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Actors, Decision-making, and Institutions in Quantitative System Modelling

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Summary

Increasing the realism with respect to the representation of actors, decision-making, and institutions is critical to better understand the transition towards a low-carbon sustainable society since actors, decision-making, and institutions are the defining elements of transition pathways. In this paper, we explore how this can be done by conducting a model-based scenario analysis. The increasing focus on implementation and transition dynamics towards long-term objectives requires a better comprehension of what drives change and how those changes can be accelerated. We explore opportunities that arise from a deeper engagement of quantitative systems modeling with socio-technical transitions studies, initiative-based learning, and applied economics. We argue that a number of opportunities for enriching the realism in model-based scenario analysis can arise through model refinements oriented towards a more detailed approach in terms of actor heterogeneity, as well as through integration across different analytical and disciplinary approaches.

Keywords: Modelling, Transition Pathways, Scenarios, Institutions, Governance

JEL Classification: C63, O10, P16, Q00, Q4, Q5

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Actors, decision-making, and institutions in quantitative system modelling

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Abstract: Increasing the realism with respect to the representation of actors, decision-making, and institutions is critical to better understand the transition towards a low-carbon sustainable society since actors, decision-making, and institutions are the defining elements of transition pathways. In this paper, we explore how this can be done by conducting a model-based scenario analysis. The increasing focus on implementation and transition dynamics towards long-term objectives requires a better comprehension of what drives change and how those changes can be accelerated. We explore opportunities that arise from a deeper engagement of quantitative systems modeling with socio-technical transitions studies, initiative-based learning, and applied economics. We argue that a number of opportunities for enriching the realism in model-based scenario analysis can arise through model refinements oriented towards a more detailed approach in terms of actor heterogeneity, as well as through integration across different analytical and disciplinary approaches.

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1 Introduction

A transition towards a low-carbon and sustainable economy requires a fundamental transformation of consumption and production systems. These transformations will involve a reconfiguration of combination of technologies, infrastructures, industrial structures, business models, dominant ideas and cultural discourses, distribution of resources and power, modes of production and consumption, and institutions. These factors can be influenced by environmental and climate policies, but also by the interest and effectiveness of other actors (Hughes and Lipsy, 2013). As such, processes of change involve a dynamic interplay of incentives, regulation, governance transparency and effectiveness, business environment, political regime, lobbying, and vested interests (Grin et al, 2010).

Model-based scenario analysis has become a key analytical approach to exploring low-carbon transitions in line with pre-defined future global environmental and sustainability goals. A number of different computational models are used to provide insight into transition pathways to sustainable low-carbon societies. These models, including Integrated Assessment Models (IAMs), Energy System Models, and Agent-Based Models (ABMs) extend historical trends by capturing several physical and economic causal-relationships in mathematical formulations and combining them into one single, consistent modelling framework to extrapolate our current understanding of future change over time.

Models also have limitations - they need to simplify existing systems in order to provide a transparent analytical framework. Models make different choices in selecting parts of the system they describe in detail and which parts are not or are only partially represented (see also further in this introduction). Despite their limitations, models are used to study the complex interactions between human, natural, and climate systems. They can provide insights into possible interactions between sectors and different sustainability goals (e.g. energy, food, water, and climate), linkages across topics (e.g. consequences of climate policy for land use), scales and regions (from global to subnational level, often geographically explicit), and on indirect economic linkages (e.g. sectoral shifts and rebound effects as stated by van Vuuren and Kok, 2012). In addition, model-based scenario analysis allows us to examine the relationship between near-term decisions and long-term trends and objectives by taking into account relevant system inertia. These scenarios have provided support to high-level decision-making in the fields of environment, sustainable development, and transition towards low-carbon economies. For example, the conclusions of the Fourth Assessment Report (AR4) by the Intergovernmental Panel on Climate Change (IPCC) provided the evidence for the European Union to adopt greenhouse gas emissions by 80%-95% in 2050 compared to 1990 levels to remain aligned with the 2°C global objective¹ (Gupta et al., 2007). Model-based scenarios have also been helpful in informing negotiators and heads of state during the establishment of the Paris Climate Agreement².

Although model-based scenarios will continue to be relevant as a reference for policymakers, the increasing focus on implementation and the transition dynamics toward long-term objectives requires greater attention to how the changes will take place and ways to accelerate them. With the adoption of the Paris Climate Agreement in 2015 (UNFCCC, 2015), the global community has committed itself to strengthen long-term ambition. This has heightened the interest in the dynamics that drive this change. Earlier model-based work, such as those presented in AR5 (Clarke et al., 2014), has already shifted from first-best transition pathways (fully oriented towards cost-optimality under perfect conditions) to second-best transition pathways (exploring socio-

¹ Council of the European Union, 2009. Brussels European Council 29/30 October 2009 - Presidency conclusions, https://www.consilium.europa.eu/uedocs/cms_data/docs/pressdata/en/ec/110889.pdf.

² G7, 2015. Leaders' declaration G7 summit - Think Ahead, Act Together, 7-8 June 2015, Schloss Elmau.

political and innovative limitations, e.g. Kriegler et al. 2013a, 2013b, 2014a, Staub-Kaminski et al., 2013, Tavoni et al. 2013, Riahi, 2015). However, given the rather techno-economic orientation of this type of assessment, several contextual factors (such as institutions, actors, power structures) remain rather underexposed. Contextual factors such as institutions influence the behavior both at the aggregate and individual levels. Although different types of models vary in their representation of actors, decision-making and institutions, it remains difficult to represent these factors in mathematical setting. Computational models are data-driven tools. They are inherently restricted to quantifiable, techno-economic relationships. As a result, decarbonization strategies are characterized by elements that have been empirically quantified or estimated, such as future technological performance or costs. Elements that cannot be empirically quantified or that go beyond the techno-economic realm are generally not addressed in models. Actors, individual decision-making and institutions are difficult to transform into model parameters due to pluralism (co-existing ideals, hence no clear solid trend to extrapolate). They are not always driven by rational decisions (formulas do not always apply) or by costs factors (unknown parameters in formulas).

