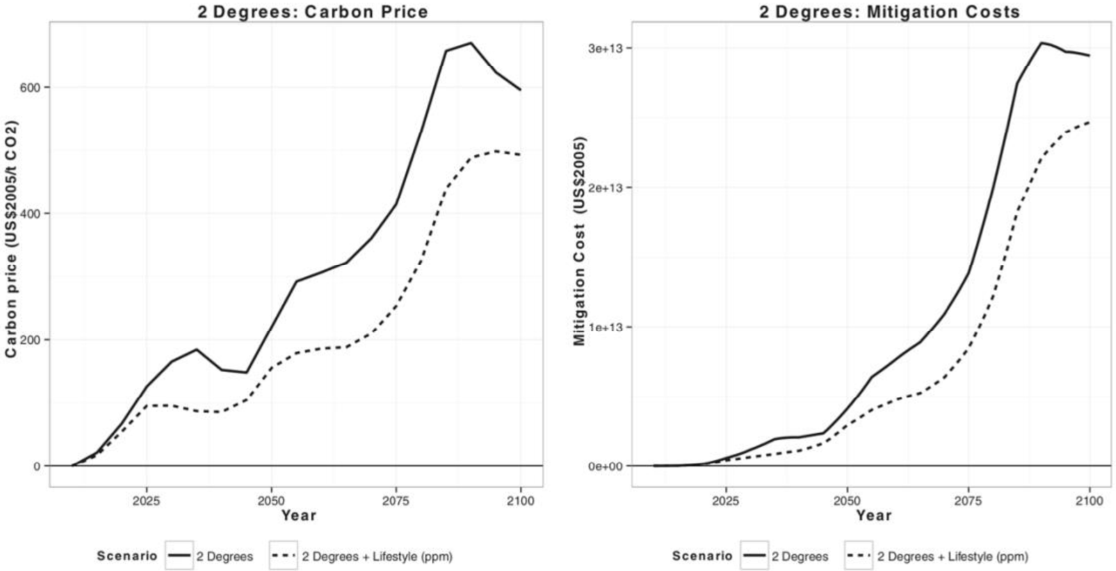

Figure 8: Comparison of carbon prices and mitigation costs in a 2 °C scenario with and without lifestyle changes. Adopted from van Sluisveld et al. (2016)

In IMAGE, overall climate targets such as 2 °C are ensured by imposing a global, uniform carbon price. In their paper, van Sluisveld et al. (2016) then compare a scenario without lifestyle changes that fulfills the 2 °C carbon budget and a scenario including the exogenously implemented lifestyle changes. Not surprisingly, carbon prices remain lower over the entire century and more importantly, mitigation costs are significantly reduced (compare Figure 8). This is due to the fact, that emission savings from the lifestyle changes open up space for less radical mitigation measures in sectors where such interventions might be expensive. However, important to keep in mind, mitigation cost reductions are expressed under the assumption that the lifestyle changes occur without any cost for people or policies. Other publications point out that transformation scenarios, which enforce decreased energy demand for example (but not exclusively) by lifestyle changes, provide a great opportunity for avoiding or at least reducing the necessity of negative emission or carbon dioxide removal (CDR) technologies. These are characterized by large cost and realization uncertainties and so far, face strong social acceptance problems (Grubler et al., 2018; van Vuuren et al., 2018).

A particular important contribution to represent preference characteristics in IAMs is made by McCollum et al. (2018) in the area of low-carbon vehicle adoption. The authors argue that consumer purchase decisions of vehicles are only partly explained by financial considerations. Many more intangible preference characteristics play an important role such as available models and brands, perceived risks, comfort, acceleration, cargo and interior space and towing capability. Especially BEVs further induce range anxiety problems. By only considering cost factors the current IAMs would make grossly misleading assumptions on future low-carbon vehicle uptake and derive wrong conclusions on policy measures, according to the authors. They employ a global and comprehensive empirical dataset on people's preferences which show significant differences across countries and cultures. The intangible factors are translated into monetary values and then incorporated into the model equations of six leading global IAMs. This approach was tested earlier for one model (McCollum et al., 2017) and is here applied to more models in order to gain diversified insights. In order to assess the effect of intangible preference factors with regard to policy choice, the authors investigate two scenarios. One scenario incorporates solely a carbon price but a high one: starting immediately at 100 \$/t CO2 in 2020 and staying constant in the future. The other one represents policy interventions that address the intangible consumer preferences by behavior-influencing measures in addition to the same carbon price level as in the first scenario. The results are striking. In the first scenario, low-carbon vehicle adoption reaches only a level of 0-3 % by 2050 despite the high carbon prices, while in the second scenario on average a penetration of 24 % (fleet-level, not new purchases) is reached. Hence, carbon prizing as a policy instrument alone may face severe problems in realizing emission reduction targets that are expected from the cost-based IAMs. A further publication by Pettifor, Wilson, McCollum, and Edelenbosch (2017) tries to implement social influence dynamics in addition to the current observable preference variations in the vehicle adoption area. It is based on Roger's technology adoption theory which is also exploited in the BLUE model by Li and Strachan (2019) and explained in detail in section 5.2.

5 Socio-technical Transition Theories

One research community that has intensively worked on understanding the decarbonization of the economy not only as a techno-economic problem but aims to incorporate social dynamics can be found within the “transition studies” or “socio-technical transition” community. A part of this broad community of technology and innovation studies has increasingly focused on ecological problems over the past two decades and emerged as an own scientific branch of “sustainability transitions” (Markard, Raven, & Truffer, 2012). The most important body of research in this area is built in the Netherlands, therefore it is often called the “Dutch approach” or “Dutch school” (Grubler, 2012; Li et al., 2015). The community organizes scientific exchange through the “Sustainability Transition Research Network” (STRN, website: https://transitionsnetwork.org) with conferences and workshops and has set up a focused journal “Environmental Innovations and Societal Transitions” (https://www.journals.elsevier.com/environmental-innovation-and-societal-transitions/).

In general, socio-technical transition theory argues that substitution of technologies in human systems must be described as transition from one socio-technical system (the current) to a new socio-technical system. Socio-technical systems are an interplay of networks of actors (individuals, firms, collective actors) and institutions (societal and technical norms, regulations, standards of good practice) as well as materials and knowledge (Geels, 2005). Reaching goals of sustainability usually requires the substitution of employed technologies for example in power, transport, water or agricultural sectors. Hence, the transformation towards sustainability is captured by the concept of socio-technical transitions (Markard et al., 2012).

Several theoretical frameworks in order to analyze socio-technical transitions have been developed. More important ones include transition management (TM) (Rotmans, Kemp, & Van Asselt, 2001), strategic niche management (SNM) (Kemp, Schot, & Hoogma, 1998) or technological innovation systems (TIS) (Carlsson & Stankiewicz, 1991). The most prominent one is called Multi-level perspective (MLP) (Geels, 2002) and described in detail in the next section.

5.1 Multi-level perspective (MLP)

One of the key analytical frameworks that have emerged over recent years for describing socio-technical transitions is the multi-level perspective (MLP). It was proposed by Geels (2002) in 2002 and subsequently developed further and refined. Derived from case studies about historic technological transitions, scholars now try to employ its analytical framework for the low-carbon transition of the present and the future (Geels, Sovacool, Schwanen, & Sorrell, 2017a, 2017b). Regarding quantitative modelling efforts, the multi-level perspective framework is used to build entirely new models upon its theoretical underpinning (Li & Strachan, 2017) as well as for improving scenarios from techno-economic models (Geels, McMeekin, & Pfluger, 2020; van Sluisveld et al., 2020).

