Three methodological contributions towards modelling endogenous policy-emergence in societal transitions

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Abstract

Today we are facing many politically driven sustainability transitions in complex sociotechnical systems. Sustainability transition scholars look at these transitions with their own theoretical lenses, often paying too little attention to the interactions of power, politics and agency. While simulation is a useful method to address the complexity of long-term sustainability transitions, the number of transition studies using simulation is limited, as the field is still dominated by the use of qualitative case studies. This has recently been recognized by transition scholars, advocating various levels of integration of case studies, theoretical frameworks and simulation methods. However, a process to support the development of coherent and conceptually compatible mixed-methods research design is still missing. Furthermore, modeling and simulation studies are often lacking the theoretical foundations to model the intricacies of transitions at the micro-level, due to a lack of formalized transition frameworks at a low level of abstraction.

In this thesis three methodological contributions are made towards modelling endogenous policy-emergence in societal transitions. First, system dynamics simulation is proposed as a method to perform a meta-analysis of Swiss energy transition scenarios, providing new insights in system level uncertainty and sensitivity, as well as policy levers. Second, a mixed-methods process model is developed based on a comprehensive literature review of sustainability transitions studies. The process model addresses the theoretical and conceptual compatibility of prominent transition frameworks and relevant simulation paradigms, facilitating the design and reporting of coherent mixed-methods research designs. Third, a formalization of the multi-level perspective is developed at the level of agents to better address the role of individuals in sustainability transitions, as well as to internalize policy-making. The presented formalization refines and extends the closely related concepts of power, agency and politics.

Keywords: agency; meta-analysis; mixed-methods; politics; power; simulation; sustainability transitions

Résumé

Aujourd’hui, nous faisons face à un nombre croissant de transitions durables partant d’initiatives politiques dans des systèmes technico-sociaux complexes. Ces transitions sont étudiées par des chercheurs utilisant une approche théorique mais qui accordant le plus souvent trop peu d'attention aux interactions de pouvoir, de politique et d’agence. Alors que la simulation est une méthode utile pour prendre en compte la complexité des transitions durables à long terme, le nombre d’études utilisant ce procédé est restreint. Ceci est dû au fait que ce domaine de recherche reste monopolisé par l’utilisation d’études de cas qualitatives. Cette tendance a récemment été reconnue par des chercheurs dans le domaine. Ils préconisent l’utilisation de différents niveaux d’intégration des méthodes telles que les cas d’étude qualitatifs, les cadres théoriques et les simulations. Malgré cela, un processus de soutien au développement de méthodes mixtes, cohérentes et compatibles au niveau conceptuel manque toujours. De plus, les études de modélisation et de simulation se basent rarement sur des fondations théoriques solides pour modéliser les particularités des transitions durables à cause du manque de formalisation de structure à un très bas niveau.

Au cours de cette thèse, trois contributions méthodologiques sont apportées sur l’émergence endogène des politiques dans les transitions sociétales. En premier, la simulation system dynamics est proposée comme méthode pour compléter les méta-analyses sur des scenarios développés pour la transition énergétique suisse. Cette simulation apporte des perspectives nouvelles sur les incertitudes et les sensibilités du système, ainsi que sur les leviers politiques. Deuxièmement, un process model de méthode mixtes est développé suivant une étude extensive de la littérature concernant les études de transitions durables. Ce process model prend en compte les compatibilités théoriques et conceptuelles des structures transitionnelles et d’approches de simulations concernées. Ceci facilite la conception et la documentation de méthodes mixtes de recherche. Troisièmement, une formalisation de la perspective multi-niveau est développée au niveau des agents pour mieux décrire le rôle des individus dans les transition durables et pour internaliser le processus de conception des politiques. Cette formalisation perfectionne et étends les concepts intiment lié de pouvoir, agences et politiques.

Mot-Clés: agences; meta-analyse; méthodes mixtes, politiques, pouvoir, simulation, transition durable

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1 Introduction

The focus of this thesis is on the politics of policy-making in sustainability transitions. Contemporary sustainability transitions are typically politically driven (Meadowcroft, 2009), where policy-making is a response to exogenous system shocks and endogenous system dynamics. Politics has come to be recognized as an important aspect to understand sustainability transitions (McDowall & Geels, 2017). However, the current state of methods and frameworks prevent scholars from addressing the endogenous policy-emergence in complex societal transitions, often resulting in overly simplistic models and exogenous policy scenario assumptions.

There are a number of characteristics of sustainability transitions which complicate the study of endogenous policy-emergence. Sustainability transitions imply significant changes to the social and technical structures of societal systems (Rotmans, Kemp, & van Asselt, 2001, p. 16): "… a gradual, continuous process of change where the structural character of a society (or a complex sub-system of society) transforms". The Swiss energy transition is used in this chapter as an example of a complex sociotechnical system. We consider energy systems to be complex sociotechnical systems (Hughes, 1987), because these systems consist of many simultaneously interacting sub-systems and exhibit emergent behavior. Understanding the emergent system behavior requires a detailed understanding of feedback mechanisms between social and technical sub-systems. Furthermore, transition pathways are difficult to anticipate due to the unpredictable nature of exogenous shocks, such as the Fukushima Daiichi disaster. Subsequent policy-responses to exogenous shocks, such as nuclear phase-out decisions in Europe, are based on feedback mechanisms from underlying social, technical and institutional factors. Geels et al. (2016) found that transitions may shift between pathways, not least due to shifts in key stakeholder's interests and power distributions (Loorbach, 2010; Voß & Bornemann, 2011). Indeed, the political struggle for power underlying sustainability transitions, such as the Energiewende in Germany (Hoppmann, Huenteler, & Girod, 2014; Jacobsson & Lauber, 2006), is far from linear. Finally, even further complicating matters is the long timeframe of energy transitions, typically multiple decades, resulting in higher levels of uncertainty with regards to the unfolding of such transitions under different conditions.

1.1 Context

This thesis is positioned within the context of the sustainability transitions research field, which is defined by Markard et al. (2012, p. 959) as follows: "… all scientific articles that are concerned with the analysis of the institutional, organizational, technical, social, and political aspects of far-reaching changes in existing socio-technical systems (e.g. transportation and energy supply), which are related to more sustainable or environmentally friendly modes of production and consumption. Sustainability transitions research includes empirical studies, as well as conceptual and methodological contributions”. Sustainability transitions is a young field of research, which has been gaining significant momentum since earlier literature reviews (Chappin, 2011; Markard et al., 2012). Many of these studies draw on popular frameworks, such as the Multi-Level Perspective (MLP) (Geels, 2002), Transition Management (TM) (Rotmans et al., 2001), Strategic Niche Management (Kemp, Schot, & Hoogma, 1998; Rip & Kemp, 1998), and Innovation Systems (Edquist, 2004; Hekkert, Suurs, Negro, Kuhlmann, & Smits, 2007). These frameworks provide a rich set of concepts to describe sustainability transitions in a detailed yet nuanced manner that covers technological, social, and institutional factors (Turnheim et al., 2015).

Sustainability transitions research is being critically assessed as the research field is maturing. Covering all theoretical and practical criticism that has surfaced is beyond the scope of this thesis. Instead, the focus is on three ongoing discussions, situated at the nexus of qualitative research methods, modeling and simulation, and the conceptualization of power, politics and agency. The remainder of this section will outline how these discussions are connected to the overarching topic of modeling endogenous policy-making in sustainability transitions.

The first discussion pertains to the use of qualitative and quantitative methods in sustainability transitions research. The sustainability transitions field has been dominated by the use of qualitative case studies documenting historical transitions (Holtz, 2011). It is difficult, if not impossible, to explore future phases in sustainability transitions with such qualitative approaches, due to the inherent complexity and uncertainty of transitions. Simulation is often the only tool available to capture the complex behaviors of a system going through a transition process (Axelrod, 1997), as well as transitions in complex systems emerging from micro-level mechanisms (Squazzoni, 2008; Timmermans, 2008; Timmermans, de Haan, & Squazzoni, 2008). However, computer simulation and other quantitative methods are rarely used in transition studies (Chappin, 2011), a finding which is corroborated by a structured literature review presented in Chapter 4 of this thesis. While simulation presents a useful method to tackle the complexity in sustainability transitions (Chappin, 2011; Holtz et al., 2015; Papachristos, 2014), it has also its limitations in the fact that it is difficult to model concepts such as institutions and power when contrasted with case-studies (McDowall & Geels, 2017). Thus, what we observe in sustainability transition studies is the traditional dichotomy of qualitative and quantitative methods, and few efforts towards integrating methods in transition research (Papachristos, 2014).

The second discussion pertains to the concepts of power, agency and politics in sustainability transitions. Transition frameworks have been criticized for not adequately capturing the concepts of power and agency (Smith, Stirling, & Berkhout, 2005; Smith, Voß, & Grin, 2010), as well as politics (Meadowcroft, 2009; Scrase & Smith, 2009). In a response to these criticisms a large number of theoretical contributions have recently been published on the concept of politics in transitions (e.g. Fuenfschilling & Truffer, 2016; Hoffman & Loeber, 2016; Jhagroe, 2016; Raven, Kern, Verhees, & Smith, 2016; Voß & Bornemann, 2011), as well as the related concepts of power (e.g. Avelino & Rotmans, 2009; Avelino & Wittmayer, 2016; Geels, 2014) and agency (e.g. Fischer & Newig, 2016; Geels & Schot, 2007; Rosenbloom, Berton, & Meadowcroft, 2016). While these concepts are closely related, an integrated theoretical solution is currently missing. Furthermore, a trend can be observed to extend existing frameworks to become more comprehensive, which runs the risk of making the frameworks less useful.

The third discussion pertains to the fact that theoretical contributions to the frameworks have not carried over to modeling and simulation studies. Meaning there is not only a lack of integration at the methodological level, but also at the theoretical level. This is especially true for agent-based modelling and simulation (ABMS). ABMS offers a bottom-up approach with autonomous agents which can be used to simulate power, agency and micro-level politics in sustainability transitions. However, the use of transition frameworks such as the MLP is hindered by a lack of formalization at the agent level. Indeed, current efforts to formalize the MLP remain at a high level of abstraction, focusing on the dynamics of niches and regimes (e.g. Haxeltine et al., 2008; Papachristos, 2011; Walrave & Raven, 2016), rather than individuals. Lessons are drawn from a research stream in political science, combining game theory, formal models (e.g. Thomson, Stokman, Achen, & König, 2006) and computer simulation (e.g. Abdollahian, Baranick, Efird, & Kugler, 2006; de Mesquita, 2011). These approaches resonate well with the bottom-up analytical approach of the MLP and ABMS as they focus on the role of individuals and micro-level mechanisms underlying political power struggles, such as bargaining and coalition forming. However, these political science approaches are missing a link to the underlying sociotechnical system. Thus, the challenge of formalizing the MLP with concepts of power, agency and politics remains.

In summary, three related statements can be made about the state of the sustainability transitions research field, which invite further research:

1. Today we are facing many politically driven sustainability transitions in uncertain complex sociotechnical systems, making it is difficult to study how these contemporary transitions will unfold.
2. Sustainability transition scholars look at these transitions with their own theoretical lenses and primarily qualitative methods, often paying too little attention to the interactions of power, politics and agency.
3. Simulation studies address the complexity of transitions in sociotechnical systems, but are often lacking the theoretical foundations to model the intricacies of transitions at the micro-level, as frameworks have not been formalized at a low level of abstraction.

1.2 Thesis structure and contributions

This thesis is comprised of three closely related papers, with each self-contained paper making a clear methodological contribution towards modelling endogenous policy-emergence in societal transitions. The papers and their individual theoretical and practical contributions are presented in detail hereafter. The contributions of combining the individual studies is primarily addressed in Chapter 5, as part of the conclusion and discussion of the thesis, but some introductory remarks are made hereafter as well.

Chapter 2 (paper 1): Meta-analysis of Swiss energy transition scenarios using System Dynamics simulation.

> This chapter is based on the following forthcoming book chapter: Verhoog, R., van Baal, P. A. & Finger, M. (n.d.). System Dynamics Simulation to Explore the Impact of Low European Electricity Prices on Swiss Generation Capacity Investments. In A. Dorsman, V. A. Ediger, & M. B. Karan (Eds.), *Energy Economy, Finance and Geostrategy - A Geo-Economic Perspective*. Springer.[1]

The objective of this chapter is to use System Dynamics modelling and simulation as a method to perform a meta-analysis of energy transition scenarios. The focus of this chapter is on the Swiss energy transition, which is characterized by a commitment to phase-out nuclear energy (around a third of the country's electricity supply), promotion of new renewables (e.g. solar PV and wind), energy efficiency and CO_2 emission reductions. A lot of debate has surrounded the Swiss Energy Strategy 2050, resulting in many organizations publishing their own scenario studies to explore the transition towards a more sustainable energy system. Recent work by Densing, Panos, & Hirschberg (2016) has highlighted the diversity in methodologies, input data and assumptions of existing energy transition scenarios for Switzerland. Comparison of these scenario studies is problematic without accounting for methodological differences. Broadly speaking three categories are identified: optimization models (Kannan & Turton, 2012, 2013; Pöyry, 2012), computational general equilibrium models (Andersson, Boulouchos, & Bretschger, 2011) and bottom-up simulation models relying on exogenous generation capacity expansion scenarios (Barmettler, Beglinger, & Zeyer, 2013; Prognos AG, 2012; Teske & Heiligtag, 2013). Principal component analysis, as used by Densing, Panos, & Hirschberg (2016), does not adequately account for differences in methodology and core assumptions.

This chapter complements the meta-analysis of Densing et al. (2016) by exploring the uncertainty of Swiss scenarios by using a novel System Dynamics model for the Swiss electricity market. The System Dynamics model is developed specifically to study the Swiss electricity market, paying specific attention to the large (pumped) hydro reservoirs in the country (Verhoog et al., n.d.). The proposed System Dynamics model is used to explore a large set of assumptions and input data, which are directly taken from the Swiss scenario studies. Furthermore, System Dynamics simulation allows for investment decisions to be modeled using bounded rationality as a base assumption, rather than perfect foresighting and optimization as is commonly used in scenario studies. This will provide a better insight into the real uncertainty of the Swiss energy strategy 2050 for policy-makers and decision-makers in the Swiss energy sector. An uncertainty analysis is performed on the System Dynamics model for all exogenous scenario parameter (boundary conditions) ranges reported in the Swiss scenario studies. The uncertainty analysis explores the full uncertainty space obtained from the Swiss scenario studies, generating insights in the range of plausible model outcomes, and to filter out less influential boundary conditions. This will

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[1] Doctoral candidate's contribution to the book chapter: idea, (partial) conceptualization, data gathering and preparation, model calibration, (partial) model verification and validation, visualization of simulation results, writing. The model presented in this paper is an extension of that in the book chapter. The conceptual extension, model implementation, model calibration, model verification and validation, meta-analysis, visualization of simulation results and writing were all performed by the doctoral student for the chapter presented in this thesis.

provide a better insight into the real uncertainty of the Swiss energy strategy 2050 for policy-makers and decision-makers in the Swiss energy sector.

The primary methodological contribution is the use of System Dynamics as a method in meta-analysis, demonstrating how modeling and simulation can be used to add analytical strength to sustainability transition scenario studies. The primary practical contribution is the exploration of system sensitivities which can be used as potential policy levers by policy-makers and firms in the Swiss energy transition. While these identified policy-levers are case specific, the method could be applied to sustainability transitions more generally. As this model builds on existing scenario studies it is also using exogenous policy scenarios. However, it will be discussed in Chapter 5 how meta-analysis using simulation can be used to help scope more in-depth modeling exercises of policy-emergence. Finally, the model builds on a vast body of literature, but does not draw on any transition framework or concepts of power, agency and politics. The bridging of modeling and simulation, case studies and transition frameworks will be the topic of Chapter 3. The concepts of power, agency and politics will be addressed in Chapter 4.

Chapter 3 (paper 2): Mixed-methods in sustainability research: a comprehensive review and process model.

> This chapter is based on the preprint version of the article currently under revise and resubmit at the Environmental Innovation and Societal Transitions journal.

The objective of this chapter is to develop a process model to aid the design of mixed-methods sustainability transition studies, focusing on research designs involving simulation and transition frameworks. This chapter directly responds to an ongoing trend in the literature and recent discussions on the integration of qualitative and quantitative methods to study sustainability transitions. The trend is a continued domination of the sustainability transitions field by qualitative case studies and a lack of modeling and simulation methods, as first observed by Chappin (2011). Discussions on the use and usefulness of simulation (Holtz et al., 2015; McDowall & Geels, 2017; Papachristos, 2014), as well as the realization that most simulation studies are not using transition frameworks as a theoretical basis has led to a call for integrating qualitative and quantitative methods.

While there is agreement on the added value of using mixed-methods, there is less agreement on the way to integrate the qualitative and quantitative methods. Papachristos (2014) suggests an integrative approach, Turnheim et al. (2015) advocate a flexible integration, and Geels, Berkhout & van Vuuren (2016) argue against full integration, suggesting a sequential research design instead. A commonality between these previous contributions is that they suggest various mixed-methods research designs. Furthermore, transition frameworks play a central role in the combination of qualitative and quantitative methods. However, a means to aid the development of a coherent and conceptually compatible mixed-methods research design is not proposed in these studies.

The first methodological contribution is the development of a process model to facilitate the design and reporting of a coherent mixed-methods research design, striking a well-informed balance between qualitative and quantitative insights. The process model builds on established general mixed-methods research literature (Collins, Onwuegbuzie, & Sutton, 2006; Heyvaert, Maes, & Onghena, 2013; Johnson & Onwuegbuzie, 2004; Onwuegbuzie & Leech, 2005, 2006), and incorporates results from a structured literature review of sustainability transitions literature. In doing so, attention is drawn to missing linkages in the general process model, which limit its usefulness for sustainability transitions research involving simulation and transition frameworks. The specific process model presented in this article addresses the missing linkages between data gathering, model conceptualization, model validation, data analysis and transition frameworks. Thus, the process model provides a means to design all recently recommended levels of integration (Geels et al., 2016; Papachristos, 2011; Turnheim et al., 2015).

The second methodological contribution is an analysis of the theoretical and conceptual foundations of commonly used frameworks and simulation methods in the sustainability transitions literature. A clear distinction is made between top-down approaches informed by systems theory, and bottom-up approaches informed by complexity theory. Emphasis is placed on the conceptual foundations and analytical approach of these methods and frameworks. While most combinations of simulation methods and popular frameworks can be found in the current literature, caution is advised in some cases. Too little attention has been paid to this theoretical and analytical compatibility, especially in the case of formalizing bottom-up frameworks such as the MLP.

While the process model informs scholars about theoretical and conceptual compatibility of transition frameworks and simulation methods, it does not address the issue of lacking formalization at the agent level. This will be the topic of the third paper, presented in Chapter 4.

Chapter 4 (paper 3): Formalizing the multi-level perspective with concepts of power, agency and politics.

The objective of this chapter is to formalize the multi-level perspective with an integrated dynamic conceptualization of power, agency, and politics at the level of individual agents. This objective is in fact twofold, responding to two developments in the sustainability transitions literature.

The first development is that repeated criticism has sparked a large number of theoretical contributions addressing the concepts of power, agency, and politics (Verhoog & Finger, 2016). The primary response has so far been to extend existing mid-range frameworks, such as the MLP, with rich conceptualizations. While the level of detail in the conceptualizations is important to gain a deeper understanding of the concepts and their role in sustainability transitions, their integration in mid-range frameworks can seriously impact the usability of the frameworks. To preserve the positive mid-range theory properties of the MLP, Verhoog & Finger (2016) developed a parsimonious conceptualization of power relationships between actors, institutions and technology.

The second development is that the current formalizations of transition frameworks, including formalizations of the MLP, focus on system level dynamics of niches and regimes (e.g. Haxeltine et al., 2008; Papachristos, 2011; Walrave & Raven, 2016). This presents a barrier for agent-based modelling and simulation in particular, which requires a formalization at the level of agents rather than system structures.