In this paper, we look into how model-based scenarios can be enriched in order to look into the role of actors, decision-making, and institutions from a deeper engagement with social sciences (Victor, 2015), specifically from a closer collaboration with socio-technical transition studies, initiative-based learning, and applied economics. We focus on three types of quantitative system models widely used in the scenario approach to transition studies: IAMs, Energy System Models, and ABMs.

IAMs provide simplified representations of both the human and natural systems. With regard to the human systems, most IAMs are outcome-oriented, i.e. they provide insights into systemic change and focus on the consequences of exogenously specified policies, with limited attention to the processes and the social interactions leading to outcomes (Hofman et al. 2004). The representation of non-technological factors such as interactions among actors and interest groups, political economy factors, and institutions, remains stylized, as they are difficult to capture in the mathematical equations of the models (van Vuuren and Kok 2012). They also lack detail in the representation of consumer behavior and external drivers affecting policy effectiveness such as actor heterogeneity, institutions, and governance. The representation of governance and institutions is limited to the actions of the state or the government for which regulations and policies are generally represented as an exogenous shock/disruption implemented by a social planner. Some IAMs have dedicated (both explicitly and implicitly) more attention to the role of different actors and actor heterogeneity, as reviewed by Krey (2014) and Wilson and McCollum (2014). Examples of heterogeneities included in models are urban-rural divide, income distribution, and household composition (Ekholm et al., 2010; van Ruijven et al., 2011; Eom et al., 2012; O'Neil et al., 2012; Krey et al., 2012; Melnikov et al., 2012, and Melnikov et al., 2017).

Energy System Models share many of the characteristics and limitations of IAMs. They are also outcome-oriented, despite the higher level of technological detail in the energy sector. Energy system models have a stronger focus on detailed technological changes of the energy sector or of a part of it (e.g. electricity system) while the macroeconomic system is modeled exogenously, thus disregarding potential inter-sectoral feedbacks. Demand is usually an exogenous input to the model while market prices are calculated endogenously. Energy system models can be categorized into three major types: optimization models, equilibrium models, and simulation models (Ventosa et al., 2005). With respect to the representation of actors and institutions, they also represent decisions in terms of actions of one or more representative social planners and institutions can be included only in a limited, highly indirect way, for example by defining exogenous constraints or preferences factors for certain technologies.

A different approach is offered by ABMs, which are dedicated models to analyze the decision-making of different actors. They provide an explicit representation of agent heterogeneity as well as of interaction across agents (Epstein and Axtell, 1996). ABMs are designed to capture the agents' perception of the relevant aspects of their environment and their decision-making according to their rationality. They often describe the interactions among different actors that operate according to prescribed behavioral rules and can capture emergent phenomena (Farmer et al., 2015). Most ABMs focus on a relatively small region or depict only parts of the energy system, for example, investments into renewable electricity or improvements of buildings, in order to deliver an explanation of the behavioral implications of agents' heuristics and interactions with other agents. These factors are assessed as being critical in determining the pathway of technology uptake and performance and are not captured in detail in other types of models.

The differences in the representation of actors, decision-making, and institutions between IAMs, energy system models, and ABMs arise from their different objectives. IAMs are intended to illustrate long-term, global emissions and technology pathways. Energy System Models are intended to provide more technologically detailed information on the energy system, while ABMs are intended to illustrate possible pathways of change at the level of individual decision-making. IAMs and Energy System Models are cost-oriented models as the decisions in these models are based on explicit (e.g. preferences) and implicit (e.g. capital, operation and maintenance) cost parameters, while decisions in ABMs depend on a richer diversity of technological and non-technological factors.

The remainder of the paper is organized as follows; Section 2 provides a detailed discussion on the models' assumptions regarding actors, decision-making, and institutions by drawing on four models used in the PATHWAYS³ project, Section 3 discusses opportunities for model improvements, and Section 4 concludes.

2 Representations of actors, decision-making, and institutions in models

This section describes how three types of models – IAMs, Energy System Models, and ABMs characterize actors, their decision-making, and institutions. We build on the examples provided by the four models used in the PATHWAYS project: two IAMs - IMAGE (Stehfest, van Vuuren et al., 2014) and WITCH (Emmerling et al., 2016), one Energy System Model - Enertile⁴, one ABM - MATISSE-KK (Köhler et al., 2009).

Section 2.1 describes the decisions makers in the models, the key decision variables, and the decision-making process. The decisions of actors are primarily determined by technological factors, as well as institutional factors (discussed in Section 2.2). The definition of institutions vary across disciplines; for the purposes of this paper we refer to Scott's definition (Scott, 1995) of institutions as including regulative, normative, and socio-cognitive institutions (Table 1).

³ www.pathways-project.eu/

⁴ www.enertile.eu

Table 1: Different types of institutions

	Regulative	Normative	Socio-cognitive
Examples	Formal rules, laws, sanctions, incentive structures, reward and cost structures, governance systems, power systems, protocols, standards, procedures	Values, norms, role expectations, authority systems, duty, codes of conduct	Priorities, problem agendas, beliefs, bodies of knowledge (paradigms), models of reality, categories, classifications, jargon/language, search heuristics
Basis of compliance	Expedience	Social obligation	Taken for granted
Mechanisms	Coercive (force, punishments)	Normative pressure (social sanctions such as 'shaming')	Mimetic, learning, imitation
Logic	Instrumentality (creating stability, 'rules of the game')	Appropriateness, becoming part of the group ('how we do things')	Orthodoxy (shared ideas, concepts)