MLP describes technological transitions "as major technological transformations in the way societal functions such as transportation, communication, housing, feeding, are fulfilled" (Geels, 2002, p. 1257). From this understanding, it directly follows that these type of transitions not only involve technological changes but include social elements. Economically, the scientific framework of MLP is grounded in evolutionary economics and combines two perspectives: on the one hand, Schumpeter's description of technological evolutions as a process of unfolding and creating new combinations which result in paths and trajectories (Schumpeter, 1934) and on the other hand, Nelson and Winter's concept of regimes in which a continuous process of variation, selection and retention occurs (Nelson & Winter, 1982).

Figure 9 shows an illustration of the overall systematic understanding of technological transitions in the MLP. The current, ongoing technological system is described as socio-technical regime (Geels, 2002). This regime is constituted by the type of technology, industry, science, markets & user preferences, policy and culture. Hence, the regime is built on a functioning configuration of routines, behaviors and communication between these different societal entities. These interdependences cause stability of the current socio-technical regime. However, the stability is of dynamic nature since continuous incremental innovations occur within the established regime (Geels, 2002). Socio-technical regimes are embedded in a so-called socio-technical landscape. The landscape refers to wider, external structures that is determined by e.g. oil prices, economic growth, demographic development, wars, emigration, broad political coalitions, cultural and normative values or environmental problems (Geels, 2002).

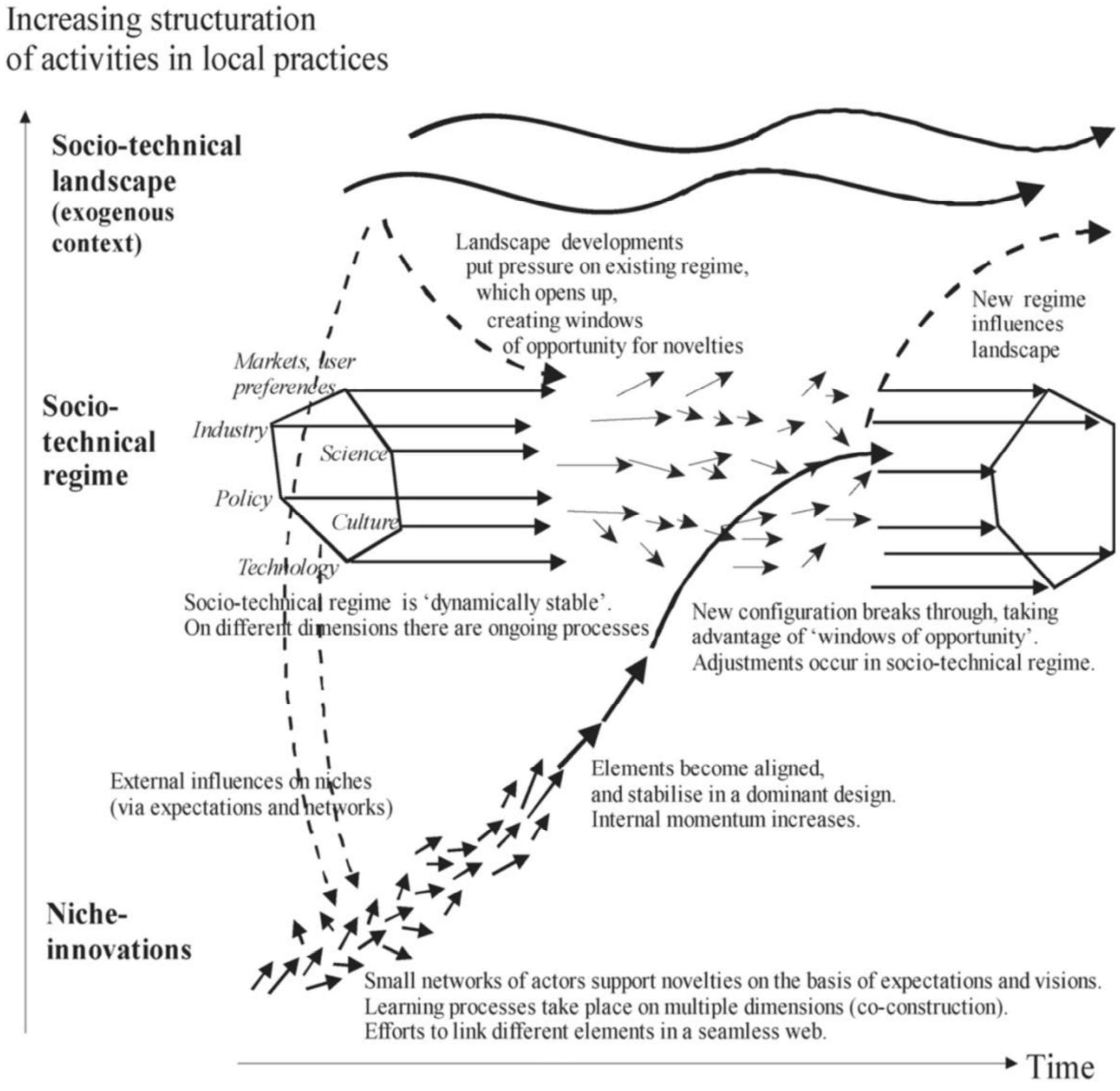

Figure 9: Illustration of the Multi-level Perspective Framework. Adopted from Geels and Schot (2007)

On the lowest level, MLP defines niche innovations as the third major player in technological transitions. They are the source of radical innovations around which the new socio-technical regime is developed after a successful transition. Niches are enclaves in the economy and society which are protected from the regular market mechanisms. Hence, they form an “incubation room” (Schot, 1998) for new technologies which usually show low performance, are expensive and cumbersome or would otherwise not withstand the unprotected economic and social environment.

Examples are the Army, Space programs and other research and development programs by governments but also companies. The concept of niches and their strategic management are further elaborated in Kemp, Rip, and Schot (2001).

The overall process of technological transitions starts in niches where a new technology is developed and nurtured. Niches “provide the seeds for change” (Geels, 2002, p. 1261) However, the key point of the multi-level perspective is that the successful establishment of a new technology is not solely governed by processes within the niche but highly determined by developments at the socio-technical regime and landscape level. Only if change processes align at the three levels simultaneously a technological transition of radical nature occurs. For example, slow changes in the landscape level (cultural change, demographic trends etc.) might put pressure on the old socio-technical regime and cause increasing mismatches in the coordination of the various, interlinked agents the regime is built upon. This hampers its stability and consequentially opens up a window of opportunity for radical innovations from niches. However, the MLP also highlights the existence of strong inertia caused by the dynamic stability of many interlinked agents. In the period of change, there is high variety of competing efforts and designs and hence, high uncertainty prevails which one or if any of the radical innovations can develop a stable new socio-technical regime. The evolvement of a new technology from a niche is characterized by a relatively slow process of niche-cumulation. That describes a gradual process of the technology to acquire more and more application domains or market niches. If successfully established, the new regime might then also affect the socio-technical landscape. This again marks the overall key idea of the multi-level perspective: that major technical transitions occur as an interdependent process of multiple layers, factors and agents and coalitions (Geels, 2002; Hasselmann et al., 2015; Scheffran, 2006).