This chapter makes two theoretical contributions to the sustainability transitions literature in general and the MLP in particular. The first theoretical contribution is a refinement of the conceptualization of power, agency and politics, as used in the MLP. Similar to the approach of Verhoog & Finger (2016), the aim is to create a parsimonious conceptualization. However, this conceptualization is at a low level of abstraction, and is fully integrated in the structures and concepts defined in the MLP. This results in a dynamic conceptualization of policy-making, institutional emergence and technological change. The formalization of the MLP draws heavily on sustainability transitions literature, but also incorporates contributions from other fields such as political science.

The second theoretical contribution is the formalization of the MLP framework, specifically targeted at agent-based modeling and simulation. This formalization allows the MLP to be used as a theoretical foundation for agent-based models, facilitating the integration of simulation approaches and transition theories more broadly. Additionally, a low level of abstraction of formalized concepts facilitates the consistent and structured application in qualitative case studies, promoting the comparability of case studies. Finally, the formalization of concepts promotes a transparent discussion to further improve the MLP.

The practical contribution is that such a formalization can be used to endogenize policy-making, providing new insights in future policy developments. In practice this means that exogenously assumed policy scenarios are replaced with an internal mechanism, increasing the understanding of the most likely policy-outcome and its impact on the sociotechnical system. In Chapter 5 this practical contribution is further explored in combination with meta-analysis using modeling and simulation approaches.

1.3 Audience & reading guide

This thesis is structured to cater to the interests of three types of readers. A reader can identify with more than one type. Depending on your level of expertise and interests, you are advised to read the chapters selected for the reader types that you associate yourself with most in Table 1.1.

- **Transition scholars:** The thesis is primarily targeted towards transition scholars and readers who want to become more familiar with this research field. Specific attention is paid to popular frameworks and methods used within the sustainability transition field. While sustainability transitions research covers many sectors, I believe that the meta-analysis of Swiss energy transition scenarios is interesting for all transition scholars due to its methodological contribution. Similarly, the methodological contributions of the mixed-methods process model and MLP formalization are of interest to transition scholars engaging in both qualitative and quantitative research. Experience with modeling and simulation is not required, but familiarity can help in understanding the current discussions surrounding the use and usefulness of modeling and simulation.

- **Modelers:** Modelers who are familiar with transition frameworks, or who want to learn more about adopting such frameworks, are advised to read the whole thesis. Chapter two and Chapter four focus on specific simulation paradigms, respectively covering a systems and complexity perspective for analyzing sustainability transitions. While most of the methodological contributions address ongoing discussions in the sustainability transitions field, important contributions come from modeling and simulation studies. It is precisely the connection between modelers and transition scholars which can help both fields advance.
- **Practitioners:** The second chapter of this thesis in particular is aimed towards practitioners and those interested in the Swiss energy transition. Specific attention is given to existing scenario studies, and how these studies can be combined using modeling and simulation. Furthermore, the presented simulation results can help practitioners to explore and understand the implications of the Swiss energy transition for their organizations.

Table 1.1 Reading guide.

Chapter	Transition scholar	Modeler	Practitioner
Introduction	■	■	■
Meta-analysis of Swiss energy transition scenarios using System Dynamics simulation	■	■	■
Mixed-methods in sustainability research: a comprehensive review and process model	■	■	☐
Formalizing the multi-level perspective with concepts of power, agency and politics	■	■	☐
Conclusion and discussion	■	■	■

2 Meta-analysis of Swiss energy transition scenarios using System Dynamics simulation

This chapter is based on the following forthcoming book chapter: Verhoog, R., van Baal, P. A. & Finger, M. (n.d.). System Dynamics Simulation to Explore the Impact of Low European Electricity Prices on Swiss Generation Capacity Investments. In A. Dorsman, V. A. Ediger, & M. B. Karan (Eds.), *Energy Economy, Finance and Geostrategy - A Geo-Economic Perspective*. Springer.[2]

Abstract

Since the conception of the Energy Strategy 2050 the Swiss energy transition has been a topic of much debate and has resulted in a large number of scenario studies to explore the transition towards a more renewable energy system. Recent work by Densing, Panos, & Hirschberg (2016) has highlighted the diversity in methodologies, input data and assumptions of existing energy transition scenarios for Switzerland. Comparison of these scenario study results requires that differences in modeling methodologies and assumptions are accounted for. This chapter complements the meta-analysis of Densing et al. (2016) by exploring the uncertainty of Swiss scenarios by using a System Dynamics model for the Swiss electricity market. The proposed System Dynamics model is used to explore a large set of assumptions and input data, which will be directly taken from the various Swiss scenario studies. While System Dynamics is a different method than used in most scenario studies, this approach has two distinct advantages: (1) it allows for a consistent comparison of underlying assumptions, data and scenarios, and (2) it allows for more realistic base assumptions (e.g. bounded rationality). An uncertainty analysis is performed on the System Dynamics model for all exogenous scenario parameter (boundary conditions) ranges reported in the Swiss scenario studies. The uncertainty analysis explores the full uncertainty space obtained from the Swiss scenario studies, generating insights in the range of plausible model

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[2] Doctoral candidate's contribution to the book chapter: idea, (partial) conceptualization, data gathering and preparation, model calibration, (partial) model verification and validation, visualization of simulation results, writing. The model presented in this paper is an extension of that in the book chapter. The conceptual extension, model implementation, model calibration, model verification and validation, meta-analysis, visualization of simulation results and writing were all performed by the doctoral student for the chapter presented in this thesis.

outcomes, and to filter out less influential boundary conditions. This will provide a better insight into the real uncertainty of the Swiss energy strategy 2050 for policy-makers and decision-makers in the Swiss energy sector.

Keywords: energy system, meta-analysis, scenario studies, Switzerland, system dynamics, transition

2.1 Introduction

Energy system analysis has a long and rich history of using modeling and simulation approaches to support policy-makers by quantitatively exploring future system developments (Bhattacharyya & Timilsina, 2010; Jebaraj & Iniyan, 2006). A wide range of specialized computer tools has since been developed, such as the popular MARKAL family of models. For a detailed review of computer tools, see (Beaver, 1993; Connolly, Lund, Mathiesen, & Leahy, 2010; Foley, Gallachóir, Hur, Baldick, & McKeogh, 2010). A recent review of energy system models in the UK (Hall & Buckley, 2016) shows there are many recent models available at the national level. Classification of models shows that the current landscape of models is dominated by equilibrium, optimization and simulation models (Kydes, Shaw, & McDonald, 1995; Nakata, 2004; Ventosa, Baıllo, Ramos, & Rivier, 2005). While the previous classifications are broad sweeps of the literature, more specific reviews draw attention to the use of system dynamics (Teufel, Miller, Genoese, & Fichtner, 2013) and agent-based modelling (Sensfuß, Ragwitz, Genoese, & Möst, 2007; K. H. van Dam, 2009). A recent review (Li, Trutnevyte, & Strachan, 2015) draws attention to sociotechnical energy transition models, currently limited to a small set of models that include both social and technical elements (Pfenninger, Hawkes, & Keirstead, 2014).

Quantitative results of future energy system developments deviate greatly between models, primarily caused by differences in underlying assumptions, input values and modeling approaches (Kann & Weyant, 2000). Scenario development is a common practice in modeling and simulation to combine sets of assumptions in scenarios for model runs. Two approaches for scenario development are identified in the literature (Kann & Weyant, 2000; Lempert, 2013; Parker, Srinivasan, Lempert, & Berry, 2015; Tietje, 2005; van Vuuren, de Vries, Beusen, & Heuberger, 2008; Webster et al., 2002):

1. Expert generated plausible scenarios that combine internally consistent model assumptions. The plausible scenarios then serve as a storyline for the simulation runs (Garb, Pulver, & VanDeveer, 2008; Nakicenovic et al., 2000; Rounsevell & Metzger, 2010).
2. Scenario discovery by using statistical methods to select a small set of scenarios from a database of simulation runs (Bishop, Hines, & Collins, 2007; Lempert, Groves, Popper, & Bankes, 2006; Pruyt & Islam, 2015; Tourki, Keisler, & Linkov, 2013). This is a model-based approach which generates a large number of runs from sampling probability distributions on uncertain or unknown model parameters, which are then clustered into a small set of scenarios (e.g. Bryant & Lempert, 2010; Dalal, Han, Lempert, Jaycocks, & Hackbarth, 2013; Gerst, Wang, & Borsuk, 2013; Hamarat, Kwakkel, & Pruyt, 2013; Kasprzyk, Nataraj, Reed, & Lempert, 2013).

A recent meta-analysis of Swiss energy transition scenarios highlights the prevalence of technological bottom-up models, diversity in methods, assumptions, input data and numerical results (Densing et al., 2016). Comparison of these scenario studies is problematic without accounting for methodological and assumption differences. Principal component analysis, as used by Densing et al. (2016), does not account for differences in modeling methodologies and core assumptions, as it relies on model outputs. Thus, the aim of their meta-analysis is on reducing complexity of the large amount of Swiss energy transition scenarios.

The focus on this chapter is to demonstrate the use of computer simulation as a method in meta-analyses of quantitative sustainability transition scenarios. The Swiss energy transition is used in this chapter as an example of a complex sociotechnical system (Hughes, 1987) with a clear infrastructure component, for which many quantitative scenario studies are already available (Andersson et al., 2011; Barmettler et al., 2013; Kannan & Turton, 2011, 2012, 2013; Osorio & van Ackere, 2016; Pöyry, 2012; Prognos AG, 2012; Teske & Heiligtag, 2013; VSE, 2012; Weidmann, 2013). The scenarios available for Switzerland can be characterized as expert generated plausible scenarios. Probability distributions of model parameters are not available for the Swiss scenario studies, nor do we have access to any of the models underlying the scenario studies. Therefore, it is not possible to perform a scenario discovery exercise without eliciting the probability distributions of model parameters. It is a difficult task to determine the joint probability distribution of the model's parameters which are included in the scenarios (Kann & Weyant, 2000). Furthermore, a large number of model parameters were identified as part of the scenarios, making it unpractical to determine all probability distributions. Alternatively, Webster et al. (2002) perform a sensitivity analysis on the MIT Emissions Prediction and Policy Analysis model (Babiker et al., 2001) to select the most important parameters, reducing the number of parameters for which probability distributions have to be acquired. A similar approach can be applied to the available expert generated scenarios for the Swiss energy transition if all scenario parameters are implemented in a single model.

This chapter is positioned to complement the meta-analysis of Densing et al. (2016) by exploring the uncertainty of Swiss scenarios by using a System Dynamics model. Implementing the scenarios in a single model is not an easy task due to hidden (undocumented) data, model assumptions and model implementations (proprietary software). This chapter presents the design and implementation of a system dynamics model for the Swiss electricity market which contains detailed endogenous investment pipelines for a large number of technologies, as well as bounded rational actors. This allows us to model investment cycles (Ford, 1999, 2001; Kadoya et al., 2005; Olsina, Garcés, & Haubrich, 2006) in a liberalized hydro-dominated market (Hammons, Rudnick, & Barroso, 2002) which is going through a nuclear phase-out (Osorio & van Ackere, 2016). While System Dynamics is a different method than used in most selected scenario studies, this approach has two distinct advantages: (1) it allows for a consistent comparison of underlying assumptions, data and scenarios, and (2) it allows for more realistic base assumptions (e.g. bounded rationality). An uncertainty analysis is performed on the System Dynamics model for all exogenous scenario parameter (boundary conditions) ranges reported in the expert scenarios (Pruyt, 2013). The uncertainty analysis identifies boundary conditions to which model outcome variables of interest are most sensitive (Bishop et al., 2007; Prinn et al., 1999), which is then used to determine a reduced set of boundary conditions.

The primary methodological contribution is the use of System Dynamics as a method in meta-analysis, demonstrating how modeling and simulation can be used to add analytical strength to sustainability transition scenario studies. The primary practical contribution is the exploration of boundary conditions which can be used as potential policy levers by policy-makers and firms in the Swiss energy transition. The exercise of implementing a large set of Swiss transition scenarios in the system dynamics model provides deeper insights in the assumptions and data driving model behavior. This will provide a better insight into the uncertainty of the Swiss energy strategy 2050 for policy-makers and decision-makers in the Swiss energy sector. The results of the meta-analysis presented in this chapter are specific to the Swiss energy transition, but the approach can be generalized to other sustainability transitions with readily available quantitative scenario studies.

This chapter is structured as follows. First, the methods used for the meta-analysis in this chapter are discussed, detailing the use of SD simulation, scenario selection and uncertainty analysis. Second, the conceptual SD model is elaborated. The model is developed to study the Swiss energy transition, containing sub-systems that model the Swiss electricity spot market, hydro reservoir dynamics, electricity imports and electricity generation investments including solar, wind, hydro, CHP and CCGT. Third, the simulation runs, based on the selected Swiss scenario studies are presented, followed by an uncertainty analysis. Finally, the chapter is concluded by reflecting on the theoretical and practical insights gained from the modelling and uncertainty analysis.

2.2 Methodology

2.2.1 Simulation method

Analyzing the Swiss energy transition is not straightforward since energy systems are complex socio-technical systems (Hughes, 1987) consisting of many sub-systems such as production, consumption, investments, and spot markets. The complexity arises from the many parts which simultaneously interact in the energy system, resulting in complex feedback loops (Simon, 1973). Furthermore, there are many factors with a high impact on the energy system that have a high uncertainty, such as natural gas prices, electricity spot markets, technological developments, and (domestic) energy policies. It is difficult to study how such transitions will unfold under deep uncertainty, due in part to the long timeframe of energy transitions, typically multiple decades (Grin, Rotmans, & Schot, 2010; Grubler, Wilson, & Nemet, 2016; Smil, 2016), although evidence of faster sector and national level transitions exists as well (Correljé & Verbong, 2004; Fouquet, 2016; Sovacool, 2016) different conditions. Computer simulation are a useful method for analyzing energy transition by means of virtual experiments (Chappin, 2011), and models have been extensively applied to study energy systems (Bhattacharyya & Timilsina, 2010; Jebaraj & Iniyan, 2006). Simulation approaches and available scenario (simulation) studies for Switzerland (Densing et al., 2016) are compared hereafter.

First, optimization models have been used to study the Swiss energy transition under the objective of cost minimization and environmental constraints (e.g. Pöyry 2012; Kannan and Turton 2016; Pattupara and Kannan 2016). These models assume perfect information, perfect foresight (DeCarolis et al., 2017) and economically rational decisions for the entire system (central planner approach) rather than individual firms. Such an approach is unsuitable to study liberalized markets with imperfect information and bounded rational investors. Indeed, such an approach would not allow for investment cycles to be explored. Furthermore, Trutnevyte (2016) found that optimization models greatly deviate (9-23%) from real system behavior in an ex-post analysis of the UK electricity system. This finding is over a period of 25 years, shorter than those typically considered for the Swiss energy transition.

Second, computational general equilibrium (CGE) models work under the assumption that the rational behavior of individuals in markets with perfect competition will find an equilibrium price (e.g. Andersson et al., 2011; Vöhringer, 2012). However, such assumptions cannot be defended in electricity markets which have shown investment cycles following liberalization (Kadoya et al., 2005), as these markets are out-of-equilibrium when transitioning to their liberalized state (Gary & Larsen, 2000). Furthermore, equilibrium searching models are not dynamic (Mitra-Kahn, 2008), making them unsuitable to simulate boom-and-bust cycles.

Third, bottom-up simulation models of the Swiss electricity market generally have a high level of generation technology detail (e.g. Prognos AG 2012; Barmettler et al. 2013; Teske and Heiligtag 2013). Most of these models are well-documented, providing rich information required for model conceptualization, assumptions and data sources. These models rely on exogenous generation capacity expansion scenarios, resulting in rather static models which are used to explore a range of internally consistent “what-if” scenarios.

Fourth, System Dynamics (SD) models have a number of fundamental advantages over the previously discussed approaches. Teufel et al. (2013) identify a number of differentiating factors of SD models in their literature review, some of which are crucial for simulating investment cycles: (1) *time lags* in feedback processes to model lead-times for generation capacity investment pipelines including permitting and construction phases, (2) *bounded rationality* to model liberalized electricity markets in which firms have *incomplete information* on generation capacity expansion, (3) *social behavior* can be modeled directly, rather than relying on optimization of some objective function (Jäger, Schmidt, & Karl, 2009). Incomplete information also implies that SD models incorporating the above differentiating factors do not use the perfect foresight assumption like most optimization models used for the Swiss electricity sector. Instead, forecasts are made endogenous to the modeled system using imperfect information, leading to sub-optimal system behavior over many scenarios. SD has been applied in a large variety of liberalized markets to study generation capacity dynamics (Arango, 2007; Bunn, Larsen, & Vlahos, 1993; Ford, 1999; Gaidosch, 2008; Gary & Larsen, 2000; Kadoya et al., 2005; Pereira & Saraiva, 2013; Vogstad, 2005).

A further argument to select SD is that system level behavior and interactions between various sub-systems are not expected to change during the studied period at a structural level. A key assumption for SD is that the behavior of a system is fundamentally determined by its own structure (Pruyt, 2013; Sterman, 2001). The system structure is represented in stocks, flows, auxiliary variables, constants, parameters and the links between these elements. Therefore, it is necessary to clearly identify the justification of each link. Links can either be *positive* or *negative*[3], and links between several elements of the model can compose feedback loops. A feedback loop is a path of links starting in one element of the system that, if followed, leads back to the starting element after passing through at least another system element. Two kinds of feedback loops can exist: *reinforcing loops* and *balancing loops*[4]. The modeled elements and links are translated into differential equations so as to allow for virtual experimentation to gain insights into the system's responses to policy designs (Pruyt, 2013).

2.2.2 Scenario study selection

Scenario studies are selected based on three criteria: (1) the study has to cover the Swiss energy transition, including the nuclear phase-out; (2) the time horizon has to extend to at least 2050; (3) sufficient detail has to be available in the model documentation to determine the boundary conditions of the presented scenarios. As a starting point we evaluate the scenarios included in the meta-analysis of Densing et al. (2016). The SCS Energiemodell (SCS, 2013) is excluded from further analysis in the uncertainty analysis as it this is a dispatch model with an annual time horizon. However, the SCS dispatch model is used in the Greenpeace scenario study (Teske & Heiligtag, 2013). Furthermore, the Cleantech scenario study (Barmettler et al., 2013) is excluded as insufficient model details are reported to determine the boundary conditions and values for the reported scenarios. Finally, one additional System Dynamics simulation study (Osorio & van Ackere, 2016) is included in the further analysis. The model was developed at the University of Lausanne and will henceforth be referred to as the UNIL model. The UNIL model addresses the Swiss energy transition in Switzerland until 2050 and provides ample information on model parameters and some unique boundary conditions for further uncertainty analysis. The selected studies are summarized in Table 2.1.

Table 2.1 Scenario studies selected for uncertainty analysis.

Model label	Model developed by	References
SFOE (Swiss Federal Office of Energy)	Prognos AG Infras AG	(Prognos AG, 2012)
VSE (Association of Swiss electricity producers)	Zephyr by Pöyry Management Consulting (Schweiz)	(Pöyry, 2012; VSE, 2012)
ETHZ	CGE model by ESC at ETH Zurich	(Andersson et al., 2011)
Greenpeace	Mesap/PlaNet by DLR at the University of Stuttgart; Dispatch model by SCS	(SCS, 2013; Teske & Heiligtag, 2013)
PSI-ELC	Swiss TIMES model by EEG at PSI	(Kannan & Turton, 2011, 2012, 2013)
PSI-SYS	Swiss MARKAL model by EEG at PSI	(Weidmann, 2013)
UNIL	System Dynamics model by DO at the University of Lausanne	(Osorio & van Ackere, 2016)

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[3] A *positive* link from A to B means that an increase in A leads to an increase in B. A *negative* link from A to B means that an increase in A leads to a decrease in B.

[4] *Reinforcing loops* are positive feedback loops which further increase a positive or negative change in the system. Reinforcing loops can be utilized in policy design to destabilize the system. *Balancing loops* have a damping effect on positive or negative changes in the system and typically stabilize the system.