Source: Scott 1995

2.1 Actors and decision-making

Table 2 summarizes the main features regarding the representation of actors and decision-making in models. WITCH, IMAGE, and Enertile are cost-oriented models that do not represent individual decision-making. We can distinguish between optimization/equilibrium models (implicit social planner with limited/perfect foresight) and simulation (recursive decision-making based on a representative agent and the relative costs differences for concurrent services and technologies per year). In WITCH and Enertile, decisions are taken by one or more social planners, who make a top-down decision between a broad set of investment choices and consumption. In WITCH, regional social planners maximize a welfare function and choose the intertemporal resource allocation between consumption and investments. While in Enertile, a European social planner minimizes total system costs across technologies and across EU countries. In the case of IMAGE, decisions regarding services and technologies are made based on the relative costs of an ensemble of choices, which are specified per region and vary dynamically over time or exogenously. The relative costs consist of explicit (e.g. capital, Operation and Maintenance (O&M) and implicit (e.g. preferences) costs factors that combine technological and economic components. Using a so-called multinomial logit approach, those factors representing the sensitivity to price differences create heterogeneity in consumer preferences.

Despite the limited explicit representation of actors, it can be argued that a multitude of actors is implicitly accounted for in the investment decisions through specific variables (Table 3). Even if the same technology is adopted in different scenarios, the associated actors may differ depending on the narrative assumed. Investments in solar PV, for instance, can be made by large utilities in the form of large-scale PV or by consumers in the form of small-scale rooftop PV. While Enertile distinguishes these two technologies, IMAGE and WITCH do not yet. This means that depending on the respective scenario, two technologically similar results may have to be interpreted in different ways in terms of associated actors. Apart from cost-specific investment decision variables, conditional settings may be used to represent various non-cost related factors in the scenarios. For example, conditional settings can promote or limit the use of a specific technology or service, emulating a managerial decision process in a specific region, sector, or supply-chain.

Table 2: Action positioning and strategies in different types of models

Action positioning and strategies	IMAGE Simulation IAM	WITCH Optimization IAM	Enertile Optimization energy system model	MATISSE-KK Agent-based model
Actors	Implicitly represented, decisions are described for individual markets. Differentiation between urban and rural households.	Aggregate regional social planners	Aggregate European social planner	Agents or behaviors are modeled explicitly, consumers, niches, regime
Decision variables	Investments and dispatch	Investments and dispatch	Investments and dispatch	Niche and Regime: Direction of technological change Consumer: Technology - lifestyles adoption
Decision-making	Constrained cost minimization without perfect foresight	Constrained welfare maximization with perfect foresight	Constrained cost minimization with perfect foresight	Niches: change the technology-lifestyle characteristics to survive Regimes: maximize market share Consumers: adopt the regime or a niche lifestyle/technology

Source: Authors' compilation

Table 3: Examples of implicit actors in models

Factors influencing investment decisions in models	Associated actor
Purchasing price	Manufacturers / R&D
Fuel cost	OPEC
Preferences	Consumers
Capital costs	Investors
O&M costs	Mechanics
CO2 tax	Government
System integration costs	Energy companies
Cost curves	Research institutes
Conditional settings	Politics

Source: Authors' compilation

A detailed and explicit representation of actors is provided in the MATISSE-KK model, which also incorporates the concepts of niches and the regime in the sense of the Multi-Level Perspective on transitions (MLP) as individual agents (Köhler et al, 2009), with a focus on the sector mobility. In this specific context, a regime refers to the dominant structure consisting of the dominant culture and practices in a system. The regime in mobility is the conventional internal combustion engine, which the majority uses for most of their mobility needs. Niches refer to individuals or a small group of actors with local practices, which differ from the regime and consumers choose whether to adopt the regime or a niche lifestyle/technology. A large number of simple agents whose function is to allocate support to the regime or a niche determine the relative strength of the regime and niches. The MATISSE-KK ABM is intended to address changes in society through changes in mobility patterns or lifestyles. These changes are modeled as the decisions of households to keep the current pattern of mobility or to change it.

A common element across the four models in Table 2 is that the adoption or investments in technologies are the key decisions being made by models' actors (e.g. decision variables, Table 3). The decision of actors is primarily determined by technological and contextual factors. Technological factors describe the characteristics, costs, and environmental performance of

technologies in terms of lifetime, efficiency, learning, and emission performance and include factors representing economic considerations such as costs. Contextual factors include social and behavioral changes or regulatory changes such as the implementation of climate policy or of technology subsidies, which we refer to as institutions in a broad sense including socio-cognitive and normative dimensions as in Table 1. These factors can be implemented as external impulses or shocks imposed by modelers (e.g. by constraining the availability of a specific technology to reflect societal or political shifts), as exogenous changes in model parameters (e.g. by changing the substitution possibilities between technologies), or can be translated into (perceived) price-based factors (e.g. preferences for specific technologies can be simulated by adjusting the interest rate for those technologies).

Despite the similarities across models in the key decision variables, the decision process describing the choices made (e.g. decision-making, Table 2) varies across models. Full optimization models with perfect foresight (WITCH and Enertile) have full future knowledge and they optimize investment decisions accounting for the whole time horizon. In WITCH, investments decisions are based on country-specific returns on investment (endogenous in the model), which in turn are affected by exogenously specified capital and operation and maintenance costs. WITCH builds on neoclassical economic theory, viewing agents as rational with a clear objective achieved through optimization. Both WITCH and Enertile rely on rational choice and optimizing decision-making rules in the form of either welfare maximization or cost minimization. Simulation models such as IMAGE assume no future knowledge and optimize investment decisions year-by-year in a recursive-dynamic way. Investment choices are based on relative technology costs, assuming a fixed discount factor (by default set at 10%). Technology costs also includes a perceived factor, which is calibrated based on historical investment data.