Clearly, this holistic concept of technological transitions lacks unambiguous and deterministic relationships which can be easily translated into mathematical equations necessary for quantitative modelling efforts. Consequently, several research efforts trying to implement MLP within climate and energy economic scenarios are located at the bridging and iterating strategy. Two highly relevant examples of publications should be named here: van Sluisveld et al. (2020) and Geels et al. (2020)

5.2 An approach to endogenously model the multi-level perspective – the model BLUE

A model that tries to dynamically represent societal and behavioral factors based on the MLP framework is the BLUE model (Behavior, Lifestyles and Uncertainty Energy model) (Li & Strachan, 2017). It covers an entire national energy system and is calibrated for the UK. The authors argue that traditional techno-economic models based on cost-efficient rational investment decisions make various over-optimistic assumptions and that a higher level of realism in human behavior and decision making as well as in broader social and political conditions is necessary. In particular, the model aims at conceptualizing the resistance to change caused by incumbent institutional arrangements and established behaviors or lifestyles, so-called landscape and actor inertia (Li & Strachan, 2017).

In order to achieve that, BLUE incorporates multiple rather than one omni-present social planner, each representing a certain economic sector. The actors "energy supply", "residential", "commercial", "industrial", and various "transport sectors" configure the current socio-technical regime. They are confronted with investment decisions according to respective replacement cycles of capital stocks. Decisions are made upon a cost-minimizing imperative from the perspective of each sector. It is important to note, that in contrast to pathway optimization models, the actors decide in a myopic foresight modus without knowing future landscape developments and in particular without knowing the decisions of the other sectors. Input factors and scenario parameters are formulated in either discrete or continuous probability functions enabling an exploration of uncertainty ranges and robustness of decisions. Consequently, BLUE operates as a stochastic Monte Carlo simulation model with a one year time step and 500 samples per scenario setting.

In order to reflect the mentioned actor inertia, investment decisions are distorted by several behavioral factors. *Demand elasticity* represents demand sensitivity to energy prices. *Market heterogeneities* try to cover differing sensitivities of investment decisions to price differences between technology options. These differences might be due to unperfect information about options or differing individual preferences. *Intangible costs/benefits* estimate other non-monetary pros/cons arising from different technology options. Finally, *hurdle rates* describe heterogenic attitudes to investment risks and varying sensitivities to upfront economic costs. Different levels of these behavioral factors are analyzed by defining four stages. A4 assumes perfect cost-optimizing behavior and a social planner perspective represented by a hurdle rate that complies with the social discount rate suggested by the UK government (3-6 %). A1 marks a world in which actors are only partial price sensitive, several intangible costs exist and the hurdle rate corresponds to a private discounting rate at 9-17%.

MLP's niche innovations are represented by key transition technologies such as renewable energy technologies, heat pumps for the building sector or electric vehicles for the transport sector and potential lifestyle changes that might disrupt the incumbent socio-technical regime as well. Innovative technologies are subject to an exogenously determined cost-reduction path making them increasingly competitive over time. Lifestyle changes are captured by various landscape scenarios that are only exogenously determined as well (see next paragraph).

Landscape inertia/changes are incorporated by assumptions on government action (imposed carbon tax levels) and lifestyle changes with regard to transport sector developments. These are clustered by four different levels (L1-L4) of climate mitigation support. L1 means no carbon tax and a baseline trajectory of future transport development while L4 assumes an increasing carbon tax to 300 £/tCO2 by 2050 and strong uptake of non-motorized travel accompanied by stabilization of road and air travel. Together with the four scenario options in actor behavior, BLUE explores an ensemble of 16 (4x4) different background scenarios for future energy system developments.

Overall, the model suggests that landscape and actor inertia both play powerful roles in slowing the decarbonization transition. Even with very favorable scenario assumptions (A4L4), which relates to a carbon price of 300 £/tCO2 by 2050, considerable lifestyle changes in transport and close to cost-optimal investment behavior of decision makers, the median emission reduction is at 56 % in 2050 in comparison to the 1990 level with a significant uncertainty range between 35 – 71 %. This is far below the declared UK goal of 80 % reduction by 2050. The worst-case world with both strong landscape inertia (no carbon price, no lifestyle change) and actor inertia (low price sensitivity etc.) emissions are only reduced by 2 % compared to 1990. In the model, landscape inertia have a significantly stronger effect on emission reductions than actor inertia. The low landscape inertia and high actor inertia scenario reaches 45 % median reduction while the high landscape inertia and low actor inertia scenario reaches only one digit percent reduction levels close to the worst-case scenario. Still, the 45 % compared to the 56 % reduction in the best-case scenario reveal a considerable effect of actor inertia if landscape inertia are favorable.

By design, BLUE provides a quantitative interface for integrating explicit micro-economic behavior. This provides a platform for exploring the effects of empirical results from behavioral economic studies on future energy system developments. The landscape level which covers the socio-political sphere (carbon tax) and the socio-cultural sphere (lifestyle decisions) however is only explored by exogenously defined scenarios. The authors suggest further endogenization by e.g. defining an explicit government actor or by representing opposing forces from lobbying. BLUE can also act as a modelling environment for capturing accelerating dynamics of system transitions such as tipping points or sudden break-out from lock-ins. However, this would require the implementation of non-linear feedback loop dynamics (Li & Strachan, 2017).

In another but similar study, BLUE is utilized in order to explore the effects of non-optimal policy making compared to an optimal policy pathway. In the optimal scenario, policy making is characterized by few barriers and a stringent carbon prizing scheme at high levels reaching 300 £/tCO2 by 2050. A second-best policy scenario and a dysfunctional policy scenario describe an increasing volatility in decarbonization policy over time caused by high barriers for policy makers and strong vested interests torpedoing policy interventions. This effect is operationalized by randomly sampled CO2 prices within a certain range in each year (Li, 2017).

In a recent publication by Li and Strachan (2019), a first step of explicit integration of governmental and societal dynamics in BLUE is performed. The government is introduced as a decision-making actor in the model, who follows an own definition of national interest. This is considered a state-centric approach in the literature (Cherp et al., 2018) in contrast to an understanding of government as the aggregate of multiple interest groups such as lobbyists, social movements or political parties. It is assumed that the government regards decarbonization of the energy system as beneficial.

Agency of the government lies in the intervention in the socio-technical system by price-based and quantity-based policy instruments. The ability to execute such interventions is constrained by public support; the authors name it the social mandate. The level of social mandate is determined by the level of ownership of low-carbon technologies by the decision-making actors in the different energy sectors. This hypothesis is backed by observations that policy interventions can only be sustained over time if considerable interest groups are present (Lockwood, 2013; Patashnik, 2003). For decision-making in energy sectors driven by consumer-demand such as buildings or private transport, several actors are formulated in order to reflect society as a whole. The authors use a Rogers diffusion curve partitioning society in innovators, early adopters, early majority, late majority and laggards (Rogers, 2003). The groups are characterized and operationalized by distinct discount rates for investment decisions, price sensitivity and the level of intangible costs. For example, innovators do not factor in any intangible costs such as lower reliability, higher time demands or other hassle factors, whereas laggards feel double the costs of the average actor. Usually, the fraction of each societal group is fixed in Roger's original work. In this study, the authors assume these fractions to be able to change over time. This is intended to represent potential society-wide changes in values and attitudes towards a sustainability transformation and to increased demand for or decreased resistance to low-carbon technologies. The model links societal changes to the level of social mandate generating a feedback loop. If more people buy low-carbon technologies (increasing social mandate), it is assumed that this influences attitudes and behaviors away from laggards towards innovators which in turn increases the favor for low-carbon technologies.