Densing et al. (2016, p. 1000) use the following taxonomy of Swiss scenario studies for their meta-analysis: (1) integration of models; (2) methodology of each model; (3) system scope; (4) geographical scope; (5) uncertainty; (6) market aspects. Based on earlier classifications of energy models this taxonomy is extended in this chapter (Table 2.2) to include: (7) time horizon (Connolly et al., 2010; Grubb, Edmonds, Ten Brink, & Morrison, 1993; Hall & Buckley, 2016; Pandey, 2002; van Beeck, 1999); and (8) time-step (Connolly et al., 2010; Hall & Buckley, 2016). A detailed description of the taxonomy and models, as provided in previous PSI publications (Densing, Hirschberg, & Turton, 2014; Densing et al., 2016), is beyond the scope of this chapter. However, several dimensions do warrant additional discussion:

- **Model integration.** Most of the selected scenario studies use multiple soft-linked models, especially for (sectoral) electricity demand and capacity expansion models (Densing et al., 2016). While soft-linking models can improve simulation results over using single models (Deane, Chiodi, Gargiulo, & Gallachóir, 2012), the feedback between the soft-linked models is limited (Densing et al., 2016). Following the levels of model integration by Antle et al. (2001), most studies are using a combination of independently running loosely-coupled models (Andersson et al., 2011; Prognos AG, 2012; Teske & Heiligtag, 2013) and models integrated at the code level (Kannan & Turton, 2013; Osorio & van Ackere, 2016; Pöyry, 2012; Weidmann, 2013). However, integrating existing does not necessarily increase the level of feedback between the models (Verhoog, Ghorbani, & Dijkema, 2016), but can increase the model's complexity and calibration requirements (Voinov & Shugart, 2013). Thus, loose coupling or partial integration of simpler models might be more desirable.
- **Model methodology.** A clear distinction between optimization and simulation models is made in the taxonomy, with a majority of simulation approaches. (Pfenninger et al., 2014) draw attention to the normative character of optimization models used for scenario analysis, whereas simulation is used for predictive purposes. However, as boundary conditions of scenarios play a large role in determining the outcomes of simulation studies, as will be detailed in section 5, they can also contain a significant normative component. An example of this are the assumption on significant generation capacity expansions which are exogenous to the capacity expansion simulation model (e.g. Osorio & van Ackere, 2016; Prognos AG, 2012; Teske & Heiligtag, 2013).
- **Geographical scope.** All models, with the exception of the VSE model (Pöyry, 2012), cover only the Swiss market. Consequently, these single region models rely on a simplified representation of electricity import and export dynamics with the neighboring countries France, Germany, Austria and Italy (Maire, Pattupara, Kannan, Vielle, & Vöhringer, 2015). However, Switzerland has a high level of electricity import (38 TWh in 2016) and export (34 TWh in 2016) relative to its domestic consumption (62.6 TWh in 2016) (SFOE, 2017b). This limitation also applies to the System Dynamics model presented in this chapter.
- **Time-step.** Many optimization models use large time-steps (e.g. yearly), relying on so called representative time-slices to cover all hours in that time-step to reduce computational and calibration demands (Pfenninger et al., 2014). Typical implementations are one representative weekday, Saturday

and Sunday at the hourly level per season (Kannan & Turton, 2013). The approach is also used for System Dynamics models using one representative day per season (Osorio & van Ackere, 2016). However, as we are investigating a transition towards the use of new intermittent renewables, such as wind and solar, the representation of electricity supply at a finer temporal level will become increasingly important (Pfenninger et al., 2014). The EPFL-MIR System Dynamics model presented in this chapter is the only model to use hourly time-steps, representing every hour of the year.

- **Uncertainty and market aspects.** The models reviewed by (Densing et al., 2016) share a number of key assumptions underlying their models: one central planner, perfect foresight, no investment uncertainty. Both the UNIL model (Osorio & van Ackere, 2016) and the EPFL-MIR model explore a liberalized electricity market, implementing bounded rational investments under uncertainty. This liberalized market approach also relaxes import and export constraints common in most studies.

Table 2.2 Taxonomy of selected scenario studies. Based on Densing et al. (2016), additions by the author.

Study	Model integration/methodology			System scope	Geographic scope	Time horizon	Time-step	Market aspects	Uncertain-ty
	Electricity demand	Capacity expansion	Dispatch						
SFOE	Simulation	Simulation	Simulation	Energy	CH	2050	Yearly	No	No
VSE	Simulation	Cost-optimization		Electricity	CH/DE/IT/AT/FR	2050	Yearly (hourly dispatch)	No	No
ETHZ	Simulation	Simulation	-	Energy	CH	2050	Yearly	No	No
Greenpeace	Simulation	Simulation	SCS-model	Energy	CH	2050	n/a (hourly dispatch)	No	No
PSI-ELC	-	Cost-optimization		Electricity	CH	2100	1-20 years	No	No
PSI-SYS	Cost-optimization		-	Energy	CH	2050	5 years	No	No
UNIL	Simulation	Simulation		Electricity	CH	2050	Yearly	Yes	Yes
EPFL-MIR	Simulation	Simulation		Electricity	CH	2050	Hourly	Yes	Yes

2.2.3 Uncertainty analysis

A set of boundary conditions is obtained from the selected scenario studies, which represent the plausible range of uncertainty according to various Swiss stakeholders and experts. The selected scenario studies follow the description by (Guivarch, Lempert, & Trutnevyte, 2017, p. 201): "…plausible descriptions of how the future may develop, based on a coherent and internally consistent set of assumptions about key relationships and driving forces". Further analysis of the scenarios and will uncover the underlying implicit assumptions regarding the relationships between boundary conditions. However, influential boundary conditions which have a plausible relationship should be endogenized (Ford & Flynn, 2005; Taylor, Ford, & Ford, 2010). Furthermore, the set of boundary conditions does not contain probability distributions for the range of uncertainty and is rather a collection of categorical factors linked to annual lookup information (e.g. electricity demand, carbon price, solar PV deployment). Uncertainty analysis can be used to explore the full uncertainty space obtained from the Swiss scenario studies (Pruyt, 2013), generate insights in the range of plausible model outcomes (Bishop et al., 2007), and to filter out less influential boundary conditions (DeCarolis et al., 2017).

From the 7 studies a total of 41 scenarios are identified with unique combinations of boundary conditions, an overview is given in Table 2.3. Scenarios allowing reinvestments in nuclear power plants are excluded from the uncertainty analysis following the positive referendum outcome on the Energy Act on 21 May 2017, meaning that all PSI-ELC Nuclear scenarios are excluded. Furthermore, in order to allow for market dynamics, net import restrictions (e.g. “annual net-imports are assumed to be zero”) are not implemented in the EPFL-MIR model. Four boundary conditions are highlighted per scenario, as they are central to the Swiss energy transition and are closely related in terms of system dynamics. First, electricity demand is arguably one of the most important boundary conditions, and large variations can be observed between the selected scenarios. Second, large amounts of nuclear generation capacity are expected to leave the market, but the timing is uncertain. An early phase-out, in combination with increasing demand can put additional strain on the system, highlighting the interaction of boundary conditions through system dynamics. Third, the question remains which generation technology will replace the nuclear power plants. How strongly are RES promoted, and are investments in CCGT allowed? Imports could also play a large role in the transition, but many studies put constraints on annual net imports. In the EPFL-MIR model import and export is unconstrained and is determined by the market dynamics.

Table 2.3 Selected scenarios for uncertainty analysis.

Study	Scenarios	Electricity demand	Nuclear phase-out (reactor lifetime)	Renewable investments	CCGT & CHP investments
UNIL	1-3. BAU-X	X covers SFOE variants: ▪ High (WWB) ▪ Medium (POM) ▪ Low (NEP)	60 years	FIT until 2034	CCGT only
	4-6. NUCind-X		Two reactors do not close	FIT until 2034	CCGT only
	7-9. NUC45-X		45 years	FIT until 2034	CCGT only
	10-12. NoFIT-X		60 years	No FIT	CCGT only
	13-15. EXP-X		60 years	FIT until 2034	CCGT only
PSI-ELC	16-18. Gas-X		50 years	Market based (optimization)	CCGT and CHP
	19-21. Import-X		50 years	Market based (optimization)	None allowed
SFOE	22. WWB-C	High (WWB)	50 years	Low (C-variant)	CCGT and CHP
	23. WWB-C/E	High (WWB)	50 years	Medium CE/E-variant)	CCGT and CHP
	24. POM-C	Medium (POM)	50 years	Low (C-variant)	CCGT and CHP
	25. POM-C/E	Medium (POM)	50 years	Medium (CE/E-variant)	CCGT and CHP
	26. POM-E	Medium (POM)	50 years	Medium (CE/E-variant)	CHP only
	27. NEP- C	Low (NEP)	50 years	Low (C-variant)	CCGT and CHP
	28. NEP-C/E	Low (NEP)	50 years	Medium (CE/E-variant)	CCGT and CHP
	29. NEP-E	Low (NEP)	50 years	Medium (CE/E-variant)	CHP only
VSE	30. Scenario 1	High	50 years	Low RES support	CCGT and CHP
	31. Scenario 2	Medium	50 years	Medium RES support	CCGT and CHP
	32. Scenario 3	Low	50 years	Strong RES support	CHP only
	33. Option 4	High	50 years	Low RES support (optimized)	CCGT and CHP
	34. Option 5	Medium	50 years	Medium RES support	CCGT and CHP
	35. Option 6	Low	50 years	Strong RES support	CHP only
	36. Option 7	Medium	50 years	Strong RES support	CCGT and CHP
ETHZ	37. Hoch	High	50 years	High potential	CCGT and CHP
	38. Mittel	Medium	50 years	High potential	CCGT and CHP
	39. Tief	Low	50 years	High potential	CCGT and CHP
GREENPEACE	40. [R]	Low/medium	40 years	High; emphasis on solar PV	None allowed
PSI-SYS	41. noClimPol	Endogenous	50 years	Market based (optimization)	CCGT and CHP

In this chapter statistical screening is used to determine which boundary conditions of the System Dynamics model are most influential (Ford & Flynn, 2005; Taylor et al., 2010). First, in section 2.4 a Latin Hypercube Sampling (LHS) design of the set of boundary conditions is generated in Vensim® DSS for Windows (Version 6.4E) to generate an ensemble of runs (McKay, Beckman, & Conover, 1979). Second, in section 2.4.1 timeseries plots with percentiles (Ford & Flynn, 2005) are generated using Python 3.6.1, Pandas 0.20.3, and Seaborn 0.8 to visually inspect the uncertainty range of outcome parameters of interest (e.g. endogenous CO_2 emissions). Timeseries plots are also used to contrast the two most extreme levels of the selected boundary conditions. Third, in section 2.4.2 the correlation coefficients (Equation 2.1) are determined using Microsoft Excel for all boundary conditions over the simulation time horizon from 2015 to 2050 (Ford & Flynn, 2005). This analysis forms the basis to for the identification and discussion of boundary conditions which are plausibly related, and which should ideally be endogenized in future model iterations.

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})\,(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\,\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}}$$

Equation 2.1 Pearson correlation.

Where:

n	Simple size
x_i, y_i	Samples indexed by i
$\bar{x}, \bar{y}$	Sample means

2.3 Modeling the Swiss energy transition

Switzerland has committed to an ambitious energy transition with far reaching social, technical and economic consequences as nuclear energy will be phased-out, while maintaining low carbon emission levels. Nuclear energy accounted for around a third (19-22 TWh) of the country's annual electricity production in 2015 and 2016 (SFOE, 2017a), and is expected to be completely replaced by other production sources by 2034. Ideally, new renewable energy sources (RES) such as solar photovoltaic (PV), wind, (micro-)hydro, biomass and geothermal energy will replace the nuclear electricity production. However, new RES face considerable challenges: social acceptance (Wüstenhagen, Wolsink, & Bürer, 2007), small potential of certain RES such as micro-hydro (SFOE, 2012), or low economic attractiveness (Prognos AG, 2012). Hence, energy import and natural gas fired power plants could play a central role in compensating the increasing production deficit caused by phasing-out nuclear energy.

Belgium and Germany are facing a similar challenge of phasing-out nuclear energy under stringent CO_2 emission targets. A system dynamics (SD) simulation study by Kunsch and Friesewinkel (2014) finds that aggressively phasing-out nuclear energy in Belgium can have adverse effects on the country's RES deployment, electricity price volatility, CO_2 emissions and energy dependency. Indeed, an early phase-out of nuclear energy can result in a large production deficit despite RES investments, requiring additional investments in fossil-based generation technologies. Such a scenario might also unfold for Switzerland, which in 2015 produced only 4.45% of its electricity from new renewables, namely 0.17% from wind, 0.45% from biomass, 1.76% from solar, 0.20% from biogas, and 1.87% from waste sources (SFOE, 2016).

Switzerland is facing the additional challenge of liberalizing its electricity market, which can lead to “boom-and-bust” investment cycles as demonstrated by (Ford, 1999; Kadoya et al., 2005; Olsina et al., 2006) using SD simulation. In liberalized markets investments are made based on price signals and incomplete information, rather than using a central planner approach. Periods of overinvestment send a lack of price signals to market players once the market is liberalized, resulting in a period of underinvestment (Finon, Johnsen, & Midttun, 2004). Conversely, long delays between permit applications and the construction of power plants lead to overinvestment, as too many projects are initiated based on price signals during capacity shortage. These time lags are an important contributor to investment cycles (Kadoya et al., 2005). Unique to the case of Switzerland are two additional factors contributing to a lack or delay of price signals: (1) low European electricity spot prices, particularly in neighboring countries, and (2) a large hydro storage capacity which dampens the electricity price and delays investment signals (Hammons et al., 2002).

Ochoa (2007) explored the likely market responses to liberalization in the Swiss electricity market, highlighting the importance of security of supply under a liberalized market design. Since then, the Fukushima disaster and subsequent decision to phase-out nuclear energy in Switzerland have further implications for the security of supply. Ochoa & van Ackere (2009) found using a SD model of Switzerland that a nuclear phase-out can result in a significant electricity import dependency. More recently, Osorio & van Ackere (2016) confirmed this import dependency using a SD model of the Swiss transition from nuclear to RES. The nuclear phase-out will lower the security of supply, leading to higher and more volatile prices as a result of the new energy-generation mix.

The conceptual model presented in this section is an extension of the model elaborated in (Verhoog et al., n.d.). Specific attention is paid to the structure, feedback loops, assumptions and publicly available data underlying the sub-systems. The model simulates the period from 2015 to 2050 with hourly time-steps, which is a unique feature compared to other simulation models available for Switzerland. This approach clears the electricity market and dispatches all production units for each hour of the year, rather than using a reduced set of representative time-slices as done in Osorio and van Ackere (2016) or monthly time-steps as in Ochoa and Van Ackere (2009). Another key-feature of the model is that it allows for dynamic endogenous generation capacity investment decisions using bounded rational investor behavior. This means that investors use incomplete information on generation capacity expansions, future demand and prices in imperfect foresight to determine the profitability of investments. In contrast to earlier models (e.g. Kadoya et al. 2005; Osorio and van Ackere 2016) the model includes hourly transmission constraints, which are required to determine the impact of low European electricity prices and interconnector congestion on developments in the Swiss market.

2.3.1 Swiss electricity spot market

In liberalized electricity markets the price signals for capacity investments are sent by the spot market. The present model implements a clearing mechanism for the Swiss spot market, based on the physical hourly match of electricity supply and demand. This is a common approach for simulation models exploring the dynamics of liberalized electricity markets (e.g. Kadoya et al. 2005; Vogstad 2005; Osorio and van Ackere 2016). Vogstad (2005) additionally implemented a futures market. However, typical investment horizons in electricity markets go well beyond the horizon of futures market, making them no more useful than expected spot price forecasting. Furthermore, capacity mechanisms as implemented by (Assili, Javidi D.B., & Ghazi, 2008; Kadoya et al., 2005) are not included in the model, as there are currently no capacity market designs for Switzerland yet.

Inputs for the spot market are most dispatchable generation, marginal costs per generation technology and the residual demand Figure 2.1. All power plants are aggregated per technology, resulting in the installed capacity. The actual dispatchable generation depends on scheduled maintenance, such as the maintenance of nuclear power plants during summer, and the availability of water in the hydropower reservoirs. The marginal cost (Equation 2.4), the price at which the dispatchable generation technologies are offered on the spot market, increases on a yearly basis for fossil-fuel fired power plants. New renewables such as PV and wind, typically offered at zero-cost, are depressing prices on EU spot markets with high shares of renewables. Switzerland has access to long-term and low-cost import contracts with France. These contracts participate in the market clearing process at 35 CHF/MWh with around 2000 MW, are gradually reduced until 2040 (Osorio & van Ackere, 2016), and are not expected to be renewed as they conflict with European market coupling rules (VSE, 2012). Hydropower is an exception to the rule of marginal cost bidding, as it is offered at opportunity cost. Since hydropower plays a central role in the Swiss energy system it will be discussed in more detail in section 2.3.3.

The system operator dispatches generation capacity in the most cost-efficient way to meet the (residual) demand in the system using the merit order. The least-cost dispatch is determined by intersecting the supply curve, which is made up of the price-sorted capacity bids, with the demand curve. The intersection point of both curves is the market clearing price, corresponding to the price of the marginal producer. The market clearing price is the highest marginal cost of dispatched capacity to meet the residual demand, which is determined by solving the optimization problem in Equation 2.2. The market clearing price will be paid for every MWh generated by dispatched generators.

Complicating the market clearing process is the import and export of electricity with neighboring countries, which happens ex-ante (i.e. before the market is cleared), increasing or decreasing the residual demand. In the present model, hourly spot markets are implemented for France, Germany-Austria and Italy using EPEX[5] and GME[6] data from 2010-2014. The hourly time series are used to create spot price profiles. A novel feature of the model is that hourly transmission capacity constraints are taken into consideration for all cross-border trades using net transfer capacity (NTC) values for 2013 and 2014, available from ENTSO-E[7]. It is important to model the NTC and potential congestion for each border since Switzerland heavily relies on electricity imports during the winter period, especially from Germany. Future developments such as increasing shares of RES production

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[5] https://www.eex.com/en/market-data/power/spot-market/

[6] https://www.mercatoelettrico.org/en/mercati/MercatoElettrico/MPE.aspx

[7] https://transparency.entsoe.eu/content/static_content/Static%20content/legacy%20data/year%20selection.html

in Switzerland and neighboring countries can lead to increased cross-border electricity flows to ensure the system balance. Switzerland also has access to interruptible contracts (Equation 2.3), assumed to be 5% of the annual peak demand, at an estimated 900 CHF/MWh (De Vries & Heijnen, 2008). Finally, in case interruptible contracts are exhausted and there is a real (physical) shortage of electricity supply, then the clearing price will be set at the Value of Lost Load (VOLL) (Hasani & Hosseini, 2011; Olsina et al., 2006), estimated at 3000 CHF/MWh (Osorio & van Ackere, 2016). The model only calculates endogenous CO_2 emissions (Equation 2.6), meaning that no CO_2 emissions are attributed to imports.