ABMs such as MATISSE-KK specify different rules and can differentiate them by type of agents. Consumers decide about the adoption of the regime or niche technologies based on a set of attributes (practices) including environmental performances (e.g. emissions), technology costs, demand split, Information and Communication Technologies (ICT) use, and the structure of the built environment with regards to provision for the different transport modes. Consumers choose regime or niches technologies/lifestyles based on their attractiveness based on their preferences. The technologies or lifestyles form niches and a regime, which are also represented as agents in the model. The regime and niches change their practices as technology improves and depending upon the support that the technology/lifestyle receives from the consumers. Preferences can be influenced by the contextual factors provided by the landscape, which is exogenously characterized. Landscape signals change the preferences of simple agents and hence their support decisions can also change the fitness of the regime and niches.

With the exception of ABMs, the representation of actors and decision-making remains very limited. Limitations concern the lack of heterogeneity in agency, the weak empirical foundation of behavioral parameters and rules, the decision criteria being most often based on rational choice models, and the assumption of perfect knowledge regarding the objective to be achieved.

2.2 Institutions

In models, institutions are often represented by exogenous decision rules describing the decision process of aggregate/representative actors or by exogenous factors influencing the outcome of the decision process. Table 4 summarizes the representation of regulatory and normative and socio-cognitive institutions by different models. Formal regulatory institutions as implemented by national or transnational political organizations are the main type of institutional change commonly implemented by IAMs and Energy System Models in transition scenarios. The main institutional drivers of change in regulatory institutions are in the form of different climate policy

instruments (e.g. carbon tax and emission trading scheme) and policy targets, which can be sector or technology specific (e.g. a PV subsidy). In the new scenario framework of the Shared Socioeconomic Pathways institutions are accounted for quantitatively with the concept of Shared Policy Assumptions (Kriegler et al., 2014a). These assumptions describe three attributes of climate policies; 1) climate policy goals, 2) policy regimes and measures, and 3) a description of how implementation limits and obstacles are addressed.

When implemented, regulations are commonly assumed to be effective at achieving the objective. In both IAMs and Energy System Models, policies are often simply represented by a global uniform carbon tax or price applied to all sectors and regions, assuming cost-optimization over sectors, regions, and time (Clarke et al., 2009 and Kriegler et al., 2013b) with the main goal of providing insight into cost-efficient reduction strategies. Once the policy is adopted, its effectiveness is generally assumed to be unaffected by the institutional framework, as models assume the same governance style and power structures over centuries (top-down steering) – which creates stylized pathways.

Even though the focus of the economic-oriented approach of models driven by technological factors is on the effects of regulations and policy prescriptions, contextual factors and normative dimensions (such as beliefs, mindsets, preferences, normative aspirations, and the notion of what is good) are also implicitly included in model assumptions and parameter choices.

In optimizing macroeconomic models, normative assumptions are embedded in the welfare function. The welfare function is used for intertemporal optimization, a process to evaluate the trade-off between current and future consumption. The representative agent of the models, a benevolent national or supranational government, decides the allocation of resources between consumptions and savings. Similar to individual decisions on consumption and savings, this decision depends on the subjective degree of risk aversion and the importance given to future consumption. A similar reasoning applies when considering the decision to choose between investing in clean energy to reduce the future damages from climate change or to achieve a long-term mitigation target. Models specify parameters affecting discounting of the future. These include the pure rate of time preference describing the weight of future generations in intertemporal welfare considerations and the intertemporal elasticity of substitution describing the willingness to smooth consumption over time. Lowering the discount factor in models places more weight on the future relative to current costs and benefits, and therefore favors technologies with high initial investment such as wind power which, after the initial investments are carried out, delivers power at almost zero marginal cost.

Socio-cognitive institutions, referring to priorities, problem agendas, and beliefs, can be represented in IAMs and Energy System Models implicitly by specifying different preferences for energy technologies by changing their relative costs. For example, societal preferences for energy technologies can be represented in an implicit way through ad-hoc adjustments in costs, or exogenous shifts imposed by modelers (e.g. phasing out of nuclear power, opposition to CCS, and services versus ownership). A premium factor (subsidy, tax, or preference for a certain technology) to modify costs can be included to calibrate against historical data. Indeed, according to historical data, it is clear that some technologies have a higher market share than can be explained by costs only.

ABMs can control for normative institutions such as values regarding lifestyle expectations of roles for individuals in energy and mobility systems and markets and socio-cognitive institutions explicitly. The MATISSE-KK model has consumer agents characterized as having different weights for different mobility lifestyles. The acceptance of households as power suppliers into the

grid can also be represented by the inclusion of consumer power producers. Changes in norms about energy and mobility behavior (e.g. lowering indoor temperatures to save on energy use or a driving style that minimizes energy use rather than driving as fast as possible) can be modeled by modifying energy and fuel demand functions for the relevant technologies. This can be done for a representative consumer/producer and for a distribution of consumer and producer decision-making types. In MATISSE-KK socio-cognitive institutions are represented more explicitly, for example by weighting of climate issues in consumers' decisions.

Table 4: Representation of institutions in different types of models

Institutional change	IMAGE	WITCH	Enertile	MATISSE-KK
Regulatory	Formal regulatory institutions as exogenous policy targets or instruments, e.g. carbon/energy tax; subsidies; standards; prescribed technology market shares; emission targets	Formal regulatory institutions as exogenous policy targets or instruments, e.g. like in IMAGE	Formal regulatory institutions as exogenous policy targets or instruments, e.g. like in IMAGE Adjustments in land use, technology and fuel prices or emission prices /limits	Formal regulatory institutions as costs and environmental performance of the regime/niche. Changes in relative prices, changes in relative emissions performance, changes in service level of alternative modes, changes in urban form
Normative & Socio-cognitive	Exogenous discount rate. Although the model formally does not optimize over time, it includes an iteratively process to find the cheapest pathway to achieve a set climate target. Discounting affects the outcome in the optimization procedure. Preferences for energy technologies based on relative costs: explicit and implicit non-monetary parameters changing the preference hierarchy for technologies and services, cheap technologies gain a higher market share. Costs include a (positive or negative) premium factor, which can also be interpreted as a subsidy, tax, or preference for a certain technology.	Discounting, given by 1) the weight assigned to future generations in the intertemporal welfare function 2) the willingness to smooth consumption over time. Discounting affects the outcome in the optimization procedure. Preferences for energy technologies based on relative costs and substitutability.	Discounting affects the outcome in the optimization procedure Interest rate driving investment choice in specific energy technologies Preference for technologies based on relative costs and substitutability.	Weighting of support for different technologies-lifestyles. Weighting of climate issues in consumers' decisions. Rates of change of preference parameters (e.g. consumer preferences and niche strategies) Changes in relative prices, changes in relative emissions performance, changes in service level of alternative modes, changes in urban form

Source: Authors' compilation. The table is not meant to be exhaustive but to provide illustrative examples.