Since there is no clear empirical basis for calibrating these dynamics, the authors argue that the simulated pathways should be understood as exploratory by nature. In order to cover a viable range of scenarios, they introduce the idea of defining a single leading actor as initiator of the transition from the two superordinate actors, society and government. Additionally, the non-leading actor can then act in a following or a resisting manner. Together, this opens up a 2x2 framework with four different parameter conditions. For example in the government leading and society resisting scenario, the government imposes strong policy interventions but the composition of society in Roger's innovation adoption groups is static which dampens the feedback loop between technological adoption and governmental intervention. In contrast, in the government leading and society following scenario, the composition of society is moving towards the innovator's characteristic by the strong uptake of low-carbon technologies due to strong policy interventions which in turn constitutes the support for even stronger policy interventions by the growing social mandate. Hence, this scenario is characterized by a strong feedback effect.

6 Conclusion

This literature review has tried to approach the scientific problem of integrating the dynamics of social processes into quantitative models of climate economics with regard to several dimensions relevant to its solution. Several empirical and theoretical insights indicate major shortcomings of the currently available quantitative models which might cause significant changes in policy recommendations. As a consequence, there is a strong necessity to pursue intensive research efforts to gain knowledge in this area.

So far, researchers have laid the ground for this endeavor by providing meta-theoretical frameworks which guide a path for more concrete research questions and projects. While some start from an economics science viewpoint (Grubb et al., 2015; Staub-Kaminski et al., 2014) which goes in parts as far as to treat dynamics of social processes as mere market failures, especially Staub-Kaminski et al. (2014) (without disregarding or talking them down as non-fundamental), others provide a theoretical problem description that stems from social scientists' school of thought which gives less reference points for quantitative modelling (Cherp et al., 2018; Geels et al., 2017a). A third group arises from the natural scientists milieu and presents a fully process-detailed, complex modelling vision of the earth system including biogeochemical, socio-economic and socio-cultural dynamics (Donges, Heitzig, et al., 2018).

All of these contributions to a research agenda of integrating social dynamics into the economics of climate stabilization provide advantages and suffer of disadvantages but all of them acknowledge the problem of defining deterministic dynamics which can be captured by a mathematical formalization which in turn are the basis for forward-looking scenario calculations. Besides the complexity of social processes this is significantly due to a lack of data which would be used for identifiying robust dynamics, a problem expressed by Otto et al. (2015) as well. It is of highest necessity to improve the collection and provision of data with regard to social dynamics in order to move forward with this research goal.

Furthermore, this literature review identified a significant number of publications which present at least in the shape of schematic ideas a list of social processes that might play a role in the emergence and the evolution of the technological transition towards a climate stabilizing energy and economic system. As such this might serve as a pool for researchers who work on collecting data of and formalizing social dynamics for integration into quantitative models. As social dynamics are essentially governed by decisions of humans the term agency is illuminated in detail. Developing and deriving policy recommendations is fundamentally determined by a profound understanding of decisions and the real agency of humans since it is these decisions that need to be bent away from the historic track record and the future reference scenario in order to ensure a pathway to climate stabilization.

Finally, several publications are presented which formulate initial approaches to quantitatively integrate certain social processes into economic models of climate stabilization. The review highlights the model BLUE since it provides a rather progressed modelling environment for the integration of social dynamics and several publications show concrete examples. However, all the other approaches should be pursued as well since as it is usually the case in science: it is not clear which approach will be successful in the end or even more likely, that different approaches will provide different insights.

Besides the models this is equally true for the theoretical frameworks emerging from different schools of thought (economics, social sciences, natural sciences) as well as the long list of social processes that might play a crucial role in the unfolding of real world decarbonization pathways. As many as possible should be investigated and considered in deriving policy recommendations from quantitative models. It must be ensured that decarbonization pathways derived from quantitative models are actually within the real world solution space which is presumably highly determined by the dynamics of social processes. If the latter are ignored, scientific policy advice risks to advocate climate economic scenarios which seemed plausible regarding technological and economical dynamics but have never been possible to unfold in the real world.

If it is successful, ambitious climate policy causes the most fundamental, industrial transformation since the industrial revolution itself. Hence, the potential is high to produce many losers. If ambitious climate policy is introduced without considering social dynamics in all facets, the risk of losing societal acceptance is high. Humanity cannnot bear this risk. Humanity cannot experiment with various policy ideas since the window of self-determined action to avoid dangerous climate change is closing rapidly.

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References

Abrahamse, W., Steg, L., Vlek, C., & Rothengatter, T. (2005). A review of intervention studies aimed at household energy conservation. *Journal of Environmental Psychology, 25*(3), 273-291. doi:https://doi.org/10.1016/j.jenvp.2005.08.002

Abroms, L. C., & Maibach, E. W. (2008). The Effectiveness of Mass Communication to Change Public Behavior. *Annual Review of Public Health, 29*(1), 219-234. doi:10.1146/annurev.publhealth.29.020907.090824

Ajzen, I. (1991). The theory of planned behavior. *Organizational Behavior and Human Decision Processes, 50*(2), 179-211. doi:https://doi.org/10.1016/0749-5978(91)90020-T

Allcott, H. (2011). Social norms and energy conservation. *Journal of Public Economics, 95*(9), 1082-1095. doi:https://doi.org/10.1016/j.jpubeco.2011.03.003

Axelrod, R. (1997). *The complexity of cooperation: Agent-based models of competition and collaboration* (Vol. 3): Princeton university press.

Bandura, A. (2006). Toward a Psychology of Human Agency. *Perspectives on Psychological Science, 1*(2), 164-180. doi:10.1111/j.1745-6916.2006.00011.x

Banerjee, A. V. (1992). A Simple Model of Herd Behavior*. *The Quarterly Journal of Economics, 107*(3), 797-817. doi:10.2307/2118364

Bauer, N., Calvin, K., Emmerling, J., Fricko, O., Fujimori, S., Hilaire, J., . . . van Vuuren, D. P. (2017). Shared Socio-Economic Pathways of the Energy Sector – Quantifying the Narratives. *Global Environmental Change, 42*, 316-330. doi:https://doi.org/10.1016/j.gloenvcha.2016.07.006

Beckage, B., Gross, L. J., Lacasse, K., Carr, E., Metcalf, S. S., Winter, J. M., . . . Hoffman, F. M. (2018). Linking models of human behaviour and climate alters projected climate change. *Nature Climate Change, 8*(1), 79-84. doi:10.1038/s41558-017-0031-7

Beckage, B., Lacasse, K., Winter, J. M., Gross, L. J., Fefferman, N., Hoffman, F. M., . . . Kinzig, A. (2020). The Earth has humans, so why don't our climate models? *Climatic Change, 163*(1), 181-188. doi:10.1007/s10584-020-02897-x

Bendor, T. K., & Scheffran, J. (2019). *Agent-Based Modeling of Environmental Conflict and Cooperation*: Taylor & Francis, CRC Press.

Bicchieri, C. (2016). *Norms in the wild: How to diagnose, measure, and change social norms*: Oxford University Press.