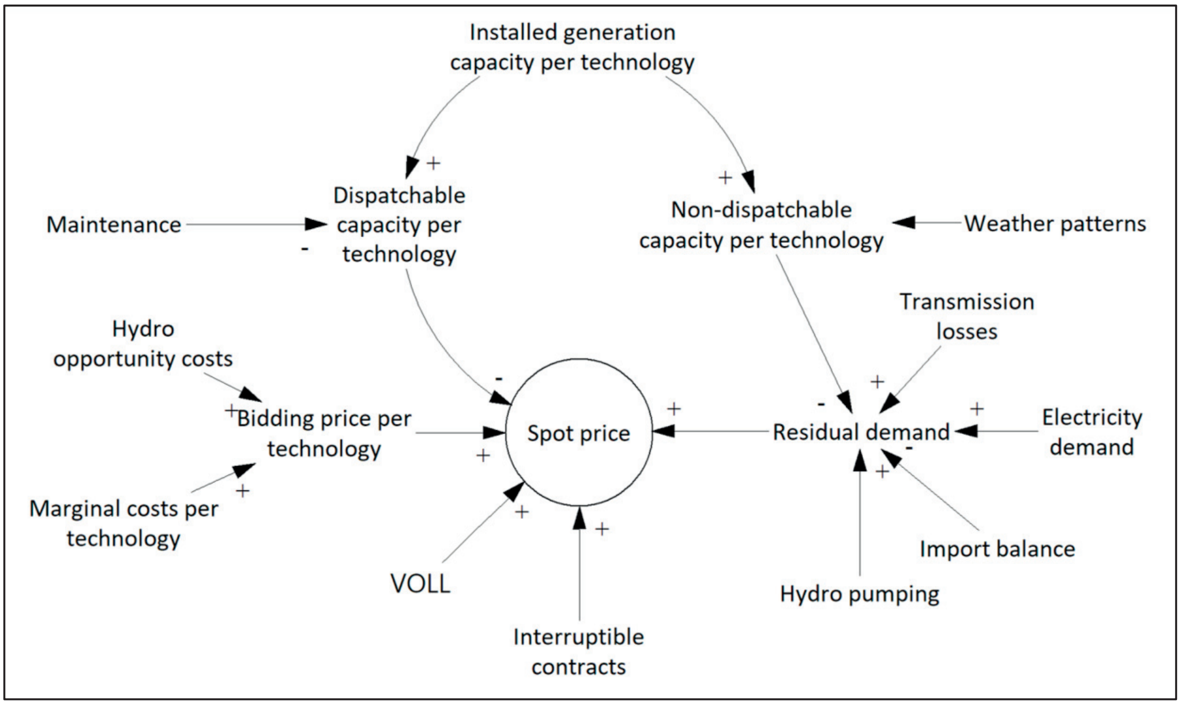

Figure 2.1 Swiss electricity spot market.

Hourly electricity demand data from Swissgrid[8] is used to create standardized profiles from 2010 to 2014, which is combined with electricity demand development assumptions taken from the selected scenario studies. Thus, the electricity demand is an exogenous variable and does not take electricity price elasticity into consideration, as evidence of such elasticities is limited for Switzerland (Filippini, 2011). The hourly electricity demand profiles are static in the sense that they are not adjusted to potential future demand profile changes as a result of electric vehicle charging, demand response, or other technological and behavioral developments. The spot market is cleared using the hourly residual demand (Equation 2.6), rather than the hourly electricity demand. First, transmission losses of 7% (Andersson et al., 2011; Kannan & Turton, 2011; Prognos AG, 2012) to 8% (Osorio & van Ackere, 2016) have to be compensated. Second, electricity demand for hydro pumping, as well as electricity exports, are added to the hourly demand. Third, electricity production from intermittent renewables such as solar, wind and run-of-river are subtracted from the demand, as they cannot be dispatched like conventional thermal or hydro storage plants. The resulting residual demand represents a shift in the merit order curve, which

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[8] https://www.swissgrid.ch/swissgrid/en/home/experts/topics/energy_data_ch.html

can push more expensive generation options such as gas fired power plants out of the market. A lower residual demand will lead to lower electricity prices and lower profits for electricity producers (Haas, Lettner, Auer, & Duic, 2013).

The available electricity generation per hour is determined by the installed capacity, maintenance and weather effects (Table 2.4; Equation 2.5). The installed capacity is driven by investment decisions, which are covered in more detail in Section 2.3.2. Currently, most of the electricity is supplied from reservoir, pumped storage and run-of-river hydropower plants. Run-of-river plants depend on relatively predictable water flows and cannot be dispatched since they cannot store their electricity. Reservoir hydro plants also depend on a relatively predictable natural inflow from meltwater and rain but are modeled as dispatchable generation capacity as they can storage large amounts of energy. Pumped hydro plants are also dispatchable and react more closely to market signals for pumping and production. Hydropower has a strong seasonal pattern in Switzerland and is heavily relied upon during the higher winter electricity demand. The seasonality of hydropower water inflow is based on weekly SFOE[9] profiles from 2010-2014 and future inflow predictions (Pöyry, 2012). Another major source of electricity production is nuclear energy, which is assumed to be phased-out according to a wide range of scenario assumptions. Furthermore, maintenance is often scheduled during the summer months, resulting in a lower dispatchable capacity. Hourly wind speed data is publicly available for non-commercial use from the NNDC Climate database[10]. Wind data from stations closest to 110 potential Swiss wind sites (Kunz et al., 2004) is weighted based on the site's size and then converted to power curves to approximate actual electricity production. Hourly wind data from 2010-2014 is used. The online European PVGIS tool (Huld, Müller, & Gambardella, 2012; Šúri, Huld, Dunlop, & Ossenbrink, 2007) was used to estimate yearly production figures for a 1 kW_{peak} solar photovoltaic installation in 200 Swiss cities, weighted according to population. Hourly solar irradiance data was obtained for all locations for the period of 1996 to 2000 from the EU S@tel-light project database[11]. An average standardized irradiance profile was calculated and adjusted with the average yearly production for a 1 kW_{peak} installation. While the periods covered by the solar data do not overlap with the other input data of the model, this is not an issue because the currently installed capacity of PV in Switzerland is very low.

$$\min_{DC_{di\subset i,t}, DIC_t, LL_t} \sum_i (DC_{i,t} MC_{i,t}) + DIC_t \cdot ICP + LL_t \cdot VOLL$$

Subject to:

$$RD_t = \sum_i (DC_{i,t}) + DIC_t + LL_t$$

$$DC_{i,t} \leq AC_{i,t}$$

$$DIC_t \leq IC_t$$

Equation 2.2 Optimization problem for the spot market clearing mechanism. Only dispatchable generation capacity di is taken into consideration here for AC, as a subset of generation technologies i. The clearing price will be paid for every MWh produced.

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[9] http://www.bfe.admin.ch/themen/00526/00541/00542/00630/index.html?lang=en&dossier_id=00767

[10] https://www7.ncdc.noaa.gov/CDO/cdo

[11] http://www.satel-light.com/indexs.htm

$$IC_t = \alpha PD_t$$

Equation 2.3 Interruptible contracts.

$$MC_{i,t} \ = \ VoW_{i,t} + VOM_{i,t} + FIT_{i,t} + \frac{CCF_{i,t}CP_t + FC_{i,t}}{FE_{i,t}}$$

Equation 2.4 Marginal cost calculation. Only reservoir and pumped hydro has a value of water. Not all technologies emit CO_2.

$$AC_{i,t} = NC_{i,t}CF_{i,t}$$

Equation 2.5 Available generation capacity. Maintenance and weather effects can all impact availability. Hydro reservoirs are a special case addressed in Section 2.3.3.

$$RD_t = D_t(1 + TL_t) - IB_t + DP_t - \sum_{ndi \subset i} AC_{ndi,t}$$

Equation 2.6 Residual demand. Only non-dispatchable generation capacity ndi is taken into consideration here for AC, as a subset of generation technologies i.

$$CO2_t = \sum_i DC_{i,t} \frac{CCF_{i,t}}{FE_{i,t}}$$

Equation 2.7 Endogenous CO_2 emission.

Where:

DC	Dispatched capacity in MWh
MC	Marginal cost in CHF/MWh
D	Hourly Swiss electricity demand in MWh
RD	Residual demand in MWh
AC	Capacity available for dispatch in MWh
IC	Capacity of available interruptible contracts in MWh
DIC	Dispatched interruptible contracts capacity in MWh
ICP	Interruptible contract price is assumed at 900 CHF/MWh (De Vries & Heijnen, 2008)
LL	Lost load in MWh
$VOLL$	Value of lost load is assumed at 3000 CHF/MWh (Osorio & van Ackere, 2016)
PD	Annual Swiss peak demand in MWh
VoW	Value of water in CHF/MWh (see Section 2.3.3, Equation 2.28)
VOM	Variable operation and maintenance cost in CHF/MWh
FIT	Feed-in-Tariff in CHF/MWh
CCF	Carbon content of the fuel in tCO_2/MWh
CP	Carbon price in CHF/tCO_2
FC	Fuel cost in CHF/MWh
FE	Firing efficiency in %
NC	Nominal installed capacity in MW

CF	Hourly capacity factor
TL	Transmission loss in %
IB	Import balance in MWh (see Section 2.3.4, Equation 2.29). Import is positive.
DP	Electricity consumed by hydro pumps in MWh
CO_2	Endogenous CO_2 emission in tCO_2
α	Proportion of interruptible contracts is assumed to be 5% (De Vries & Heijnen, 2008)
i	Index of Generation technologies
$di \subset i$	Subset of dispatchable generation technologies
$ndi \subset i$	Subset of non-dispatchable generation technologies
t	Index of simulation timesteps in hours
k	Index of countries neighboring Switzerland

Table 2.4 Generation capacity assumptions. De-rated capacities are used for geothermal, renewable CHP, waste burning and other thermal plants to avoid overestimating their contribution to the meeting peak-demand (Pöyry, 2012). However, using de-rated capacities can underestimate their overall contribution to the electricity generation mix.

Generation option	Investments	Dispatchable	Hourly availability factor
CCGT	Endogenous	Yes	100%
CHP	Endogenous	Yes	100%
Solar PV	Endogenous or exogenous (scenario)	No	Weather profile
Wind	Endogenous or exogenous (scenario)	No	Weather profile
Interruptible contracts	n/a (5% of peak electricity demand)	Yes	100%
Nuclear	n/a (phase-out schedule)	Yes	Seasonal profile
Run-of-river	Exogenous (scenario)	No	Seasonal profile
Reservoir hydro	Endogenous or exogenous (scenario)	Yes	Dynamic
Pumped hydro	Exogenous (scenario)	Yes	Dynamic
FR import contracts	n/a (cannot be renewed)	Yes	100%
Geothermal	Exogenous (scenario)	Yes	89%
Renewable CHP	Constant	Yes	51%
Waste burning	Constant	Yes	53%
Other thermal	n/a (re-investment not possible)	Yes	51%

2.3.2 Capacity investments

In the current model implementation only CCGT, CHP, hydro reservoir, wind and solar investments are determined endogenously. The project pipeline in Figure 2.2, based on the work by Vogstad (2005), is central to model bounded rational investment behavior, capacity expansion delays and resulting boom-and-bust cycles. Project permit applications are initiated when the project is expected to be profitable enough, given the investment risk associated with that technology. A proven way to model this investor behavior is by comparing the project's internal rate of return (IRR) with a corporate hurdle rate (Bunn & Larsen, 1992; Hasani & Hosseini, 2011; Ibanez-Lopez, Martinez-Val, & Moratilla-Soria, 2017; Olsina et al., 2006; Pereira & Saraiva, 2010). The IRR is the discount rate *r* at which the Net Present Value (NPV) is equal to zero (Equation 2.8).

The market forecast module is used to estimate the cashflow over the entire project's economic lifetime (Equation 2.9). The market forecast module has a similar structure to the spot market described in section 2.3.1, but uses imperfect information for future generation capacity, electricity demand and spot prices. The forecast module combines an assumed investor foresight of 5 years for generation capacity expansion and decommissioning (Bunn & Larsen, 1992; Bunn et al., 1993), as well as trend extrapolations (Kadoya et al., 2005). Planned capacity expansions are not known in the market if they are not yet under construction. Forecast heuristics are used to estimate the revenue over the asset's economic lifetime, considering the expected utilization as well as the average price during typical production hours (e.g. daylight for solar)(Equation 2.10-2.13). Capital cost, fixed cost and variable cost scenarios are taken from Pöyry (2012) to calculate the IRR. Hurdle rates are assumed to be 8% for hydro reservoirs, 9% for CCGT and CHP, 11% for wind and 12% for solar (Pöyry, 2012). If the IRR is greater than this hurdle rate, then the project application is started (Equation 2.14-2.15). Subsidies for solar and wind projects play an important role in guaranteeing their profitability. However, subsidies are linked to government targets and are finite, which has resulted in large waiting lists for solar projects. Under certain conditions future investments might be feasible without subsidies. A potential limitation is the number of suitable sites, which are assumed to allow for a maximum of 2282 MW installed wind capacity in the UNIL model (Osorio & van Ackere, 2016). This resource constraint is also taken into consideration in wind scenario assumptions in other Swiss scenario studies.

Returning to the investment pipeline; permit applications are assumed to be granted after a delay (Equation 2.16-2.17). The delay for CCGT project applications is assumed to be 2 years in our model to simulate the effect of long permit application delays. Consequently, the economics of the project might have changed by the time the permit is obtained, requiring new IRR calculations. Changes in the project's economics might result in delayed investments (Ibanez-Lopez et al., 2017), or even complete project abandonment (Equation 2.18). Longer delays cause the system to respond more slowly to market signals, increasing the system's susceptibility to investment cycles (Kadoya et al., 2005). In the event that the approved project is still profitable, the investment decision is made (Equation 2.19). The capacity under construction is based on the average size of projects for that technology, meaning that capacity investments are not continuous, but rather occur in blocks of capacity representing typical power plants (Equation 2.20). Once under construction, the capacity is communicated to the market and will be taken into consideration for IRR calculations. The capacity construction introduces another delay (Equation 2.21). The installed capacity is available (Equation 2.22) until the power plants are decommissioned (Equation 2.23) after their technical lifetime of 20-35 years for wind, 20-40 years for solar, 25-30 years for CCGT, 20-25 years for CHP and 80 years for hydro reservoirs (Andersson et al., 2011; Kannan & Turton, 2011; Pöyry, 2012; Weidmann, 2013).

There is an important feedback loop between the spot market and investment pipeline, indicated as (1) in Figure 2.2. When electricity generation is short during peak demand, then spot prices will increase. Increased spot prices send investment signals to market players, who will respond by initiating project permit applications. Capacity becomes available after the application and construction delays, resolving the market shortage and reducing the spot price. As the spot price decreases, investment signals are no longer sent to market players. The delays play an important role, as investment signals might be broadcasted for too long (i.e. permit applications are already underway), and do not allow market players to resolve shortages quickly (Kadoya et al., 2005). There is another feedback loop (2), which gives an earlier signal to market players as soon as capacity is under construction. Expected profitability is lower as more capacity is under construction. Both feedback loops are negative feedback loops, which means that they balance the system. However, given the bounded rational behavior of market players, relying on price signals and incomplete information, it is unlikely that investments are perfectly aligned with demand and supply changes.

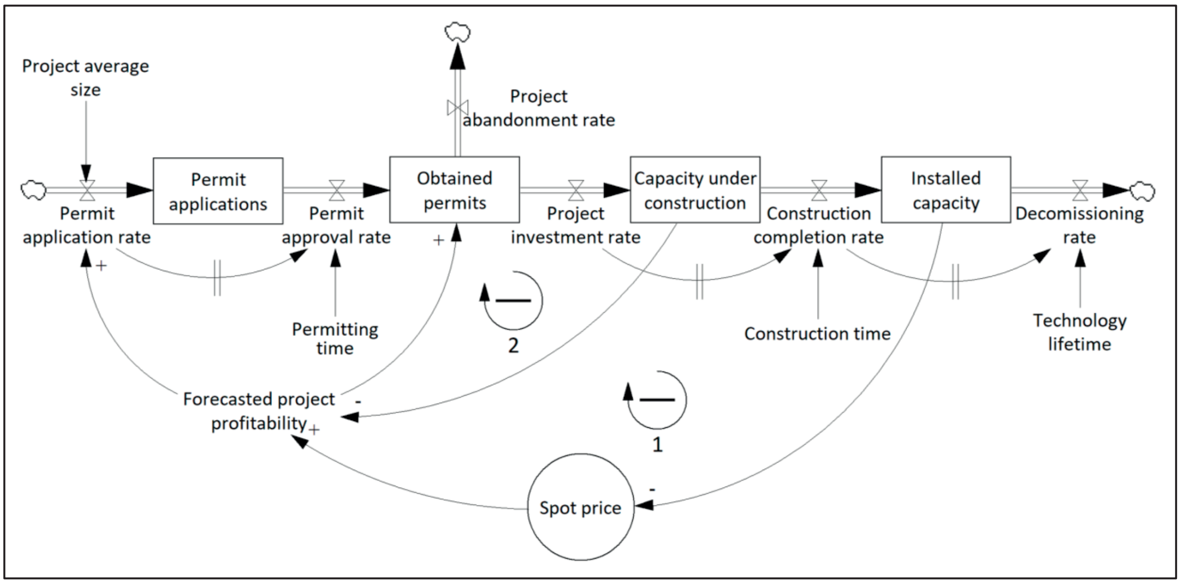

Figure 2.2 Generic investment pipeline.

$$IRR_i(r) = \sum_{n=0}^{N} \frac{C_{i,n}}{(1+r)^n} = 0$$

Equation 2.8 Internal rate of return calculation.

$$C_{i,n} = U_{i,n} H\left(FSP_{i,n} - MC_{i,n}\right) - CC_{i,n} - FOM_{i,n}$$

Equation 2.9 Forecasted cash flow.

$$U_{i,n} = \sum_{t=y_n}^{Y_n} \frac{DC_{i,t}}{NC_{i,t}}$$

Equation 2.10 Utilization factor of installed generation capacity.

$$FSP_{i,n} = \sum_{t=y_n+5H}^{Y_n+5H} FP_t DC_{i,t} \Bigg/ \sum_{t=y_n+5H}^{Y_n+5H} DC_{i,t}$$

Equation 2.11 Forecasted selling price. Calculated on a yearly basis, forecasting five years ahead. The forecasted spot price FP is found by solving the optimization problem in Equation 2.12.

$$\min_{DC_{di\subset i,t},DIC_t,LL_t} \sum_i \left(DC_{i,t}MC_{i,t}\right) + DIC_t \cdot ICP + LL_t \cdot VOLL$$

Subject to:

$$RD_t = \sum_i \left(DC_{i,t}\right) + DIC_t + LL_t$$

$$DC_{i,t} \leq FAC_{i,t}$$

Equation 2.12 Optimization problem for the spot price forecast. Only dispatchable generation capacity di is taken into consideration here for FAC, as a subset of generation technologies i. Residual demand RD, forecasted available capacity FAC, and marginal costs MC are forecasted for five years.

$$FAC_{i,t} = CF_{i,t}\left(NC_{i,t-5H} + CUC_{i,t-5H} - \sum_{x=o}^{5} DR_{i,t-xH}\right)$$

Equation 2.13 Forecasted available capacity.

$$PAR_{i,t} = \beta_i \cdot \varepsilon_{i,t} ANC_i$$

Where:

$$\beta_i = \begin{cases} 0, & \text{if investments are not allowed} \\ 1, & \text{if investments are allowed} \end{cases}$$

$$\varepsilon_{i,t} = \begin{cases} 0, & HR_{i,t} > IRR_{i,t} \\ 1, & HR_{i,t} < IRR_{i,t} \end{cases}$$

Equation 2.14 Permit application rate.

$$\frac{\partial PA_i}{\partial t} = PAR_{i,t} - AR_{i,t}$$

Equation 2.15 Permit applications.

$$AR_{i,t} = PAR_{i,t+pH}$$

Equation 2.16 Permit approval rate. The permit approval delay p is assumed to be constant.

$$\frac{\partial OP_i}{\partial t} = AR_{i,t} - PABR_{i,t} - PIR_{i,t}$$

Equation 2.17 Obtained permits.

$$PABR_{i,t} = \varepsilon_{i,t} ANC_i$$

Where:

$$\varepsilon_{i,t} = \begin{cases} 1, & HR_{i,t} > IRR_{i,t} \\ 0, & HR_{i,t} < IRR_{i,t} \end{cases}$$

Equation 2.18 Project abandonment rate. Used to reevaluate project profitability.

$$PIR_{i,t} = \varepsilon_{i,t} ANC_i$$

Where:

$$\varepsilon_{i,t} = \begin{cases} 0, & HR_{i,t} > IRR_{i,t} \\ 1, & HR_{i,t} < IRR_{i,t} \end{cases}$$

Equation 2.19 Project investment rate. Used to reevaluate project profitability.

$$\frac{\partial CUC_i}{\partial t} = PIR_{i,t} - CCR_{i,t}$$

Equation 2.20 Capacity under construction.

$$CCR_{i,t} = PIR_{i,t+cH}$$

Equation 2.21 Construction completion rate. The construction delay c is assumed to be constant.

$$\frac{\partial NC_i}{\partial t} = CCR_{i,t} - DR_{i,t}$$

Equation 2.22 Installed capacity.

$$DR_{i,t} = CCR_{i,t+lH}$$

Equation 2.23 Decommissioning rate. The technology lifetime delay l is assumed to be constant.