Overall, we can conclude that the representation of institutions in models is stylized. ABMs offer a richer framework for characterizing institutional heterogeneity, though still mostly exogenously

as specified by the modeler. While institutions affect the decision process in models, actors cannot affect the broader institutional setting. Although the elements of models can be associated with different assumptions on institutions, modelers usually exogenously specify them.

3 Improving the representation of actors, decision-making, and institutions in models

The need to improve the representation of the behavioral and institutional components in IAMs is being explored by a growing number of researchers⁵. Work in this direction is necessary as the increasing focus on implementation and the transition dynamics toward long-term objectives requires more attention on how the changes will take place and ways to accelerate them. Opportunities to improve behavioral realism, the degree of heterogeneity, and the representation of institutional and governance factors can arise through collaboration among scientists from different disciplines such as modelers, sociologists, empirical economists, and political scientists. This section discusses possible routes of improvements in the modeling of actors, their decision-making, and institutions. Section 3.1 discusses the opportunities that arise by means of i) making use of transition narratives, ii) improving actor heterogeneity, iii) linking empirical evidence and modeling tools, iv) linking ABMs and IAMs, and v) linking initiative-based learning and modeling. Section 3.2 discusses whether the existing framework of IAMs, Energy System Models, and ABMs can attend to the institutional dimensions outlined in Table 1 or whether the analysis of the governance of transition pathways should instead rely on a partnership with other approaches.

3.1 Actors and decision-making

As discussed in the previous sections, models rely on mathematical equations, variables, and parameters to quantitatively describe contextual factors that influence models' choices in addition to price and technological factors. When establishing different climate policy scenarios, models generally vary the regulatory or technological dimension (Kriegler et al., 2013a; 2013b; 2014a; Tavoni et al., 2013) but social and behavioral factors are often left unchanged. Stabilization scenarios aimed at achieving a predefined level of greenhouse gases concentration are often characterized by incremental changes and technological substitution without requiring major reconfiguration in the underlying societal configuration of actors. The remainder of this section discusses several ways to improve the representation of actor and decision-making explored in the PATHWAYS project, via more detailed narrative structures and by pursuing model refinement.

Transition narratives based on insights from Multi-Level Perspective studies

In order to provide better heuristic insights on long-term sustainability transition scenarios, the PATHWAYS project has applied a new interdisciplinary approach that systematically bridges through a form of soft integration (Turnheim et al., 2015) by aligning quantitative system modelling with socio-technical transition studies⁶.

Insights from the MLP assessment have been used to refine the quantitative transition scenarios from models, with the aim of developing a richer narrative than assumed under cost-optimality.

⁵ See for example COBHAM (http://cordis.europa.eu/project/rcn/191138_en.html), ADVANCE (<http://www.fp7-advance.eu/> and Wilson and Mcollum, 2014), WholeSEM (<http://www.wholesem.ac.uk/>).

⁶ See van Sluisveld et al., (2016) for a detailed description of this form of integration, specifically, MLP theoretical framework (Geels, 2002 and Geels and Schot, 2007).

Starting from a typology of transition narratives (Geels and Schot, 2007) based on selected case studies; two archetypical transition pathways have been defined. Two global IAMs - IMAGE and WITCH – have been used to set the boundary conditions for five domains: electricity, transport, heating, agri-food, and land use. The two pathways achieve the same quantitative goals in terms of emission reduction and carbon budget but entail a different constellation of systemic change with respect to the configuration of actors and institutions, or in the MLP jargon, in terms of niches, regimes, and landscapes. In the pathway named “technological substitution”, the currently dominant and incumbent actors are at the center of the transition process, which is characterized by changes in technical components. The pathway named “broader regime change” entails a shift to a new socio-technical system based on the breakthrough of radical niche-innovations that involve not only technical change but also wider behavioral and cultural changes supported by new institutional and systems of governance. The MLP assessment has classified a number of niche-innovations (from specific technologies to new methods and practices for mobility and heating) with respect to their potential towards the near future (e.g. momentum) and in terms of configuration of actors driving the change (e.g. incumbents versus new actors). Input parameters in models have been used as levers to integrate qualitative insights regarding actor reconfigurations and to represent exogenously defined social developments or actor preferences. Broader regime changes entailing actors’ reconfiguration by changing key model assumptions and parameters connected to social and behavioral factors and implicitly to different actors, summarized in Table 5.

In the electricity domain, to emulate an increased interest in solar-PV systems the WITCH, IMAGE, and Enertile models introduced external impulses to represent regulatory (e.g. subsidy) and technological changes (e.g. faster social learning reinforcing technical learning) by modifying the cost of PV and thus the penetration and momentum of that particular technological option. In Enertile, a change in preferences towards a higher willingness of small actors to invest in solar-PV was simulated by lowering its cost and interest rate, which can be interpreted as representing different underlying developments. The first option is government support targeted at policies to lower interest rates or costs for solar-PV investments. These might include special state-aided loans to encourage investment or feed-in-tariffs. The second option is that a low interest rate represents a high acceptance among private investors, who lower their profit expectations in favor of investing in a new promising technology.