Blondeel, M., Colgan, J., & Van de Graaf, T. (2019). What Drives Norm Success? Evidence from Anti–Fossil Fuel Campaigns. *Global Environmental Politics, 19*(4), 63-84. doi:10.1162/glep_a_00528

Bowles, S. (1998). Endogenous Preferences: The Cultural Consequences of Markets and Other Economic Institutions. *Journal of Economic Literature, 36*(1), 75-111. Retrieved from www.jstor.org/stable/2564952

Bury, T. M., Bauch, C. T., & Anand, M. (2019). Charting pathways to climate change mitigation in a coupled socio-climate model. *PLOS Computational Biology, 15*(6), e1007000. doi:10.1371/journal.pcbi.1007000

Cao, X., Mokhtarian, P. L., & Handy, S. L. (2007). Cross-Sectional and Quasi-Panel Explorations of the Connection between the Built Environment and Auto Ownership. *Environment and Planning A: Economy and Space, 39*(4), 830-847. doi:10.1068/a37437

Carlsson, B., & Stankiewicz, R. (1991). On the nature, function and composition of technological systems. *Journal of Evolutionary Economics, 1*(2), 93-118. doi:10.1007/BF01224915

Carrico, A. R., Vandenbergh, M. P., Stern, P. C., & Dietz, T. (2015). US climate policy needs behavioural science. *Nature Climate Change, 5*(3), 177-179. doi:10.1038/nclimate2518

Castree, N., Adams, W. M., Barry, J., Brockington, D., Büscher, B., Corbera, E., . . . Wynne, B. (2014). Changing the intellectual climate. *Nature Climate Change, 4*(9), 763-768. doi:10.1038/nclimate2339

Cherp, A., Vinichenko, V., Jewell, J., Brutschin, E., & Sovacool, B. (2018). Integrating techno-economic, socio-technical and political perspectives on national energy transitions: A meta-theoretical framework. *Energy Research & Social Science, 37*, 175-190. doi:https://doi.org/10.1016/j.erss.2017.09.015

Christakis, N. A., & Fowler, J. H. (2008). The Collective Dynamics of Smoking in a Large Social Network. *New England Journal of Medicine, 358*(21), 2249-2258. doi:10.1056/NEJMsa0706154

Chudek, M., & Henrich, J. (2011). Culture–gene coevolution, norm-psychology and the emergence of human prosociality. *Trends in Cognitive Sciences, 15*(5), 218-226. doi:https://doi.org/10.1016/j.tics.2011.03.003

Cialdini, R. B. (2003). Crafting Normative Messages to Protect the Environment. *Current Directions in Psychological Science, 12*(4), 105-109. doi:10.1111/1467-8721.01242

Clifford, P., & Sudbury, A. (1973). A model for spatial conflict. *Biometrika, 60*(3), 581-588. doi:10.1093/biomet/60.3.581

Costa, L. d. F., Rodrigues, F. A., Travieso, G., & Villas Boas, P. R. (2007). Characterization of complex networks: A survey of measurements. *Advances in Physics, 56*(1), 167-242. doi:10.1080/00018730601170527

Coulthard, S. (2012). Can We Be Both Resilient and Well, and What Choices Do People Have? Incorporating Agency into the Resilience Debate from a Fisheries Perspective. *Ecology and Society, 17*(1). Retrieved from http://www.jstor.org/stable/26269013

Creutzig, F. (2016). Evolving Narratives of Low-Carbon Futures in Transportation. *Transport Reviews, 36*(3), 341-360. doi:10.1080/01441647.2015.1079277

Creutzig, F., Fernandez, B., Haberl, H., Khosla, R., Mulugetta, Y., & Seto, K. C. (2016). Beyond Technology: Demand-Side Solutions for Climate Change Mitigation. *Annual Review of Environment and Resources, 41*(1), 173-198. doi:10.1146/annurev-environ-110615-085428

Creutzig, F., Javaid, A., Soomauroo, Z., Lohrey, S., Milojevic-Dupont, N., Ramakrishnan, A., . . . Zausch, J. M. (2020). Fair street space allocation: ethical principles and empirical insights. *Transport Reviews, 40*(6), 711-733. doi:10.1080/01441647.2020.1762795

Creutzig, F., Roy, J., Lamb, W. F., Azevedo, I. M. L., Bruine de Bruin, W., Dalkmann, H., . . . Weber, E. U. (2018). Towards demand-side solutions for mitigating climate change. *Nature Climate Change, 8*(4), 260-263. doi:10.1038/s41558-018-0121-1

Crutzen, P. J. (2002). Geology of mankind. *Nature, 415*(6867), 23-23. doi:10.1038/415023a

Czupryna, M., Franzke, C., Hokamp, S., & Scheffran, J. (2020). An Agent-Based Approach to Integrated Assessment Modelling of Climate Change. *Journal of Artificial Societies and Social Simulation, 23*(3). doi:10.18564/jasss.4325

Davis, T., Hennes, E. P., & Raymond, L. (2018). Cultural evolution of normative motivations for sustainable behaviour. *Nature Sustainability, 1*(5), 218-224. doi:10.1038/s41893-018-0061-9

Dellas, E., Pattberg, P., & Betsill, M. (2011). Agency in earth system governance: refining a research agenda. *International Environmental Agreements: Politics, Law and Economics, 11*(1), 85-98. doi:10.1007/s10784-011-9147-9

Dietz, T., Gardner, G. T., Gilligan, J., Stern, P. C., & Vandenbergh, M. P. (2009). Household actions can provide a behavioral wedge to rapidly reduce US carbon emissions. *Proceedings of the National Academy of Sciences, 106*(44), 18452. doi:10.1073/pnas.0908738106

Donges, J. F., Heitzig, J., Barfuss, W., Kassel, J. A., Kittel, T., Kolb, J. J., . . . Wiedermann, M. (2018). Earth system modelling with complex dynamic human societies: The copan: Core World-Earth modeling framework. *Earth System Dynamics Discussion*, 1-27.

Donges, J. F., Lucht, W., Heitzig, J., Barfuss, W., Cornell, S. E., Lade, S. J., & Schlüter, M. (2018). Taxonomies for structuring models for World-Earth system analysis of the Anthropocene: subsystems, their interactions and social-ecological feedback loops. *Earth Syst. Dynam. Discuss., 2018*, 1-30. doi:10.5194/esd-2018-27

Donges, J. F., Winkelmann, R., Lucht, W., Cornell, S. E., Dyke, J. G., Rockström, J., . . . Schellnhuber, H. J. (2017). Closing the loop: Reconnecting human dynamics to Earth System science. *The Anthropocene Review, 4*(2), 151-157. doi:10.1177/2053019617725537

Edenhofer, O., Bauer, N., & Kriegler, E. (2005). The impact of technological change on climate protection and welfare: Insights from the model MIND. *Ecological Economics, 54*(2), 277-292. doi:https://doi.org/10.1016/j.ecolecon.2004.12.030

Eker, S., Reese, G., & Obersteiner, M. (2019). Modelling the drivers of a widespread shift to sustainable diets. *Nature Sustainability, 2*(8), 725-735. doi:10.1038/s41893-019-0331-1

Engels, A. (2016). Anthropogenic climate change: how to understand the weak links between scientific evidence, public perception, and low-carbon practices. *Energy Emiss. Control Technol, 4*, 17-26.