Where:

IRR	Internal rate of return
C	Forecasted cash flow in CHF
U	Utilization factor of installed capacity in %
FSP	Forecasted selling price in CHF/MWh
MC	Marginal cost in CHF/MWh
CC	Capital cost in CHF/MW
FOM	Fixed O&M cost in CHF/MW
DC	Dispatched capacity in MWh
FP	Forecasted spot price in CHF/MWh
RD	Residual demand in MWh
FAC	Forecasted capacity available for dispatch in MWh
CF	Hourly capacity factor
NC	Capacity available for dispatch in MWh
CUC	Stock of capacity under construction in MW
DR	Decommissioning rate in MW/t
PAR	Permit application rate in MW/t
ANC	Average nominal capacity in MW
HR	Hurdle rate
PA	Stock of permit applications in MW
AR	Permit approval rate in MW/t
OP	Stock of obtained permits in MW
$PABR$	Project abandonment rate in MW/t
PIR	Project investment rate in MW/t
NC	Nominal installed capacity in MW
CCR	Construction completion rate in MW/t
i	Index of generation technologies
$di \subset i$	Subset of dispatchable generation technologies

n	Index of $years$ in the project's economic lifetime
N	Economic lifetime of the project in years
t	Index of simulation timesteps in hours
r	Discount rate
y	Timestep t at the start of a year
Y	Timestep t at the end of a year
H	Number of hours per year
β	Binary indicator if investments in a generation technology are permitted
ε	Binary project profitability indicator in 1/t
p	Permitting time (delay) in years
C	Construction time (delay) in years
l	Technology lifetime (delay) in years

2.3.3 Hydropower

The misalignment of investments and required generation capacity is exacerbated if market signals are interfered by the presence of large amounts of hydro production. Cross-border trading using large interconnector capacity (section 2.3.4) permits Swiss dam and pumped storage operators to directly respond to seasonal and diurnal trading opportunities on foreign spot markets (Kannan & Turton, 2011). Hydropower is a seasonal resource and depends on weather and climate factors for the inflow of water. Thus, accurately modeling the capacity and utilization of hydropower is crucial for capturing seasonal patterns and effects on price signals.

Dam and pumped hydro reservoirs are modeled as stocks of water with flow variables representing natural inflow, overflow, production and in the case of pumped reservoirs, pumped inflow (Figure 2.3; Equation 2.24). Natural inflow is based on standardized profiles using weekly reservoir data from 2010-2014, reported by the SFOE[12]. Reservoir levels and natural inflows are split according to installed dam and pumped hydro capacities in the model as these respond differently to market dynamics (Equation 2.25). First, dam and pumped hydro installations place bids using a different value of water (Equation 2.28), which is the opportunity cost of using stored water at a given moment (Densing, 2013; van Ackere & Ochoa, 2010). The value of water is directly determined by the reservoir level, as a reservoir which is not using enough stored water has a risk of overflowing. This also means that seasonal inflow patterns have to be taken into consideration for hydro reservoirs. The higher the relative filling grade of the reservoir, the lower the value of water (and bidding price), resulting in larger amounts of hydro capacity to be dispatched by the market. Feedback loops (1) and (2) ensure more hydroelectricity is produced when market prices are high, which is balanced by increasing the value of water when reservoir levels are low, resulting in less hydro capacity to be dispatched. However, there is also an implicit component to the value of water. While the value of water hovers around typical market prices its operators

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[12] http://www.bfe.admin.ch/themen/00526/00541/00542/00630/index.html?lang=en&dossier_id=00766

have a degree of flexibility to price above or below the expected marginal bid to increase or decrease the odds of being dispatched (Osorio & van Ackere, 2016). As implemented, the value of water has a value between 6 and 500 CHF/MWh, with fluctuations based on the reservoir level and spot prices. Thus, while strategic bidding behavior (Ibanez-Lopez et al., 2017; Kadoya et al., 2005; Sánchez, Barquin, Centeno, & Lopez-Pena, 2007) is not directly implemented in this model, bidding does not follow perfect competition dynamics using marginal cost bids either (Alishahi, Moghaddam, & Sheikh-El-Eslami, 2012) due to scarcity pricing by hydro operators (Ochoa & van Ackere, 2015). Similarly, hydropower pumps are not dispatched by the market, but rather by the individual operators. Feedback loops (4) and (5) ensure that pumped reservoir levels are replenished when the value of water is high and spot prices are low, while not overflowing the reservoir (Equation 2.26). These feedback mechanisms also ensure that pumping is stopped as reservoir levels increase and the value of water drops. The most common "bang-bang" strategy found in competitive markets (Densing, 2013) is implemented in the model (Equation 2.27). Under this strategy pumps only operate at full capacity when there is an economic incentive and are fully stopped otherwise. If available, cheap foreign electricity can be used to pump hydro reservoirs as well. The endogenous operation of pumped hydro is a unique feature of our model, as pumping is assumed to follow an exogenously defined pattern in other Swiss SD models, such as the UNIL model which follows historical data from 2009-2013 (Osorio & van Ackere, 2016; van Ackere & Ochoa, 2010).

Finally, there is a positive feedback loop (3) which can destabilize the electricity prices in a hydro dominated market such as Switzerland. If the value of water is increased under scarcity conditions[13], then the spot price will increase as long as hydro is the marginal producer. Consequently, the market power of hydro producers could be used strategically to increase electricity prices. However, such behavior would send investment signals and result in new capacity to be constructed, which would lower the spot price through feedback loop (1) in Figure 2.2. In general, the availability of hydropower storage is expected to dampen electricity prices. Large storage capacities can be used to arbitrage between spot markets, within spot markets (e.g. diurnal and seasonal), and respond to supply shortages in the Swiss market. Using hydropower for these purposes, and for covering periods of shortage in particular, will delay price signals to the market until the available hydropower is inadequate to provide these services. In such an event price signals are likely to be much more pronounced.

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[13] This is not physical scarcity, but scarcity in the sense that other generation options cannot satisfy demand if dam and pumped hydro are not dispatched. In such situations hydro operators could set monopolistic prices.

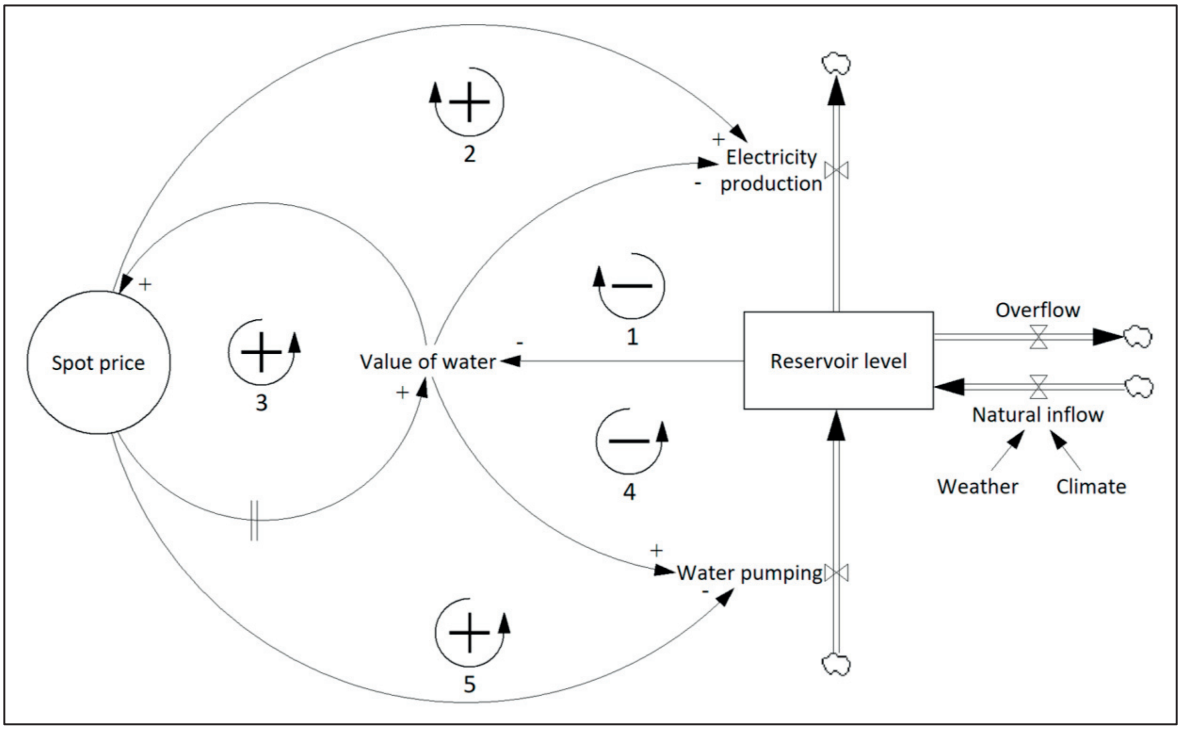

Figure 2.3 Generic (pumped) hydro reservoir. Dam and pumped hydro reservoirs are implemented separately in the model.

$$\frac{\partial RL_i}{\partial t} = WI_{i,t} - WO_{i,t} + WP_{i,t} - DC_{i,t}$$

Equation 2.24 Reservoir level.

$$WI_{i,t} = maxRL_{i,t}HWIP_{i,t}$$

Equation 2.25 Natural inflow. Note that the natural inflow WI is proportional to the reservoir size $maxRL$.

$$WO_{i,t} = \max(RL_{i,t-1} - maxRL_{i,t}, 0)$$

Equation 2.26 Overflow. This implementation corrects any maximum reservoir capacity violations with a delay of one hour.

$$WP_{i,t} = \theta_{i,t}AC_{i,t}$$

Equation 2.27 Pumping inflow.

Where:

$$\theta_{i,t} = \begin{cases} 1, VoW_{i,t} > \frac{SP_t}{\mu} \\ 0, VoW_{i,t} < \frac{SP_t}{\mu} \end{cases}$$

$$VoW_{i,t} = \min\left(\max\left(\rho SP_t + (1-\rho) \cdot VoW_{lookup}\left(\frac{RL_{i,t}}{maxRL_{i,t}}\right), minVoW_{i,t}\right), maxVoW_{i,t}\right)$$

Equation 2.28 Value of water. See Figure 2.4 for the dynamic lookup value returned by VoW_{lookup}.

Where:

RL	Reservoir stock in MWh
WI	Natural water inflow in MWh/t
WO	Overflow in MWh/t
WP	Pumping inflow in MWh/t
DC	Dispatched capacity in MWh/t
$maxRL$	Maximum reservoir stock in MWh
$HWIP$	Hourly water inflow profile
AC	Available capacity for dispatch in MWh
θ	Binary bang-bang pumping decision
μ	Pumped hydro round-trip efficiency, which is assumed to be 80% (Kannan & Turton, 2012)
SP	Hourly spot price in CHF/MWh
VoW	Value of water in CHF/MWh
$minVoW$	Minimum VoW, which is assumed to be 6 CHF/MWh (Osorio & van Ackere, 2016)
$maxVoW$	Maximum VoW, which is assumed to be 500 CHF/MWh (Osorio & van Ackere, 2016)
VoW_{lookup}	Value of water returned by looking up the y-value in Figure 2.4 by inputting $\frac{RL_{i,t}}{maxRL_{i,t}}$
ρ	Market price fraction, set at 0.7 following model calibrations
i	Index of generation technologies
t	Index of simulation timesteps in hours

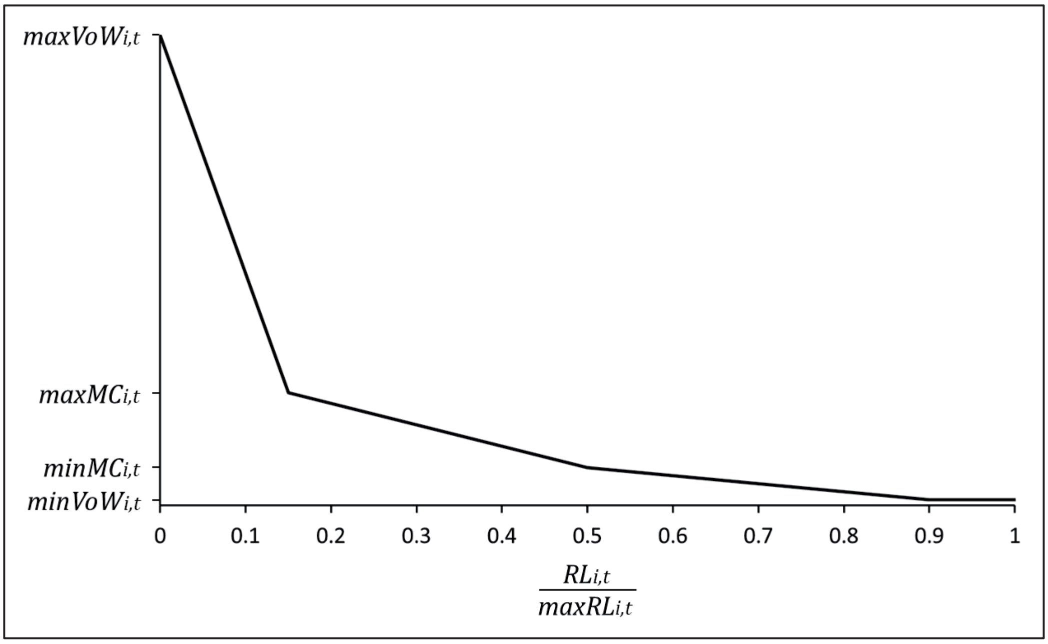

Figure 2.4 Dynamic Value of Water lookup graph. The curve is based on the implementation by (Ochoa & van Ackere, 2015; Osorio & van Ackere, 2016; van Ackere & Ochoa, 2010), but has been adjusted and calibrated for model implementation.

2.3.4 International trading

The misalignment of investments and required generation capacity is further exacerbated if market signals are interfered by structurally relying on imports from foreign markets such as France. There are a few key factors contributing to import reliance, especially during winter months (Figure 2.5). Residual demand is higher during winter, which will increase the domestic spot price. Investment signals leading to increased investments, as part of balancing feedback loop (4), do not immediately broadcast as the market can rely on domestic hydro and foreign imports. When foreign spot prices or long-term contract prices are lower than domestic spot prices, and sufficient NTC is available at interconnectors with that country, then electricity will be imported (Equation 2.29-2.31). The model is calibrated using historical transmission data from Swissgrid to import more electricity when the price difference is larger, as imports reduce the residual demand and domestic spot price. This is implemented via a lookup function, adapting the approach by (Vogstad, 2005) and calibrating it for the Swiss situation. Switzerland is connected to the French, Italian, and German-Austrian spot markets using ex-ante volume-based bids. Commitments are made to volume exchanges before the respective spot markets are cleared, which recalling the assumption of imperfect foresight does not necessarily guarantee optimal outcomes in the model. No impact on foreign spot prices is modeled, as these markets are much larger than the Swiss market. This means that Swiss prices will converge with foreign spot prices, as shown in balancing feedback loop (1). Conversely, electricity is exported proportionally when foreign spot prices are lower than domestic spot prices, which increases the domestic demand and domestic spot prices as indicated in balancing feedback loop (2). Thus, imports and exports balance the reinforcing feedback loop (3), as discussed in section 2.3.3. However, these balancing dynamics are limited by the availability of cheaper electricity and available NTC. As soon as transmission connections are congested (run out of NTC), then feedback loop (3) will be activated until the investment signal is strong enough. As a result, price signals in Switzerland are suppressed and delayed by the availability of large transmission capacities, low foreign spot prices and large hydro reservoirs. Due to delays in CHP and CCGT permitting and construction, the market is slow to respond once price signals are broadcasted.

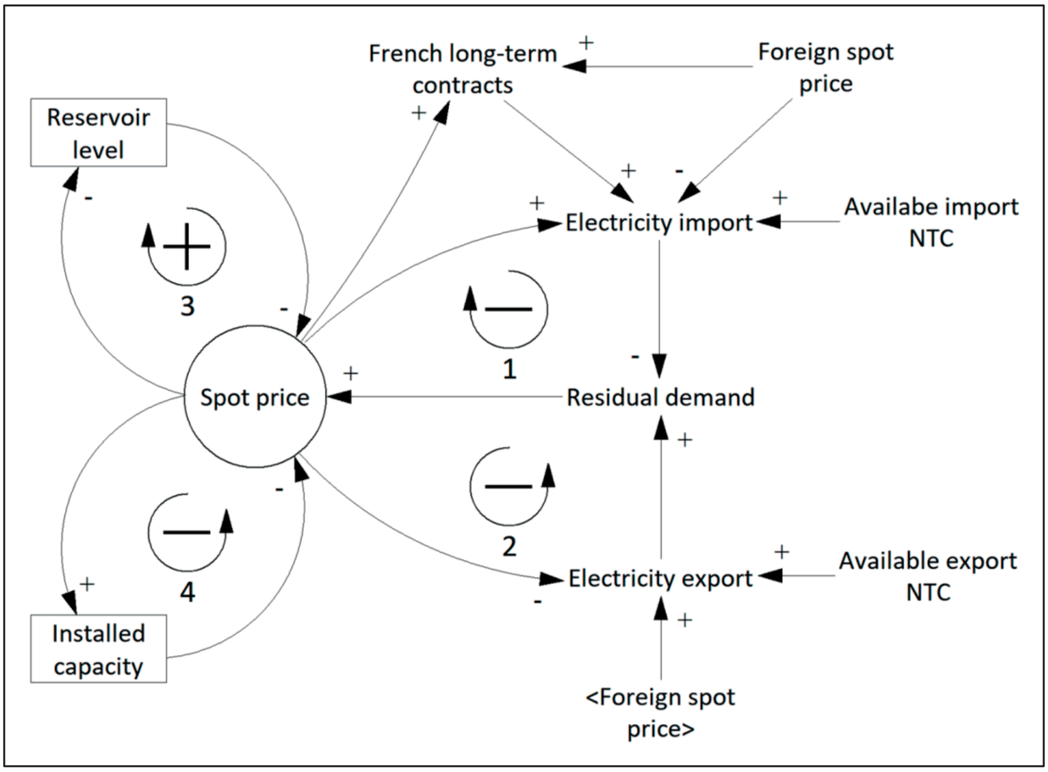

Figure 2.5 Generic Swiss import and export dynamics. French, Italian and the coupled German-Austrian spot markets are implemented as separate exogenous spot markets in the model.

$$IB_{k,t} = \sum_{k} \left(XL_{k,t} \left(\frac{SP_t - SP_{k,t}}{referenceSP_t} \right) \cdot ANTC_{d,k,t} \right) + DFRC_t$$

Equation 2.29 Import balance. See Figure 2.6 for the lookup value returned by $XL_{k,t}$.

Where:

$$ANTC_{d,k,t} = \begin{cases} ANTC_{d=imp,k,t} & ,XL_{k,t} > 0 \\ ANTC_{d=exp,k,t} & ,XL_{k,t} < 0 \end{cases}$$

$$ANTC_{d,k,t} = \begin{cases} NTC_{d,k,t} - DFRC_t & ,d = imp \text{ and } k = FR \\ NTC_{d,k,t} & ,otherwise \end{cases}$$

Equation 2.30 Available net transfer capacity.

$$DFRC_t = \begin{cases} \min(XL_{k=FR,t} FRC_t \,, NTC_{d=imp,k=FR,t}) & ,XL_{k=FR,t} > 0 \\ 0 & ,XL_{k=FR,t} < 0 \end{cases}$$

Equation 2.31 Dispatched French import contracts.