In the mobility domain, the IMAGE model mostly focuses on the allocation to various transport modes and the composition of the vehicle fleet for each mode. Actor heterogeneity can only be expressed as a reconsideration of preferences for modes and vehicles used to meet the total travel demand. Some degree of behavioral change can be implemented by tweaking specific parameters such as vehicle occupancy rates, time, and monetary budgets for travel and preference factors that increase the weight on one mode or vehicle over the other. As such, IMAGE has emulated mode shifts and car sharing by increasing the preferences for public transportation and by increasing the vehicle occupancy rate. Moreover, the total travel budget has been lowered to emulate an overall decrease in travel demand as a consequence of urban reconfiguration towards a compact city scheme.

In WITCH, similar changes have been made (i.e. a slower increase in vehicle ownership, an increase in the vehicle occupancy rate, and a decrease in travel demand). While in MATISSE-KK, a change to either car sharing, domination of a public transport based lifestyle, or a mobility lifestyle based on cycling and walking requires not only a change in preferences towards less CO₂ emissions but also a change in consumer preferences towards mixed use of urban structures and a shift away from private conventional car ownership.

In the heating domain, the IMAGE model implemented lifestyle and behavioral changes in terms of heating demand reduction due to more efficient insulation, smaller dwelling sizes, reduced rate for appliances, and a more efficient use of household appliances. A more in-depth discussion of the implementation and the initial parameterization can be found in van Sluisveld et al., (2016).

Increasing actor heterogeneity

If we follow the insight that more disaggregated and detailed IAMs are more appropriate to address socio-technical transitions (as stated in Li et al., 2017), then further model-development towards such direction is desirable⁷. As the IAM community is following a trend to refine existing model structures and disaggregate their processes into more specific processes on a higher resolution (Edmonds et al, 2012), one could assume that IAMs will become more appropriate for soft integration with social sciences over time. By creating a more explicit representation of either (1) processes or the (2) representative agents, IAMs allow further inspection of the impact of these elements in forward-looking low-carbon transitions studies.

A richer model structure will offer more levers that could be used to integrate inputs and insights from other disciplines, providing further opportunities to address social actor behavior within the broader scope of global system change modelling (Li et al., 2017). Table 5 illustrates how IMAGE due to its richer characterization of the heating and transport sector, was able to implement a number of interventions to simulate social and behavioral change. Actor heterogeneity can be accounted for by making regional and demographic elements explicit, through differentiating between urban and rural areas, income classes, and cultural variation in energy demand. The decision mechanisms, however, remain broadly driven by techno-economic considerations without endogenously incorporating socio-technical aspects and influences. Hence, another line of development is to make actor behavior more internally dynamic and conditional to non-economic factors. For instance, recent developments in the IAM community have focused on expanding the representations of actors by explicating several types of “consumer groups” in the transport sector (e.g. McCollum et al., 2016, in review). Specific attitudes towards technology adoption (e.g. early adopter, laggard) are implemented by monetizing qualitative concepts (such as preference, social influence, and risk aversion) and including these as factors in the decision-making mechanisms of the computational models.

Another example is provided by the MATISSE-KK model, which has a range of parameterizations for different actor groups (Köhler, et al, 2009). The four main groups are; “conventional” car drivers, “green” car drivers, public transport users, and cyclists/pedestrians. The groups have different preferences that reflect the characteristics of the dominant technologies in each of these mobility lifestyles. An important limitation is that the agents are still individual decision makers, although there is strong evidence that individual consumers are influenced by the surrounding culture and social contacts (Shelley, 2012; Köhler, 2006). While the MATISSE-KK model does allow changes in preferences over time as a representation of changes in mobility culture in the society to reflect situations such as an increasing priority of emissions reduction, the model could be extended to include direct interactions among the individual consumer agents.

⁷ Contrary to the idea that disaggregation of complex IAMs yield more appropriate model results for socio-technical transition analysis, some scholars would therefore argue that more simple and transparent models could be equally as effective in being a heuristic tool of future change as a further specialized high-resolution IAM (Risbey et al., 1996; Rotmans and van Asselt, 2001; Worrell et al., 2004). Indeed it could be argued that refinement may (1) add to the parametric uncertainty in the model (Rotmans and van Asselt, 2001) as well as (2) maintain (or “lock-in” into) the techno-economic perspective (with the human dimension having no direct analogue in IAMs) (Rotmans and van Asselt, 2001), which could paralyze or substantially delay any further collaborative effort with other disciplinary fields (Voinov and Bousquet, 2010).

Table 5: Examples of intervention changes to simulate actor re-configuration in transition pathways

		IMAGE	WITCH	Enertile	MATISSE-KK
Electricity	PV	Equalize PV price to overall electricity price	Learning rate to +25%, floor cost - 12.5%	Lower interest rate Higher land availability	
	Car sharing	Increased vehicle occupancy	Increased vehicle occupancy		Government support and publicity for car sharing. Restrictions and taxes on private car use, leading to increased costs and lower convenience of driving your own ICE car.
Mobility	Transportation mode	Reducing available travel budget per person Increased preference for public transport	Lower travel demand and vehicle ownership growth		Change in lifestyle, with less car use, more emphasis on environment and on mixed zones and public transport
	Low-energy housing	15% energy reduction due to improved insulation			
Heat	Behavioral change/ Smart metering	Change base temperature by 1°C No growth of appliance ownership after 2010 No tumble dryer after 2010 More efficient use of appliances			
	Lower size of dwelling	Floor space is fixed to 2010 values (rural 50m ² /cap and urban 40m ² /cap)			

Source: Authors' compilation.