Farmer, J. D., Hepburn, C., Ives, M. C., Hale, T., Wetzer, T., Mealy, P., . . . Way, R. (2019). Sensitive intervention points in the post-carbon transition. *Science, 364*(6436), 132. doi:10.1126/science.aaw7287

Farmer, J. D., Hepburn, C., Mealy, P., & Teytelboym, A. (2015). A Third Wave in the Economics of Climate Change. *Environmental and Resource Economics, 62*(2), 329-357. doi:10.1007/s10640-015-9965-2

Geels, F. W. (2002). Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Research Policy, 31*(8), 1257-1274. doi:https://doi.org/10.1016/S0048-7333(02)00062-8

Geels, F. W. (2005). *Technological transitions and system innovations: a co-evolutionary and socio-technical analysis*. Cheltenham, UK: Edward Elgar.

Geels, F. W., Berkhout, F., & van Vuuren, D. P. (2016). Bridging analytical approaches for low-carbon transitions. *Nature Climate Change, 6*(6), 576-583. doi:10.1038/nclimate2980

Geels, F. W., McMeekin, A., & Pfluger, B. (2020). Socio-technical scenarios as a methodological tool to explore social and political feasibility in low-carbon transitions: Bridging computer models and the multi-level perspective in UK electricity generation (2010–2050). *Technological Forecasting and Social Change, 151*, 119258. doi:https://doi.org/10.1016/j.techfore.2018.04.001

Geels, F. W., & Schot, J. (2007). Typology of sociotechnical transition pathways. *Research Policy, 36*(3), 399-417. doi:https://doi.org/10.1016/j.respol.2007.01.003

Geels, F. W., Sovacool, B. K., Schwanen, T., & Sorrell, S. (2017a). The Socio-Technical Dynamics of Low-Carbon Transitions. *Joule, 1*(3), 463-479. doi:10.1016/j.joule.2017.09.018

Geels, F. W., Sovacool, B. K., Schwanen, T., & Sorrell, S. (2017b). Sociotechnical transitions for deep decarbonization. *Science, 357*(6357), 1242. doi:10.1126/science.aao3760

Green, F. (2018a). Anti-fossil fuel norms. *Climatic Change, 150*(1), 103-116. doi:10.1007/s10584-017-2134-6

Green, F. (2018b). The logic of fossil fuel bans. *Nature Climate Change, 8*(6), 449-451. doi:10.1038/s41558-018-0172-3

Grubb, M., Hourcade, J.-C., & Neuhoff, K. (2015). The Three Domains structure of energy-climate transitions. *Technological Forecasting and Social Change, 98*, 290-302. doi:https://doi.org/10.1016/j.techfore.2015.05.009

Grubler, A. (2012). Energy transitions research: Insights and cautionary tales. *Energy Policy, 50*, 8-16. doi:https://doi.org/10.1016/j.enpol.2012.02.070

Grubler, A., Wilson, C., Bento, N., Boza-Kiss, B., Krey, V., McCollum, D. L., . . . Valin, H. (2018). A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. *Nature Energy, 3*(6), 515-527. doi:10.1038/s41560-018-0172-6

Hasselmann, K., Cremades, R., Filatova, T., Hewitt, R., Jaeger, C., Kovalevsky, D., . . . Winder, N. (2015). Free-riders to forerunners. *Nature Geoscience, 8*(12), 895-898. doi:10.1038/ngeo2593

Holley, R. A., & Liggett, T. M. (1975). Ergodic Theorems for Weakly Interacting Infinite Systems and the Voter Model. *Ann. Probab., 3*(4), 643-663. doi:10.1214/aop/1176996306

IPCC. (2014). Summary for Policymakers. In Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (Ed.), Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Jacobsson, S., & Johnson, A. (2000). The diffusion of renewable energy technology: an analytical framework and key issues for research. *Energy Policy, 28*(9), 625-640. doi:https://doi.org/10.1016/S0301-4215(00)00041-0

Kalkuhl, M., Edenhofer, O., & Lessmann, K. (2012). Learning or lock-in: Optimal technology policies to support mitigation. *Resource and Energy Economics, 34*(1), 1-23. doi:https://doi.org/10.1016/j.reseneeco.2011.08.001

Kalkuhl, M., Edenhofer, O., & Lessmann, K. (2013). Renewable energy subsidies: Second-best policy or fatal aberration for mitigation? *Resource and Energy Economics, 35*(3), 217-234. doi:https://doi.org/10.1016/j.reseneeco.2013.01.002

Kemp, R., Rip, A., & Schot, J. W. (2001). Constructing transition paths through the management of niches. In Path Dependence and Creation (pp. 269-299). R. Garud & P. Karnoe (Eds.), Mahwah, NJ: Lawrence Erlbaum.

Kemp, R., Schot, J., & Hoogma, R. (1998). Regime shifts to sustainability through processes of niche formation: The approach of strategic niche management. *Technology Analysis & Strategic Management, 10*(2), 175-198. doi:10.1080/09537329808524310

Kinzig, A. P., Ehrlich, P. R., Alston, L. J., Arrow, K., Barrett, S., Buchman, T. G., . . . Saari, D. (2013). Social Norms and Global Environmental Challenges: The Complex Interaction of Behaviors, Values, and Policy. *BioScience, 63*(3), 164-175. doi:10.1525/bio.2013.63.3.5

Kohring, G. A. (1996). Ising Models of Social Impact: the Role of Cumulative Advantage. *J. Phys. I France, 6*(2), 301-308. Retrieved from https://doi.org/10.1051/jp1:1996150

Lamb, W. F., & Minx, J. C. (2020). The political economy of national climate policy: Architectures of constraint and a typology of countries. *Energy Research & Social Science, 64*, 101429. doi:https://doi.org/10.1016/j.erss.2020.101429

Lempert, R., Scheffran, J., & Sprinz, D. F. (2009). Methods for Long-Term Environmental Policy Challenges. *Global Environmental Politics, 9*(3), 106-133. doi:10.1162/glep.2009.9.3.106

Li, F. G. N. (2017). Actors behaving badly: Exploring the modelling of non-optimal behaviour in energy transitions. *Energy Strategy Reviews, 15*, 57-71. doi:https://doi.org/10.1016/j.esr.2017.01.002

Li, F. G. N., & Strachan, N. (2017). Modelling energy transitions for climate targets under landscape and actor inertia. *Environmental Innovation and Societal Transitions, 24*, 106-129. doi:https://doi.org/10.1016/j.eist.2016.08.002

Li, F. G. N., & Strachan, N. (2019). Take me to your leader: Using socio-technical energy transitions (STET) modelling to explore the role of actors in decarbonisation pathways. *Energy Research & Social Science, 51*, 67-81. doi:https://doi.org/10.1016/j.erss.2018.12.010

Li, F. G. N., Trutnevyte, E., & Strachan, N. (2015). A review of socio-technical energy transition (STET) models. *Technological Forecasting and Social Change, 100*, 290-305. doi:https://doi.org/10.1016/j.techfore.2015.07.017

Lister, R. (2003). What is Citizenship? In Citizenship: Feminist Perspectives (pp. 13-42). R. Lister & J. Campling (Eds.), London: Macmillan Education UK.