Where:

IB	Import balance in MWh. Import is positive.
XL	Exchange lookup using the graph in Figure 2.6.
SP	Spot price in CHF/MWh
$referenceSP$	The spot price reference follows the average spot price, with a maximum of 50 CHF/MWh based on model calibrations.
NTC	Net transfer capacity in MWh
$ANTC$	Available net transfer capacity in MWh

FRC	Available French import contracts in MWh
$DFRC$	Dispatched French import contracts in MWh
d	Index of cross-border flows {imp=import, exp=export}
k	Index of countries neighboring Switzerland, indicated by the country codes {FR=France, DE=Germany, AT=Austria, IT=Italy}
t	Index of simulation timesteps in hours

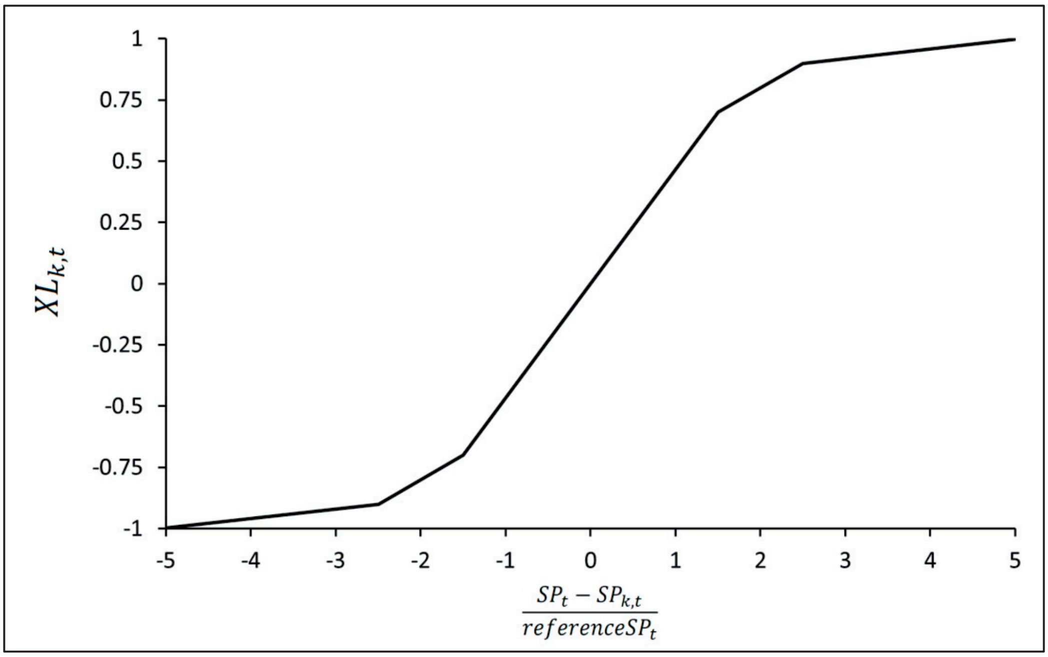

Figure 2.6 Exchange lookup. Positive values indicate a net import from country k, while negative values indicate a net export to country k. The curve is based on the implementation by (Vogstad, 2005), but has been adjusted and calibrated for model implementation.

2.3.5 Model verification and validation

The model is tested along the principles laid out by Sterman (2000), who argues that all models are inherently false since they cannot pass the standard tests of falsification. Verification and validation tests of simulation models should thus aim to establish credibility and usefulness of a model. Both structural and behavioral tests were performed on the model (Barlas, 1996). This section focuses on the following two tests: the boundary adequacy and behavioral reproduction. Furthermore, a comparison is made with model outputs of the selected studies, in order to explore the impact of differences in methodologies and key model assumptions. Direct structure tests were performed iteratively when building the model, as it draws on a rich set of scenario models and complementary literature. The direct structure tests included (Sterman, 2000): structure assessment, dimensional consistency, parameter assessment, and extreme conditions test. Leading up to final model description in Section 2.2, various model structures and parameter values were solicited from the literature, implemented and tested.

2.3.5.1 Boundary adequacy test

The boundaries of the model are set at which technology is developed endogenously through investment dynamics (i.e. wind, solar, hydro, CCGT and CHP), versus those whose development is determined exogenously through boundary conditions. Technologies driven by boundary conditions are either phased-out (e.g. nuclear), or not expected to change significantly (e.g. waste burning). Hydropower is an exception as investments are expected. However, hydro asset lifetimes far exceed the models time horizon of 35 years and will thus not contribute to investment cycles. Pumped hydro investments are therefore modeled as exogenous, as a significant amount of pumped hydro capacity will become available after 2015. Conversely, a significant amount of dam reservoirs will have to be considered for reinvestment before 2050, which is why hydro reservoir (re)investments are modeled endogenously. However, many scenarios considered in this study exogenously determine the level of installed dam reservoir capacity.

The model takes foreign spot market developments (e.g. Germany) as scenarios, making it impossible to identify the effect that the dynamics within Switzerland have on those markets. The focus of the model is Switzerland, which has a small market compared to its neighboring countries. This approach collapses details of foreign markets (e.g. hourly demand, installed capacities, energy and climate policies) into a single hourly spot price. All models, with the exception of the VSE model (Pöyry, 2012), follow a similar implementation. The UNIL model assumes constant spot prices, but tests are performed for the robustness of results (Osorio & van Ackere, 2016). Thus, the current implementation is a single region models, relying on a simplified representation of electricity import and export dynamics with the neighboring countries (Maire et al., 2015), while Switzerland has a high level of electricity import and export (SFOE, 2017b). To address this limitation the robustness of model results was tested using historical demand and spot price profiles from 2010-2014. Furthermore, physical transmission constraints for each border are implemented to model congestion.

The last boundaries are variables such as fuel prices, carbon prices, and technology cost developments (learning curves of technologies). Since these are predominantly determined on global markets, Switzerland has virtually no impact on these values. Therefore, these variables are all implemented as uncertain boundary conditions.

2.3.5.2 Behavioral reproduction test

The behavioral reproduction test contrasts model output versus historical observations. It is an important and intuitive check on the validity of simulation models, and arguably one of the most important tests (Suryani, Chou, Hartono, & Chen, 2010). Switzerland only has a partially liberalized market since a few years, hence the period with which model outputs can be contrasted is limited. Data from 2010-2014 is used to cover the same periods as the standardized input profiles of the model. Additionally, 2015 data is used to contrast the model as well. Models are by definition a simplification of reality, which is why the objective is not to reproduce exact historical values, but rather to replicate dynamic system behavior under imperfect information. The results of the behavioral reproduction test one of the key model output parameters, domestic spot price, is given in Figure 2.7. Closely linked to this parameter is the import and export balance of Switzerland in Figure 2.8, and the relative hydro reservoir levels in Figure 2.9. The most important property of all three parameters is their seasonal pattern, which is captured well in the simulation runs. However, certain peaks in spot prices and import balances occur earlier in the observed data. Regardless, the behavioral fit of the modeled and observed data is acceptable, given the fact that we modeled a market under the assumption of a full liberalization. The behavioral reproduction for the hydropower module, a unique and central part of the Swiss electricity system, shows a good fit with important seasonal patterns.

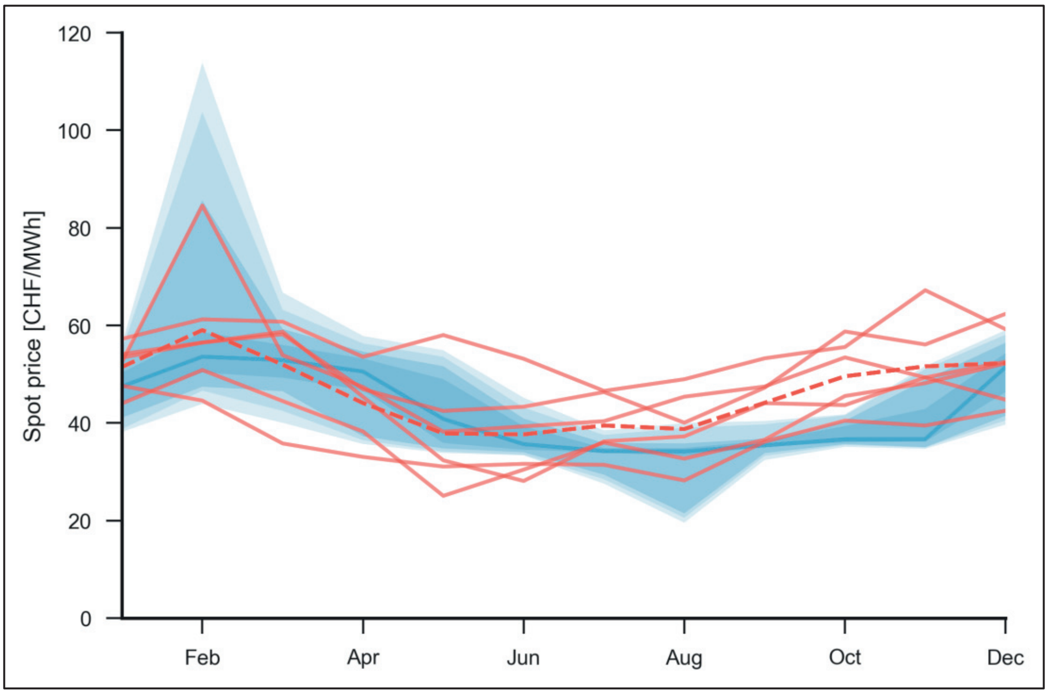

Figure 2.7 Behavioral reproduction test: average monthly Swiss spot price. The blue line represents the median simulated spot price. The blue shaded areas respectively represent 50%, 75%, 95% and 100% of the simulation outputs. The solid red lines are the observed average monthly SWISSIX spot prices from 2010 to 2015, based on hourly values from the EEX platform. The dashed line is the average observed value.

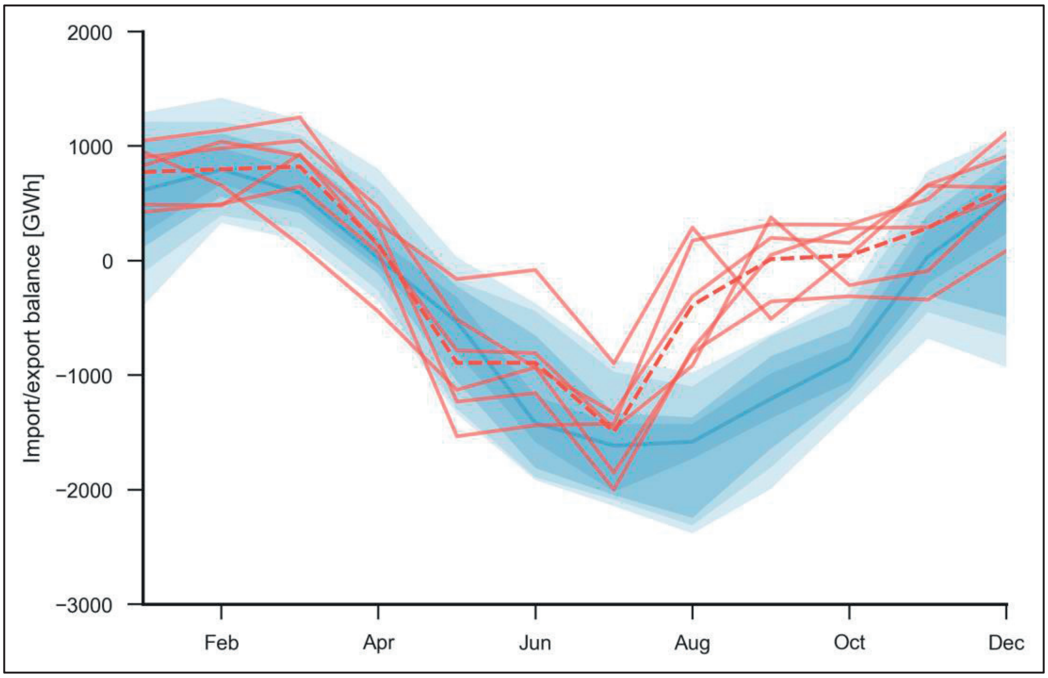

Figure 2.8 Behavioral reproduction test: monthly import and export balance. The blue line represents the median simulated import and export data. The blue shaded areas respectively represent 50%, 75%, 95% and 100% of the simulation outputs. The solid red lines are the observed monthly net import and export from 2010 to 2015, based on 15 minute values from Swissgrid. The dashed line is the average observed monthly net import and export. Positive values represent a monthly net import, and negative values a net export.

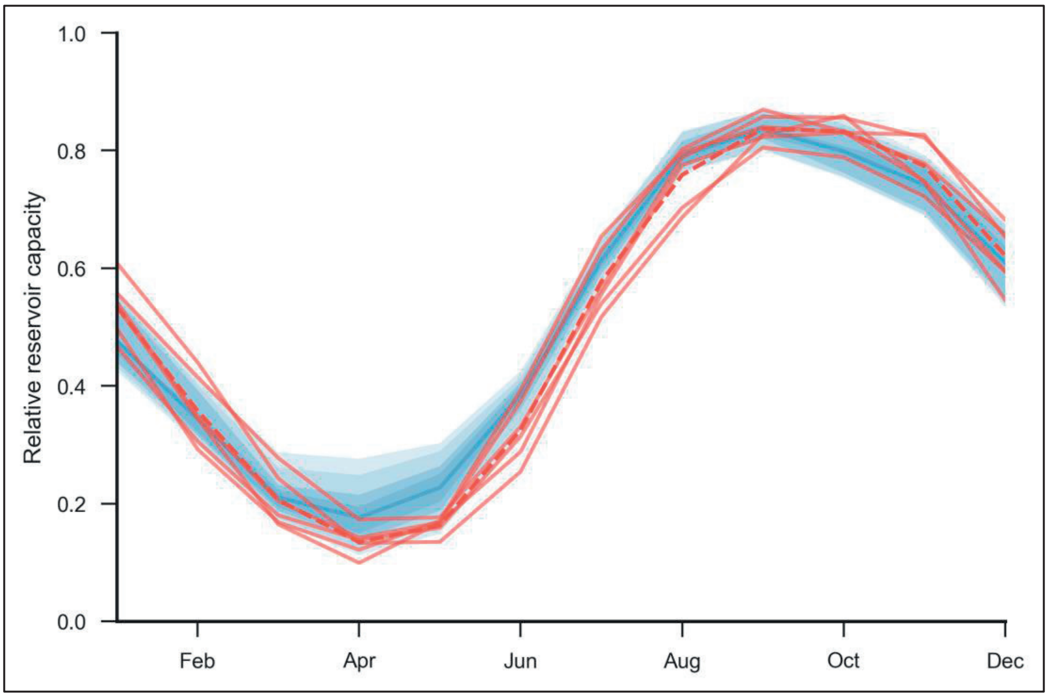

Figure 2.9 Behavioral reproduction test: relative reservoir capacity. The blue line represents the simulated median hydro reservoir levels. The blue shaded areas respectively represent 50%, 75%, 95% and 100% of the simulation outputs. The solid red lines are the observed reservoir filling grade from 2010 to 2015, based on weekly values from the Swiss Federal Office of Energy. The dashed line is the average observed reservoir filling grade.

2.3.5.3 Model output comparison

Output of the EPFL-MIR model is compared with selected scenario study results, if electricity sector specific outcomes are reported for that study. The aim of the comparison is to determine the correspondence of endogenous CO_2 emissions from 2015 to 2050, and to establish whether differences in model outputs can be explained by differences in methodologies and key model assumptions. Endogenous CO_2 emission is used for the model output comparison as it captures the electricity generation mix, which is partly scenario driven and partly market driven by factors such as the electricity demand, installed capacities, imports and weather effects.

All 41 scenarios selected in Table 2.3 are implemented in the EPFL-MIR model by modeling their boundary conditions and assumptions, if the information is available for that scenario. A full description of the boundary conditions is given in Appendix A, Tables A.1-A.3. As the boundary conditions are already pre-selected per scenario, we have a relatively low number of variables that can be varied for the simulation runs. Thus, it is possible to use a full factorial design, resulting in 2050 runs (Iman, Helton, & Campbell, 1981). A sensitivity analysis with 2050 runs is performed using Vensim® DSS for Windows (Version 6.4E) for all 41 scenarios, 2010-2014 demand and market data, 1996-2000 weather profiles and 2013-2014 NTC profiles. Figure 2.10 contains the output of the simulation runs, with an overlay of the endogenous CO_2 emissions reported in the selected scenario studies.

While the modeled CO_2 emissions and those reported in the scenario studies show a good fit, some additional remarks are in order. First, only 21 out of 41 scenarios reported endogenous emissions for the electricity sector, which could shift the percentile scores of the simulated CO_2 emissions. Second, all observed differences in values can be explained by market dynamics and modeling assumptions. There are two outliers, VSE Option 4 (forced lower imports compared to VSE Scenario 1), and SFOE WWB-C (forced CCGT investments). The EPFL-MIR model does not put restrictions on imports, nor does it force CCGT investments, as both are determined endogenously by market dynamics. Around 2035 a spike in CO_2 emissions can be observed for gas-focused scenarios which assume that the last nuclear reactor will go offline in 2034. The EPFL-MIR model generally shows a higher dependence on imports during this period, which does not contribute to endogenous CO_2 emissions.

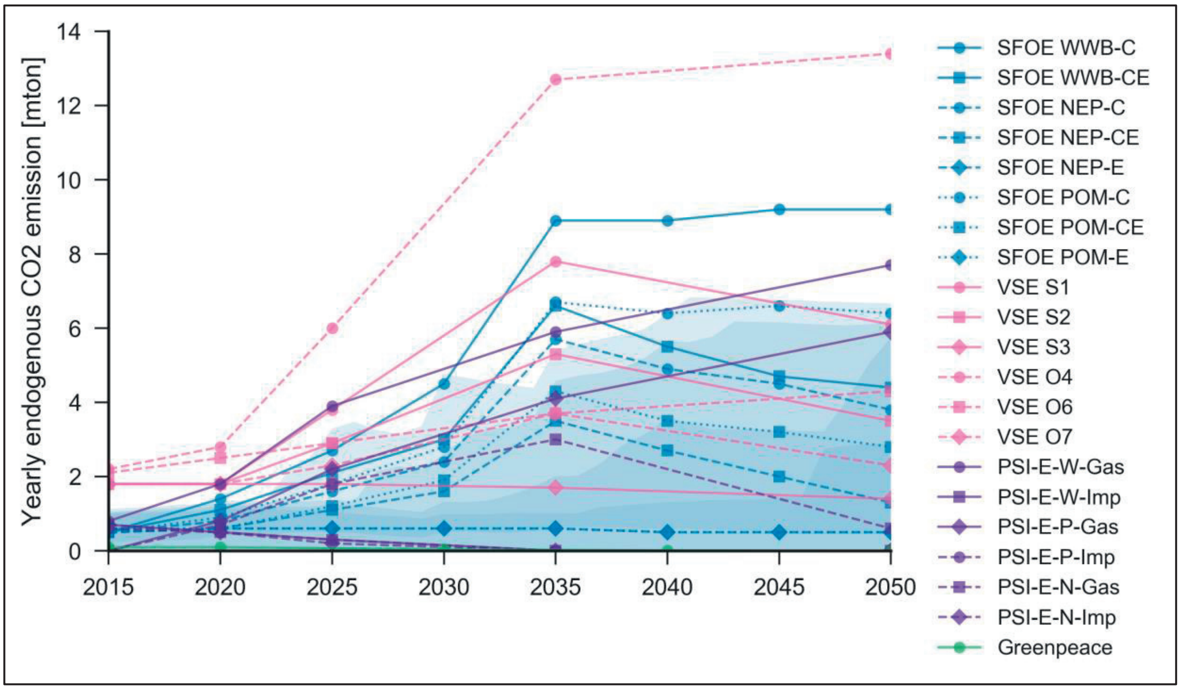

Figure 2.10 Model output comparison: yearly endogenous CO_2 emissions. The blue shaded areas respectively represent 50%, 75%, 95% and 100% of the EPFL-MIR simulation outputs.