Empirical evidence and modeling tools

Table 5 illustrates examples of model parameters that offer a lever to integrate evidence from other disciplines. Empirical evidence from microeconomic studies could be used to introduce increased heterogeneity in preferences and behaviors across sectors and regions. There is indeed a broad empirical literature on microeconomic behaviors related to technology adoption, highlighting the great variety of technical and non-technical determinants of technology investments and adoption that could be used for this purpose. For opportunities in this direction see (Mundaca et al., 2010; Wilson and McCollum, 2014; Wilson et al., in review).

ABMs and IAMs

In theory, it is possible to develop Agent-Based IAMs. The simplest possibility would be to have two different types of agents rather than a single representative agent or a centralized social welfare maximizer. However, this would represent a change in the underlying theory, which would require a reconsideration of other principles of the model as well. An alternative approach is to use the results of ABMs to inform the calibration of the IAMs. For example, results from an ABM could be used to adapt the rate of technology adoption in the IAMs, or to enrich the set of solutions for society that go beyond technological substitutions. This could be achieved by defining these lifestyle solutions and their emissions and price characteristics as part of the choice sets in the IAM. In the field of passenger transport, an example of such a lifestyle change could entail a change from personal automobiles to public intermodal transportation. This could be achieved by changes in the preference structure of the consumers and by changes in the

generalized costs of the different modes. In the field of energy, this could involve a shift from buying energy as a consumer to becoming a combined supplier and consumer, with an automated energy management system optimizing a combination of decentralized generation, energy storage, and energy purchase - depending on real time current prices and costs.

Initiative-based learning and modeling tools

The evidence from initiative-based learning can also be used to enrich the representation of actor behavior and decision-making in models. De Cian et al. (2016) explore whether the evidence from initiative-based learning can be combined with IAMs to offer a more realistic representation of learning dynamics in the context of solar PV technologies. Whereas initiative-based learning highlights learning mechanisms involving the interaction among agents and actors (social learning), IAMs emphasize the learning mechanisms related to the process of production and use of specific technologies (learning-by-doing). IAMs rely on empirical evidence to parameterize the learning curves describing learning-by-doing dynamics but the empirical estimates 1) span a very broad range and 2) are not able to disentangle the role of less tangible forms of learning such as social learning. The omission of the less tangible forms of learning may have important implications for the future penetration of technologies, energy transition, and energy systems in scenarios. A systematic analysis of a large sample of case studies, with a great attention to the unfolding of short-run learning dynamics, could yield robust general patterns that could be used by IAMs. In turn, IAMs could assess the sensitivity that learning dynamics have on energy and technology scenarios and could interpret the results in light of the insights provided by other disciplines such as initiative-based learning.

3.2 Institutions

As discussed in section 2.2, quantitative system models represent institutions either implicitly or in an exogenous, ad-hoc manner. As a consequence, models are unable to generate insights into the institutional changes entailed by certain transitions that rely on broader systemic changes. In this section we describe two different opportunities for enriching this component; i) linking the applied economic literature and modelling and ii) comparative analysis of transition pathways.

Linking the applied economic literature and modelling

The applied economic literature on the environment and institutions can offer empirical guidance by establishing quantitative patterns and stylized facts that can be used to improve models' representation of institutions. It examines relationships between institutions as described in Table 1 and indicators of policy adoption, policy effectiveness, and environmental outcomes quantitatively, relying on observed historical data. The literature provides empirical evidence on reduced-form relationships between decisions variables (e.g. R&D investments, policy stringency Dasgupta, De Cian, and Verdolini, 2016), outcomes (e.g. energy intensity, green investments, emissions), and institutional contextual factors at the aggregate country level, which is the scale relevant to most models.

In this context institutions and governance refers to the actions of the state or the government. Governance is defined as the traditions and institutions that determine how authority is exercised in a country (Kaufmann et al., 2010). Institutions are grouped into legal, political, and economic institutions (Acemoglu et al., 2005). Legal institutions take the form of legislature, public or state-devised legal institutions, and private legal institutions, while political institutions shape policy decisions by constraining the set of feasible choices of the decision-makers and by creating and enforcing laws, and governmental policy making. The most commonly used indicators are the Polity IV indicators (democracy, autocracy, and polity), the World Governance Indicators (rule of

law, voice and accountability, government effectiveness, and control of corruption), the Freedom House Index, and corruption perception index from Transparency International⁸. The main insights from this field of study as summarized by Dasgupta and De Cian (2016) are:

- Democracy, civil and political freedom, transparency, and free flow of information allow the electorate to exert policy pressure on the government and facilitate or constraint the ability of governments to implement environmental measures. Therefore, democratic countries and open societies are generally associated with more participation into international environmental agreements and with better performance in terms of environmental indicators.
- Good governance encourages the adoption of environmental policies and generally leads to better environmental outcomes.
- Corruption can be a channel for environmental degradation, as it could lead to a sub-optimal use of resources and inefficiencies.

These results suggest that institutional factors such as corruption, transparency of governments, the quality of bureaucratic quality and speed, are likely to influence the ability to implement environmental policies, the type of policy chosen, policy stringency, as well as the effectiveness of the policy implemented. This is in contrast for example with what generally is assumed by models, where environmental policies, once implemented, are equally effective across regions. Indeed, despite the existence of quite a broad empirical literature on institutions and the environment, that evidence has not been used explicitly in models. The empirical evidence available in the current literature might not be suitable to be directly used in models, either because the empirical specification is not directly comparable to the equations used in the computational models or because the indicators used are not represented in the models. For example, the empirical literature has focused mostly on physical environmental performance indicators such as emissions and less so on decision variables such as investments. In the case of environmental policy decisions, the focus has been on dated policy adoption choices (e.g. ratification of the Kyoto Protocol). An example of tailoring empirical evidence for use in models is provided by Iyer et al., (2015), which use historical data to conclude that investment risks are higher in regions with inferior institutions. That empirical result was then used to differentiate investment risks across regions in an IAM to assess the implications for regional mitigation costs.