Lockwood, M. (2013). The political sustainability of climate policy: The case of the UK Climate Change Act. *Global Environmental Change, 23*(5), 1339-1348. doi:https://doi.org/10.1016/j.gloenvcha.2013.07.001

Luderer, G., Bosetti, V., Jakob, M., Leimbach, M., Steckel, J. C., Waisman, H., & Edenhofer, O. (2012). The economics of decarbonizing the energy system—results and insights from the RECIPE model intercomparison. *Climatic Change, 114*(1), 9-37. doi:10.1007/s10584-011-0105-x

Marchand, R. D., Koh, S. C. L., & Morris, J. C. (2015). Delivering energy efficiency and carbon reduction schemes in England: Lessons from Green Deal Pioneer Places. *Energy Policy, 84*, 96-106. doi:https://doi.org/10.1016/j.enpol.2015.04.035

Markard, J., Raven, R., & Truffer, B. (2012). Sustainability transitions: An emerging field of research and its prospects. *Research Policy, 41*(6), 955-967. doi:https://doi.org/10.1016/j.respol.2012.02.013

Martinez-Alier, J. (2009). Social Metabolism, Ecological Distribution Conflicts, and Languages of Valuation. *Capitalism Nature Socialism, 20*(1), 58-87. doi:10.1080/10455750902727378

Mattauch, L., & Hepburn, C. (2016). Climate policy when preferences are endogenous— and sometimes they are. *Midwest Studies in Philosophy*(1).

McCollum, D. L., Wilson, C., Bevione, M., Carrara, S., Edelenbosch, O. Y., Emmerling, J., . . . van Vuuren, D. P. (2018). Interaction of consumer preferences and climate policies in the global transition to low-carbon vehicles. *Nature Energy, 3*(8), 664-673. doi:10.1038/s41560-018-0195-z

McCollum, D. L., Wilson, C., Pettifor, H., Ramea, K., Krey, V., Riahi, K., . . . Fujisawa, S. (2017). Improving the behavioral realism of global integrated assessment models: An application to consumers' vehicle choices. *Transportation Research Part D: Transport and Environment, 55*, 322-342. doi:https://doi.org/10.1016/j.trd.2016.04.003

Meckling, J., Kelsey, N., Biber, E., & Zysman, J. (2015). Winning coalitions for climate policy. *Science, 349*(6253), 1170. doi:10.1126/science.aab1336

Meckling, J., Sterner, T., & Wagner, G. (2017). Policy sequencing toward decarbonization. *Nature Energy, 2*(12), 918-922.

Müller-Hansen, F., Schlüter, M., Mäs, M., Donges, J. F., Kolb, J. J., Thonicke, K., & Heitzig, J. (2017). Towards representing human behavior and decision making in Earth system models – an overview of techniques and approaches. *Earth Syst. Dynam., 8*(4), 977-1007. doi:10.5194/esd-8-977-2017

Nelson, R. R., & Winter, S. G. (1982). *An evolutionary theory of economic change*. Cambridge, MA: Bellknap Press.

Nordhaus, W. D. (1992). An Optimal Transition Path for Controlling Greenhouse Gases. *Science, 258*(5086), 1315. doi:10.1126/science.258.5086.1315

Nordhaus, W. D. (1993). Rolling the 'DICE': an optimal transition path for controlling greenhouse gases. *Resource and Energy Economics, 15*(1), 27-50. doi:https://doi.org/10.1016/0928-7655(93)90017-O

Nyborg, K., Anderies, J. M., Dannenberg, A., Lindahl, T., Schill, C., Schlüter, M., . . . de Zeeuw, A. (2016). Social norms as solutions. *Science, 354*(6308), 42. doi:10.1126/science.aaf8317

Nyborg, K., & Rege, M. (2003). On social norms: the evolution of considerate smoking behavior. *Journal of Economic Behavior & Organization, 52*(3), 323-340. doi:https://doi.org/10.1016/S0167-2681(03)00031-3

Olsson, L., Jerneck, A., Thoren, H., Persson, J., & O'Byrne, D. (2015). Why resilience is unappealing to social science: Theoretical and empirical investigations of the scientific use of resilience. *Science Advances, 1*(4), e1400217. doi:10.1126/sciadv.1400217

Ostrom, E. (2005). Doing Institutional Analysis Digging Deeper Than Markets and Hierarchies. In Handbook of New Institutional Economics (pp. 819-848). C. Menard & M. M. Shirley (Eds.), Boston, MA: Springer US.

Ostrom, E. (2007). A diagnostic approach for going beyond panaceas. *Proceedings of the National Academy of Sciences, 104*(39), 15181. doi:10.1073/pnas.0702288104

Ostrom, E. (2009). A General Framework for Analyzing Sustainability of Social-Ecological Systems. *Science, 325*(5939), 419. doi:10.1126/science.1172133

Otto, I. M., Biewald, A., Coumou, D., Feulner, G., Köhler, C., Nocke, T., . . . Beck, U. (2015). Socio-economic data for global environmental change research. *Nature Climate Change, 5*(6), 503-506. doi:10.1038/nclimate2593

Otto, I. M., Donges, J. F., Cremades, R., Bhowmik, A., Hewitt, R. J., Lucht, W., . . . Schellnhuber, H. J. (2020). Social tipping dynamics for stabilizing Earth's climate by 2050. *Proceedings of the National Academy of Sciences, 117*(5), 2354. doi:10.1073/pnas.1900577117

Otto, I. M., Wiedermann, M., Cremades, R., Donges, J. F., Auer, C., & Lucht, W. (2020). Human agency in the Anthropocene. *Ecological Economics, 167*, 106463. doi:https://doi.org/10.1016/j.ecolecon.2019.106463

Pahle, M., Burtraw, D., Flachsland, C., Kelsey, N., Biber, E., Meckling, J., . . . Zysman, J. (2018). Sequencing to ratchet up climate policy stringency. *Nature Climate Change, 8*(10), 861-867. doi:10.1038/s41558-018-0287-6

Palmer, P. I., & Smith, M. J. (2014). Earth systems: Model human adaptation to climate change. *Nature, 512*(7515), 365-366. doi:10.1038/512365a

Patashnik, E. (2003). After the Public Interest Prevails: The Political Sustainability of Policy Reform. *Governance, 16*(2), 203-234. doi:https://doi.org/10.1111/1468-0491.00214

Pattberg, P., & Stripple, J. (2008). Beyond the public and private divide: remapping transnational climate governance in the 21st century. *International Environmental Agreements: Politics, Law and Economics, 8*(4), 367-388. doi:10.1007/s10784-008-9085-3

Pettifor, H., Wilson, C., McCollum, D., & Edelenbosch, O. Y. (2017). Modelling social influence and cultural variation in global low-carbon vehicle transitions. *Global Environmental Change, 47*, 76-87. doi:https://doi.org/10.1016/j.gloenvcha.2017.09.008

Popp, A., Lotze-Campen, H., & Bodirsky, B. (2010). Food consumption, diet shifts and associated non-CO2 greenhouse gases from agricultural production. *Global Environmental Change, 20*(3), 451-462. doi:https://doi.org/10.1016/j.gloenvcha.2010.02.001

Revesz, R. L., Howard, P. H., Arrow, K., Goulder, L. H., Kopp, R. E., Livermore, M. A., . . . Sterner, T. (2014). Global warming: Improve economic models of climate change. *Nature News, 508*(7495), 173.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E. F., . . . Foley, J. A. (2009). A safe operating space for humanity. *Nature, 461*(7263), 472-475. doi:10.1038/461472a

Rogers, E. M. (2003). *Diffusion of Innovations* (5th edition ed.). New York, NY, USA: Free Press Simon and Schuster.