2.4 Uncertainty analysis

System Dynamics is a deterministic simulation approach, but long-term simulation of complex socio-technical systems is inherently uncertain. The uncertainty analysis in this section explores the uncertainty space obtained from Swiss scenario studies (Pruyt, 2013), generates insights in the range of plausible model outcomes (Bishop et al., 2007), and filters out less influential boundary conditions (DeCarolis et al., 2017). A full overview of the boundary conditions and their possible values can be found in Appendix A, Tables A.1-A.3. Due to the large number of boundary conditions, only the most contrasting levels are analyzed visually in Section 2.4.1.1, and the reported statistical screening is limited to the 6 most influential boundary conditions in Section 2.4.1.2.

Due to the high number of boundary conditions included in the uncertainty analysis it is not possible to perform a full factorial design. Instead, Latin Hypercube Sampling (LHS) is used to create a fractional factorial design, as this approach is found to be efficient for simulation models with a large number of uncertain boundary conditions (Iman & Helton, 1988; Kleijnen, 2005; McKay et al., 1979). The efficiency of LHS was confirmed for a System Dynamics model in the electricity sector (Ford & Flynn, 2005). Using Vensim a Latin Hypercube Sampling (LHS) design (Seed: 1234) of all categorical boundary conditions is created with 6400 simulation runs (virtual experiments) over a simulation period of 35 years with hourly timesteps. All simulation runs are performed sampling 1996-2000 weather data, 2010-2014 market data and 2013-2014 NTC data. This is necessary to explore the full uncertainty space of the model and to generate insights in the range of plausible model outcomes.

2.4.1 Simulation results

Three important observations can be made from plotting the model outcomes for the average Swiss spot price (Figure 2.11), endogenous CO_2 emissions (Figure 2.13) and net electricity imports (Figure 2.14). First, the confidence intervals are much larger than the range of model outputs found in Swiss transition scenarios with predefined sets of boundary condition values. The larger confidence intervals are inherent to the uncertainty analysis approach, as it contains many runs with boundary condition combinations not included in the Swiss scenario studies. However, relying on scenarios with a limited predefined set of boundary conditions, and often limited treatment of uncertainty (Densing et al., 2016), can lead to an underestimation of uncertainty, as well as an underestimation of the influence of certain boundary conditions.

Second, Figure 2.11 is visually dominated by the occurrence of electricity shortages on the medium and long-term, leading to very high spot prices. While these events are less likely to occur, further investigation is warranted due to their disproportionate impact on consumers (De Vries, 2007). The modeled price spikes indicate a shortage of electricity supply, despite investments in RES. In fact, installed capacities should be more than enough to cover electricity demand, even during peak hours. However, not all installed capacity is available during winter peak hours, especially intermittent renewables such as PV. For this reason capacities are de-rated (Osorio & van Ackere, 2016), and plotted against the peak demand in Figure 2.12. Currently, peak demand is well below the de-rated capacity in Switzerland, which is reflected by the low and stable spot prices. When the de-rated capacity falls below the peak demand, then shortages, blackouts and scarcity prices can occur (Cepeda & Finon, 2013). However, even periods leading up to scarcity can be marked by higher price volatility (Osorio & van Ackere, 2016). This mainly occurs in the simulation runs where demand increases or stabilizes, highlighting the important role electricity demand reduction can play during the nuclear phase-out. However, scarcity pricing does not always occur in the increasing and stabilizing demand scenarios. Moreover, there seems to be a delayed and severe response by the spot market when the de-rated capacity falls below the peak demand, and the market response is more often than not inadequate to resolve the capacity shortage. The observed delayed and lacking response by the market, which is well beyond delays introduced by the investment pipeline, is due to the fact that market signals are being distorted by hydropower and imports. Hydropower plays an import role in maintaining stable and low electricity prices as long as there is adequate production capacity available. As soon as the electricity market is faced with shortages, and especially when imports are constrained, then hydro reservoirs quickly prove inadequate. Additionally, the majority of Swiss scenario studies give very little freedom to the model for additional capacity investments, as most capacity expansion is exogenously assumed. However, in a significant amount of runs with increasing electricity demand (e.g. left-hand side in Figure 2.12) the system is expected to experience shortages as early as 2025-2030, which are not met by scarcity pricing in as many cases. This implies that Switzerland can meet increased electricity peak demand through imports in those cases.

Third, Switzerland can develop a long-term dependency on high levels of electricity imports, much higher than reported for the UNIL model. On the long-term imports are reduced, and Switzerland is overall less dependent on electricity imports. However, capacity is expanded too late, and too slowly, resulting in higher electricity prices in a majority of cases. It is unlikely that this will result in boom-and-bust cycles, especially when the power plants replacing the phased-out nuclear power plants are much smaller in terms of installed capacity (e.g. solar, wind and CCGT). Furthermore, a large part of the capacity expansion is already determined through the boundary conditions (e.g. solar, wind and hydro). Finally, removing import constraints shows a market tendency towards import reliance. While net exports can be observed throughout the model horizon, this only occurs in slightly more than 12.5% of the runs. It should be noted that removing the import constraint also leads to an important difference in modeling assumptions with most optimization studies, so caution is advised when comparing to those studies.

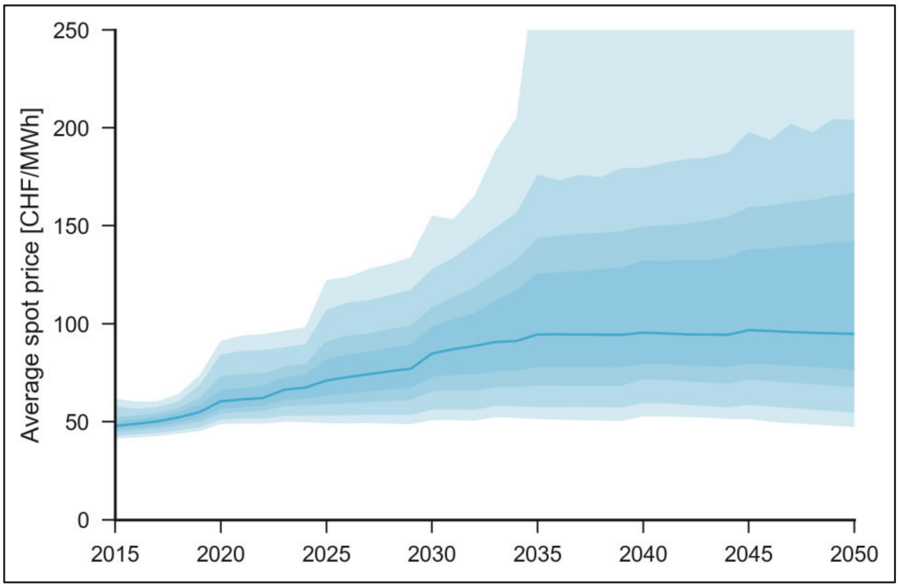

Figure 2.11 Uncertainty analysis: average spot price. The blue line represents the modeled average Swiss spot price. The blue shaded areas respectively represent 50%, 75%, 95% and 99% of the EPFL-MIR simulation outputs.

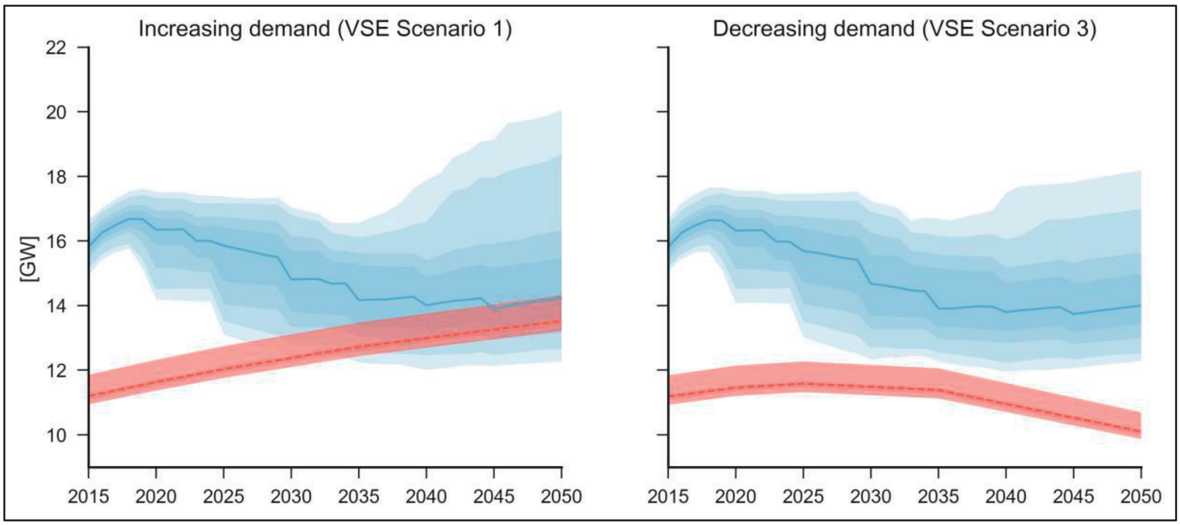

Figure 2.12 De-rated capacity and peak demand. The blue line represents the modeled median de-rated capacity. The red line represents the modeled median the peak demand. The blue and red shaded areas respectively represent 50%, 75%, 95% and 99% of the EPFL-MIR simulation outputs.

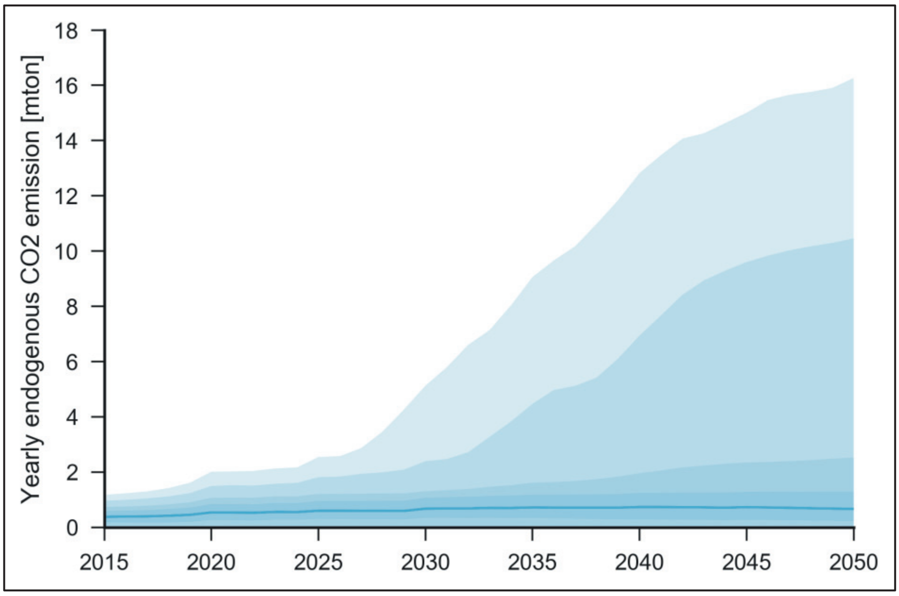

Figure 2.13 Uncertainty analysis: yearly endogenous CO_2 emission. The blue line represents the modeled median yearly endogenous Swiss CO_2 emissions. The blue shaded areas respectively represent 50%, 75%, 95% and 99% of the EPFL-MIR simulation outputs.

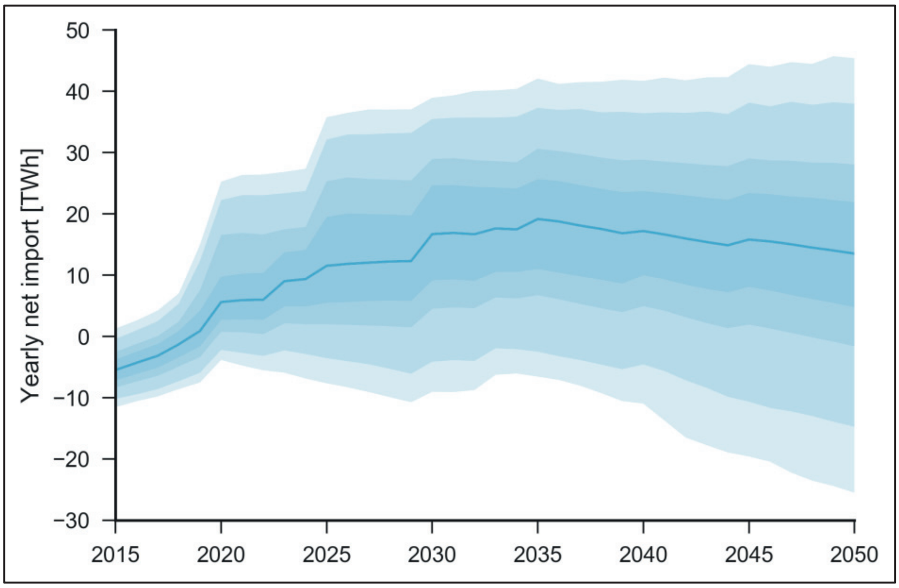

Figure 2.14 Uncertainty analysis: yearly net import. The blue line represents the modeled median yearly net import. The blue shaded areas respectively represent 50%, 75%, 95% and 99% of the EPFL-MIR simulation outputs. Net import is positive, net export is negative.

To aid visual comparison of contrasting scenarios, the remaining graphs in this section, as well as Figures B.1-B.4 in Appendix B, report 2.5-97.5 percentile ranges only. While this makes the graphs easier to interpret, some system behavior is no longer observable in most graphs, such as the occurrence of scarcity pricing in up to 2.5% of the simulation runs. The first comparison in Figure 2.15 highlights the influence and importance of electricity demand in the Swiss energy transition. While the influence is noticeable across the board, it is most pronounced for the CO_2 emissions and import dependence, where different system behavior (trends) are observed under increasing and decreasing electricity demands. Similarly, scarcity pricing is significantly less likely to occur under decreasing electricity demand scenarios. This draws attention to the importance of electricity demand reduction policies when phasing out nuclear energy and is a strong indicator that the uncertainty pertaining to electricity demand warrants further investigation.

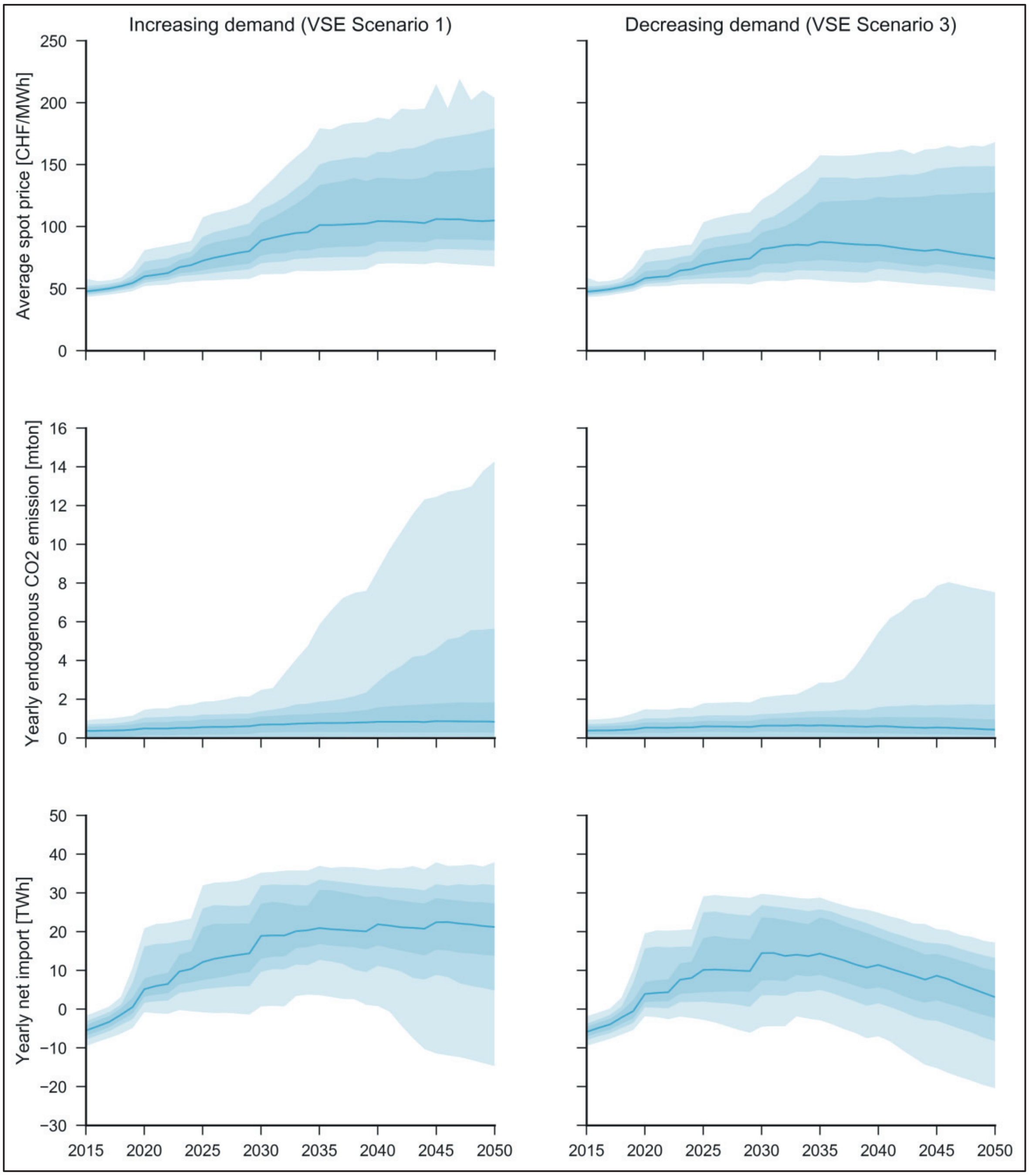

Figure 2.15 Uncertainty analysis: demand boundary condition. The blue line represents the modeled average values. The blue shaded areas respectively represent 50%, 75% and 95% of the EPFL-MIR simulation outputs.

The second comparison in Figure 2.16 highlights the influence of foreign spot prices on the behavior of the Swiss electricity system. Price convergence is to be expected due to Switzerland's high level of interconnection with its neighboring countries France, Germany, Austria and Italy. Lower foreign prices also make it more attractive to import electricity, resulting in a growth and stabilization of net imports across most simulation runs. Foreign spot price developments have a large impact on electricity imports and exports, significantly distorting market investment signals. Lower foreign spot prices lead to a higher electricity import dependency. However, due to low import prices the market is slower to respond to shortages as less hydropower is used to export to foreign markets. This highlights the interaction between foreign spot prices, electricity exports and hydropower as conceptualized in Figure 2.4 by feedback loops (2) and (3). As imports do not contribute to endogenous CO_2 emissions this also leads to lower emissions. The high influence of foreign spot prices draws attention to two issues in the current landscape of Swiss scenario studies: most studies use single market models with highly simplified import/export dynamics, with the exception of the VSE model (Pöyry, 2012); relatively little information is given on the boundary condition values for electricity demand in the Swiss scenario studies.

The model appears to be less sensitive to carbon prices (Figures 2.19-2.20; B.3) and natural gas price (Figure B.2). These boundary conditions primarily influence the endogenous CO_2 emission and to a lesser extent the net import. It can also be observed that a restriction on new CCGT plants (Figure B.1) has a comparable influence on the system as high natural gas prices, as the market response under high prices is to refrain from building centralized fossil generation capacity.

The third comparison in Figure 2.17 highlights the influence of the nuclear phase-out, which has a clear temporal component. Due to investment lead-times, and only moderate investments in new RES at that point in time, an early nuclear phase-out will sharply increase net imports and electricity prices. The scarcity in the market will send investment signals which lead to investments in CCGT and CHP (Section 2.3.2, Figure 2.2), thus increasing the endogenous CO_2 emissions. The phase-out schedule is too aggressive to be addressed with new RES and will increase the share of fossil-fired power plants in the generation mix. As a result of the new investments, net imports will decrease over time (Section 2.3.4, Figure 2.5). Thus, it is expected that the influence of the nuclear phase-out will decrease over time. This hypothesis is further explored using statistical screening in Section 2.4.2. It should be noted that scarcity pricing occurs in less than 2.5% of the runs under the conditions of an early nuclear phase-out, but these are not shown in Figure 2.17. While the exploration of the full uncertainty space leads to the identification of conditions under which undesirable system behavior is observed, such as scarcity pricing, it also highlights the robustness of the system to combinations of extreme boundary conditions.