Future empirical research could explore the role of institutions in contexts that are more relevant for futures studies on low-carbon energy transitions. For example, a parameter of high relevance in decarbonization studies is energy intensity. IAM-based scenarios suggest strong absolute convergence in energy intensity across regions not only in the long run but also in the short run. However, empirical evidence does not necessarily support this assumption (Le Pen and Sévi, 2010). Instead, conditional convergence, i.e. countries tend to converge in energy intensity if they share common characteristics, seems more likely. Introducing more realism in the characterization of energy intensity convergence can improve the reliability of assessments of climate policies using models. Comprehending the institutional factors that hinder convergence is also important to understand the complementary measures that need to be implemented in order to ensure policy effectiveness. Model-based scenarios assume strong convergence in energy intensity across regions, requiring improvements rates that for some regions (e.g. energy exporters) to far exceed their historically observed rates. The question is why those regions have lagged behind in terms of energy efficiency? Is it reasonable to assume that those reasons will disappear in the future? If not, what are the implications of considering the institutional barriers that have prevented energy intensity convergence also in future scenarios?

⁸ See Dasgupta and De Cian (2016) for a detailed review of institutional indicators used in this literature.

Comparative analysis of transition pathways

In the PATHWAYS project, a comparative analysis of transition pathways has been proposed by exploiting complementarities between MLP and quantitative system models. Starting from the quantitative, techno-economic oriented scenarios (Hof et al., this issue; Sluisveld et al., this issue), richer socio-technical scenarios describing the change needed in order to make those scenarios materialize have been developed (Geels et al., this issue). These socio-technical scenarios focus on societal and behavioral aspects such as types of actors, their goals, strategies, and resources (e.g. role of policy makers versus civil society) as well as institutional change (e.g. social and cultural changes to foster social acceptance of new technologies). Given the broad definition of institutions used in this paper, the transition narratives approach described in section 3.1 to enrich actor and decision-making representation in models using MLP insights also involves some degree of institutional changes to some extent (e.g. see definition provided in Table 1). Some of the interventions described in Table 5 are indeed regulatory changes (e.g. government support for car sharing in the MATISSE-KK model) and social and behavioral changes (e.g. preferences for technologies).

Neither the approach that links the empirical evidence and modeling nor the comparative analysis of transition pathways would require major structural changes in quantitative system models, as they do not intend to achieve full integration. As a consequence, institution dynamics remain exogenous. Introducing endogenous dynamics of institutions more explicitly in the models used in transition scenarios would require deep structural changes in IAMs. However, depicting both large energy systems and more complex social systems in the same model would imply extremely high computational requirements and extensive result evaluation processes. Schmitt (2014) developed a numerical IAM to analyze how endogenous political turnover between governments with heterogeneous preferences with respect to the level of greenhouse emissions affect climate change mitigation policies. The model builds on WITCH but a number of simplifications were made to keep the problem computationally tractable. In other words, a richer and endogenous representation of institution dynamics comes at the cost of realism with respect to the techno-economic components, which is the strength of quantitative models such as IAMs.

4 Conclusions

Adopting greater realism with respect to the representation of actors, decision-making, and institutions is important to improve the understanding transitions towards a low-carbon sustainable society since actors, decision-making, and institutions are the defining elements of transition pathways. In this paper, we explore how this can be done by adopting model-based scenarios. The increasing focus on implementation and transition dynamics towards long-term objectives requires a better understanding of what drives change and how those changes can be accelerated. We have explored opportunities that arise from a deeper engagement of quantitative systems modeling with socio-technical transitions studies, initiative-based learning, and applied economics.

By focusing on three types of quantitative system models, we find that, with the exception of ABMs, the explicit representation of actors and decision-making remains very limited. Limitations concern the lack of heterogeneity in agency, weak empirical foundation for behavioral patterns and rules, decision mechanisms driven by techno-economic relationships and rational choice paradigms, the assumption of perfect knowledge of the objective. The representation of institutions is also stylized and implicitly accounted for in quantitative systems modelling. ABMs include a richer representation of institutional heterogeneity but within the limitations of quantitative computational modelling (exogenously as specified by the modeler).

Although actors, behaviors, and institutions are recognized to affect the emulated decision process in computational models, many of the socio-institutional factors remain highly stylized and are only captured through proxies. To expand on the knowledge, a number of opportunities for enriching the realism in model-based scenario analysis have been identified:

- i) Using detailed transition narratives developed by socio-technical transition studies to provide context to missing elements in quantitative systems modeling.
- ii) Model refinement in the form of improving actor heterogeneity will provide more explicit leads to assess the influence of actors, behaviors, and institutional change.
- iii) Expanding the disciplinary scope by linking modelling tools with the applied economic literature, ABMs, initiative-based learning, and by developing comparative analysis of transition pathways.

Some of these opportunities entail a higher degree of integration across different analytical and disciplinary approaches (e.g. ii), whereas others rely on softer forms of integration (e.g. i and iii). Other opportunities (e.g. comparative analysis) focus on a pluralism of perspective approach, exploiting complementarities to provide a multi-perspective assessment of transition pathways, whereby quantitative techno-economic scenarios are accompanied with richer qualitative storylines describing the broader institutional and governance changes required to support systemic changes.

The extent to which different analytical and modelling approaches from the different disciplines can be linked varies but it generally entails establishing common concepts, agreeing on common problem frame that requires integration, identifying operational linkages, and agreement on parameters, metrics, indicators, and data. Integrating a much wider combination of real life aspects and dynamics into models leads to an increased complexity that would restrict them to smaller fields of applications (e.g. sectoral analysis, country-level analysis). The respective weaknesses are inherent in their approaches and existing models are unable to cover all aspects of energy transition simultaneously. Therefore, in future exercises, a well-defined combination of models covering the same domain (e.g. electricity, heat) complemented by other social science approaches could deliver new insights. Such an approach would also allow combining the strengths of the different approaches rather than trying to work around their respective weaknesses.

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