Rotmans, J., Kemp, R., & Van Asselt, M. (2001). More evolution than revolution: transition management in public policy. *Foresight, 3*(1), 15-31.

Sanchez-Sabate, R., & Sabaté, J. (2019). Consumer Attitudes Towards Environmental Concerns of Meat Consumption: A Systematic Review. *International Journal of Environmental Research and Public Health, 16*(7). doi:10.3390/ijerph16071220

Scheffran, J. (2006). The Formation of Adaptive Coalitions. In Advances in Dynamic Games: Applications to Economics, Management Science, Engineering, and Environmental Management (pp. 163-178). A. Haurie, S. Muto, L. A. Petrosjan, & T. E. S. Raghavan (Eds.), Boston, MA: Birkhäuser Boston.

Scheffran, J. (2008). Adaptive management of energy transitions in long-term climate change. *Computational Management Science, 5*(3), 259-286. doi:10.1007/s10287-007-0044-1

Scheffran, J. (2016). From a Climate of Complexity to Sustainable Peace: Viability Transformations in the Anthropocene. In Handbook on Sustainability Transition and Sustainable Peace. Springer (pp. 305-346). H. G. Brauch, Ú. Oswald Spring, J. Grin, & J. Scheffran (Eds.).

Schellnhuber, H. J. (1999). 'Earth system' analysis and the second Copernican revolution. *Nature, 402*(6761), C19-C23. doi:10.1038/35011515

Schellnhuber, H. J., Crutzen, P. J., Clark, W. C., & Hunt, J. (2005). Earth System Analysis for Sustainability. *Environment: Science and Policy for Sustainable Development, 47*(8), 10-25. doi:10.3200/ENVT.47.8.10-25

Schleussner, C.-F., Donges, J. F., Engemann, D. A., & Levermann, A. (2016). Clustered marginalization of minorities during social transitions induced by co-evolution of behaviour and network structure. *Scientific Reports, 6*(1), 30790. doi:10.1038/srep30790

Schmid, E., & Knopf, B. (2012). Ambitious mitigation scenarios for Germany: A participatory approach. *Energy Policy, 51*, 662-672. doi:https://doi.org/10.1016/j.enpol.2012.09.007

Schot, J. (1998). The usefulness of evolutionary models for explaining innovation. The case of the Netherlands in the nineteenth century. *History and Technology, 14*(3), 173-200. doi:10.1080/07341519808581928

Schumpeter, J. A. (1934). Entrepreneurship as innovation. In Entrepreneurship: The social science view (pp. 51-75). R. Swedberg (Ed.), Oxford, UK: Oxford University Press.

Simon, H. A. (1955). A Behavioral Model of Rational Choice. *The Quarterly Journal of Economics, 69*(1), 99-118. doi:10.2307/1884852

Simon, H. A. (1959). Theories of Decision-Making in Economics and Behavioral Science. *The American Economic Review, 49*(3), 253-283. Retrieved from http://www.jstor.org/stable/1809901

Sovacool, B. K. (2009). Rejecting renewables: The socio-technical impediments to renewable electricity in the United States. *Energy Policy, 37*(11), 4500-4513. doi:https://doi.org/10.1016/j.enpol.2009.05.073

Sovacool, B. K. (2014a). Diversity: energy studies need social science. *Nature News, 511*(7511), 529.

Sovacool, B. K. (2014b). What are we doing here? Analyzing fifteen years of energy scholarship and proposing a social science research agenda. *Energy Research & Social Science, 1*, 1-29. doi:https://doi.org/10.1016/j.erss.2014.02.003

Staub-Kaminski, I., Zimmer, A., Jakob, M., & Marschinski, R. (2014). CLIMATE POLICY IN PRACTICE: A TYPOLOGY OF OBSTACLES AND IMPLICATIONS FOR INTEGRATED ASSESSMENT MODELING. *Climate Change Economics, 05*(01), 1440004. doi:10.1142/S2010007814400041

Stern, N. (2016). Economics: Current climate models are grossly misleading. *Nature, 530*(7591), 407-409.

Stern, N., Stiglitz, J., & Taylor, C. (2021). *The Economics of Immense Risk, Urgent Action and Radical Change: Towards New Approaches to the Economics of Climate Change*. Retrieved from https://EconPapers.repec.org/RePEc:nbr:nberwo:28472

Sunstein, C. R. (2015). The ethics of nudging. *Yale Journal on Regulation, 32*, 413-591.

Trutnevyte, E. (2016). Does cost optimization approximate the real-world energy transition? *Energy, 106*, 182-193. doi:https://doi.org/10.1016/j.energy.2016.03.038

Trutnevyte, E., Hirt, L. F., Bauer, N., Cherp, A., Hawkes, A., Edelenbosch, O. Y., . . . van Vuuren, D. P. (2019). Societal Transformations in Models for Energy and Climate Policy: The Ambitious Next Step. *One Earth, 1*(4), 423-433. doi:https://doi.org/10.1016/j.oneear.2019.12.002

Turnheim, B., Berkhout, F., Geels, F. W., Hof, A., McMeekin, A., Nykvist, B., & van Vuuren, D. (2015). Evaluating sustainability transitions pathways: Bridging analytical approaches to address governance challenges. *Global Environmental Change, 35*, 239-253. doi:https://doi.org/10.1016/j.gloenvcha.2015.08.010

van Sluisveld, M. A. E., Hof, A. F., Carrara, S., Geels, F. W., Nilsson, M., Rogge, K., . . . van Vuuren, D. P. (2020). Aligning integrated assessment modelling with socio-technical transition insights: An application to low-carbon energy scenario analysis in Europe. *Technological Forecasting and Social Change, 151*, 119-177. doi:https://doi.org/10.1016/j.techfore.2017.10.024

van Sluisveld, M. A. E., Martínez, S. H., Daioglou, V., & van Vuuren, D. P. (2016). Exploring the implications of lifestyle change in 2°C mitigation scenarios using the IMAGE integrated assessment model. *Technological Forecasting and Social Change, 102*, 309-319. doi:https://doi.org/10.1016/j.techfore.2015.08.013

van Vuuren, D. P., Stehfest, E., Gernaat, D. E. H. J., van den Berg, M., Bijl, D. L., de Boer, H. S., . . . van Sluisveld, M. A. E. (2018). Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. *Nature Climate Change, 8*(5), 391-397. doi:10.1038/s41558-018-0119-8

Victor, D. (2015). Climate change: Embed the social sciences in climate policy. *Nature, 520*(7545), 27-29.

Weber, M., Barth, V., & Hasselmann, K. (2005). A multi-actor dynamic integrated assessment model (MADIAM) of induced technological change and sustainable economic growth. *Ecological Economics, 54*(2), 306-327. doi:10.1016/j.ecolecon.2004.12.035

Weinberger, R., & Goetzke, F. (2010). Unpacking Preference: How Previous Experience Affects Auto Ownership in the United States. *Urban Studies, 47*(10), 2111-2128. doi:10.1177/0042098009357354

Weinberger, R., & Goetzke, F. (2011). Drivers of Auto Ownership: The Role of Past Experience and Peer Pressure. In Auto Motives (pp. 121-135). L. Karen, B. Evelyn, & W. Rachel (Eds.): Emerald Group Publishing Limited.

Williamson, O. E. (1998). Transaction Cost Economics: How It Works; Where It is Headed. *De Economist, 146*(1), 23-58. doi:10.1023/A:1003263908567