The fourth comparison in Figure 2.18 highlights the importance of new RES deployment for Switzerland to limit its overall import dependence. The merit order effect of increased levels of RES can also be observed in the structurally lower spot price (Section 2.3.1, Figure 2.1). There is a large variation in the levels of deployed solar and wind capacity until 2050, with very high levels of installed capacity. The range for hydro reservoir developments (Figure B.4) is much more constrained, as a large part of its potential is already exploited, resulting in a lower influence than new RES.

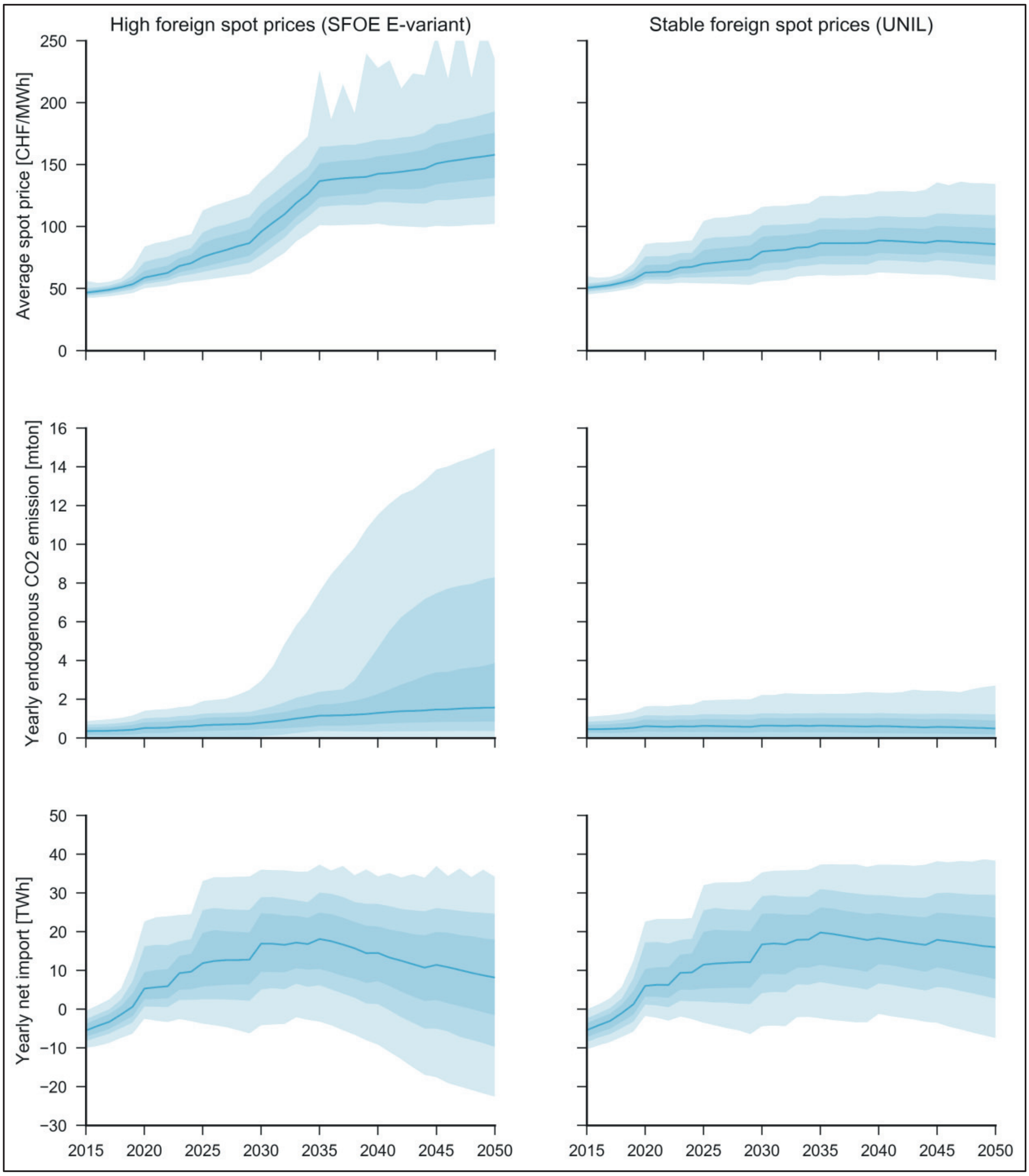

Figure 2.16 Uncertainty analysis: foreign spot price boundary condition. The blue line represents the modeled average values. The blue shaded areas respectively represent 50%, 75% and 95% of the EPFL-MIR simulation outputs.

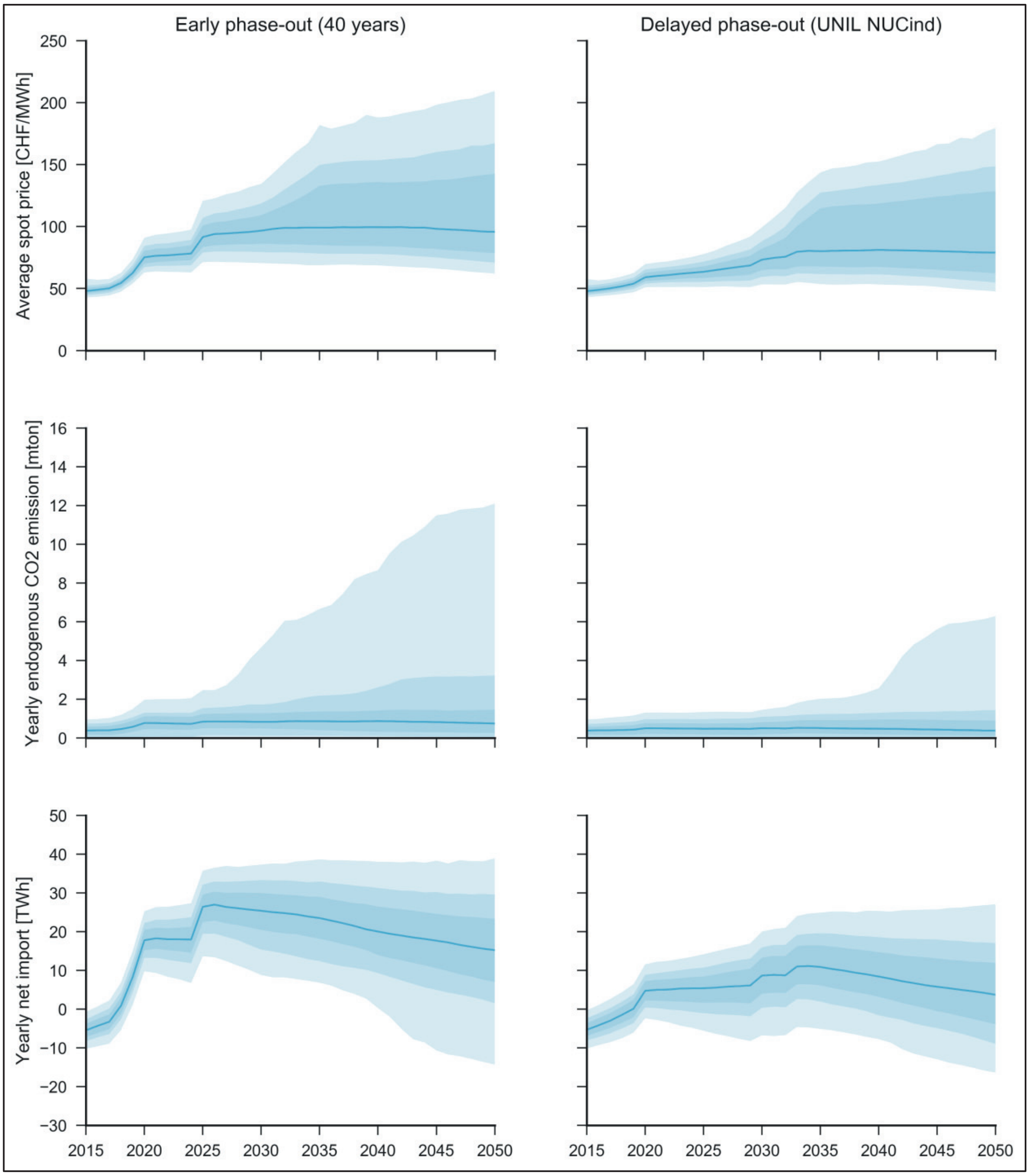

Figure 2.17 Uncertainty analysis: nuclear phase-out boundary condition. The blue line represents the modeled average values. The blue shaded areas respectively represent 50%, 75% and 95% of the EPFL-MIR simulation outputs.

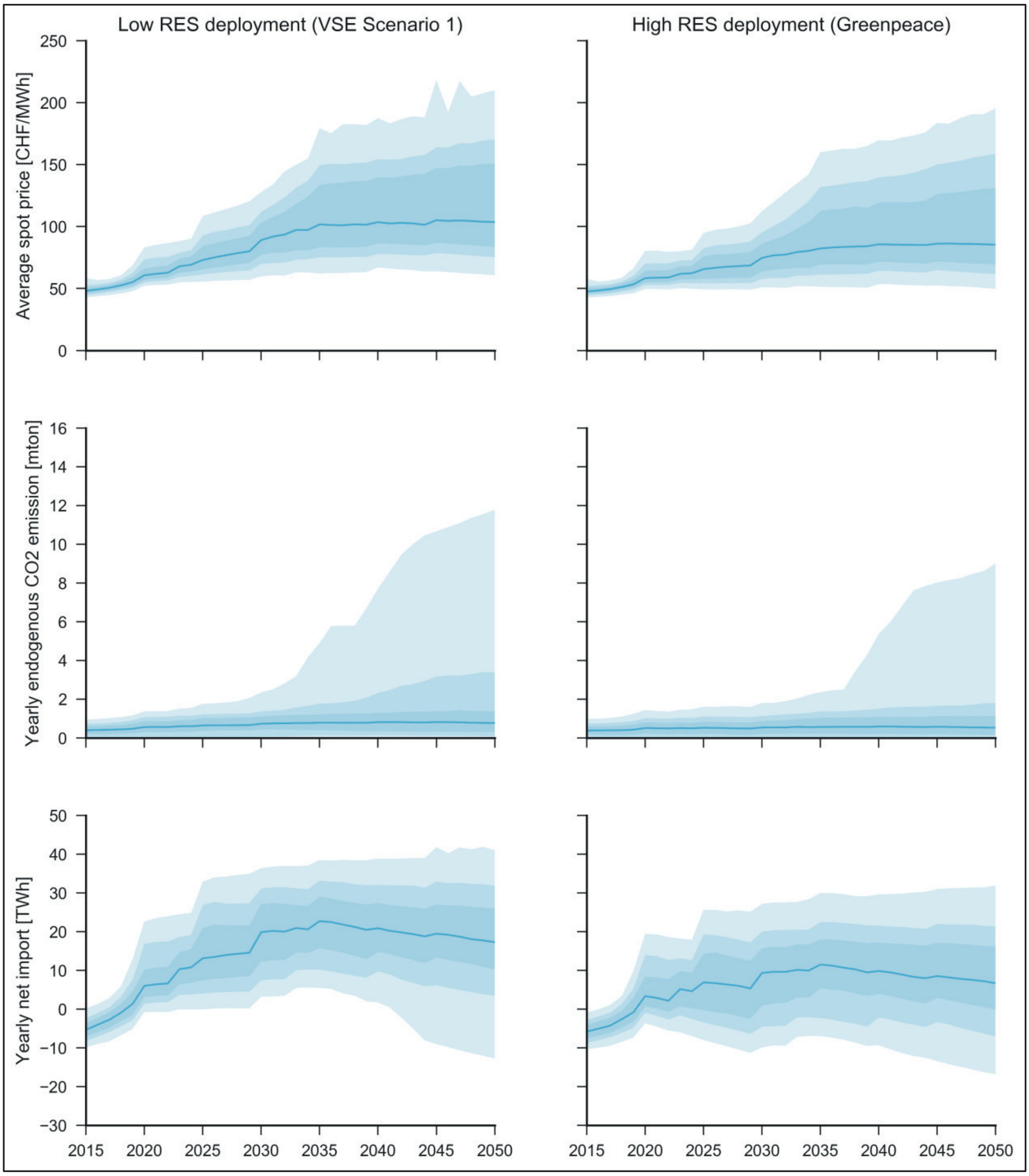

Figure 2.18 Uncertainty analysis: RES investment boundary condition. The blue line represents the modeled average values. The blue shaded areas respectively represent 50%, 75% and 95% of the EPFL-MIR simulation outputs.

2.4.2 Statistical screening

Statistical screening cannot be performed on the nominal boundary conditions, which are mapped to implement the unique boundary condition values in the EPFL-MIR model, but are performed on the model variables they are directly connected to. Following the first statistical screening step (Ford & Flynn, 2005; Taylor et al., 2010), the range of uncertainty for the boundary conditions is set according to Tables A.1-A.3. Then, 6400 simulation runs were performed using a LHS design, for which the correlation coefficients were determined.

While the (in)dependence of influential boundary conditions is discussed in this section, it is beyond the scope of this chapter to perform multiple model iterations to endogenize dependent boundary conditions. Following the statistical screening, future research is suggested in Section 2.5 to address two groups of boundary conditions.

The correlation coefficients are calculated for the entire model horizon to gain insight in changes to the relative influence of boundary conditions to the transition pathway, rather than a static endpoint. First, from the correlation coefficients of the spot price (Figure 2.19) it can be concluded that electricity demand and the foreign spot price have a relatively high correlation with the spot price during the first few years of the simulation. This can be explained by different boundary condition inputs in 2015, as the values are taken from models that generally simulate from 2010 to 2050. A potential solution could be to force historical data in 2015 and to apply a linear interpolation until the next available data point (often 2020). As observed in Figure 2.17, an early nuclear phase-out has a large impact on the spot price. Overall, the nuclear phase-out has a relatively strong correlation until 2033, when it is overtaken by the foreign spot price. Electricity demand becomes less influential over time compared to other boundary conditions, but still plays a significant role. Solar installed capacity, other thermal installed capacity and natural gas price play a smaller, but still significant role in the early years until around 2030. It should be noted that the installed capacities for other thermal and solar are determined exogenously in most scenario studies. However, installed capacities are dependent (Section 2.3.2, Figure 2.2) and should therefore be endogenized using an investment pipeline as described in Section 2.3.2. Foreign spot prices are assumed to be exogenous in the MIR-EPFL model, but can be endogenized by using a multi-region model, such as the Zephyr model used in Pöyry (2012).

Second, for CO_2 emissions we see lower correlations and less variation over time, but two boundary conditions stand out (Figure 2.20). The foreign spot price has a low correlation during the first half of the simulation but becomes more pronounced over time. The positive correlation could be observed from Figure 2.16 as well, as higher foreign spot prices increase domestic CO_2 emissions. The uncertainty range for other thermal installed capacity is as large as 0-760 MW (Table A.1) over the entire simulation time horizon. As a result, the energy mix and share of fossil-based power plants is substantial between simulation runs, strongly contributing to the (low) CO_2 emission levels in early years when dispatched by the market. As expected, the natural gas price has a negative correlation with the endogenous CO_2 emission, but this is the only outcome of interest that it has a moderate correlation on[14]. As early phased-out nuclear power plants are primarily compensated for by increased imports which do not contribute to endogenous CO_2 emissions, we expect to see lower correlation coefficients as in Figure 2.20.

Third, for net electricity imports (Figure 2.21) the observed correlations for nuclear installed capacity and RES production are similar to those for the spot price (Figure 2.19). These correlations indicate that an aggressive nuclear phase-out, as well as the availability of other thermal installed capacity, is more influential than the rate

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[14] However, there are even more boundary conditions with a lower correlation across all three outcomes of interest.

at which solar energy can be deployed on the short-term. Overall, electricity demand has a relatively high correlation coefficient, but also the correlation coefficients of nuclear installed capacity and solar installed capacity remain at a moderate level. Interestingly, the foreign spot price has a relatively low correlation coefficient for most of the simulation but reaches a moderate negative correlation by 2050. The correlation coefficient of the foreign spot price also switches polarity during the simulation. This can be explained by the fact that imports are generally increasing over this period, due to other factors, and that the implemented boundary conditions only contain stable or increasing spot prices. Thus, what is being observed here is a relationship, by chance, as higher foreign spot prices should not lead to higher levels of import.

Overall, it can be concluded that the nuclear phase-out, electricity demand and new RES deployment (in particular solar) are the most important energy policy related boundary conditions based on the analysis in sections 2.4.1 and 2.4.2. The foreign spot price and natural gas price are the most important uncertain boundary conditions. These boundary conditions are thus suggested for further analysis to uncover their uncertainty distribution, and to endogenize foreign spot markets, solar installed capacity and other thermal installed capacity in the model structure.

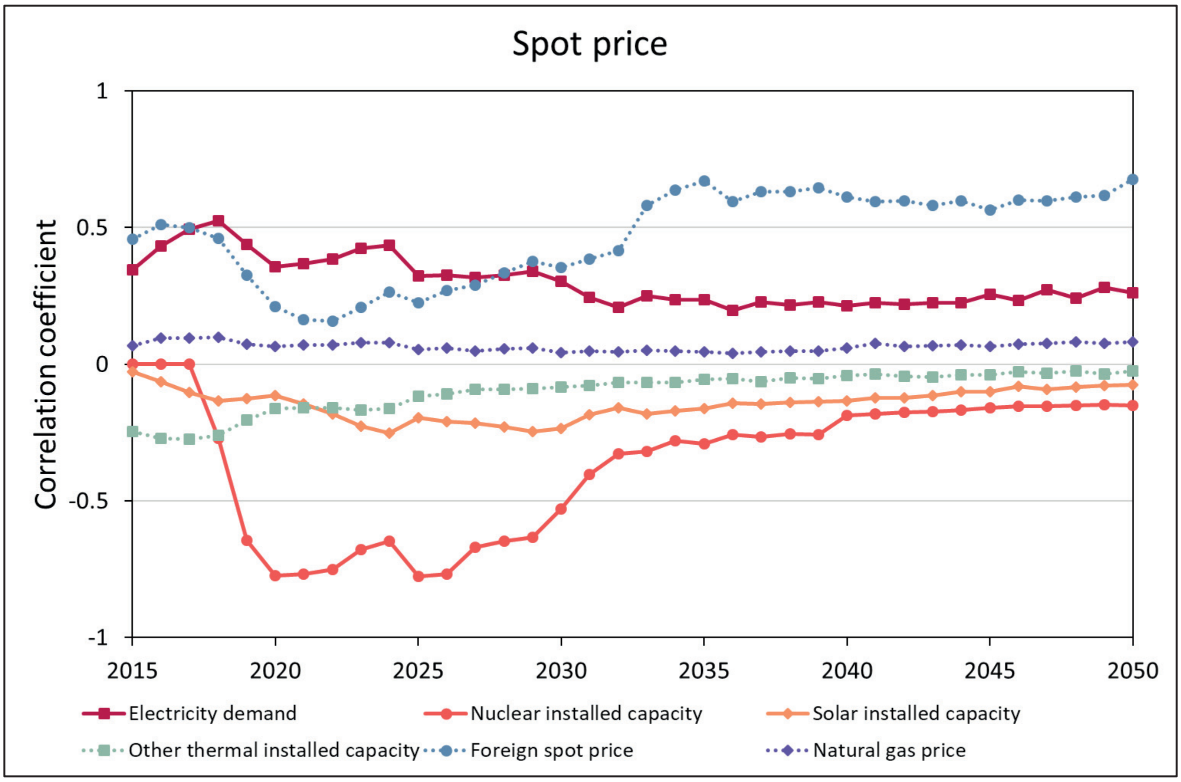

Figure 2.19 Correlation coefficients: spot price. Only six boundary conditions with the highest correlation coefficients are reported here.

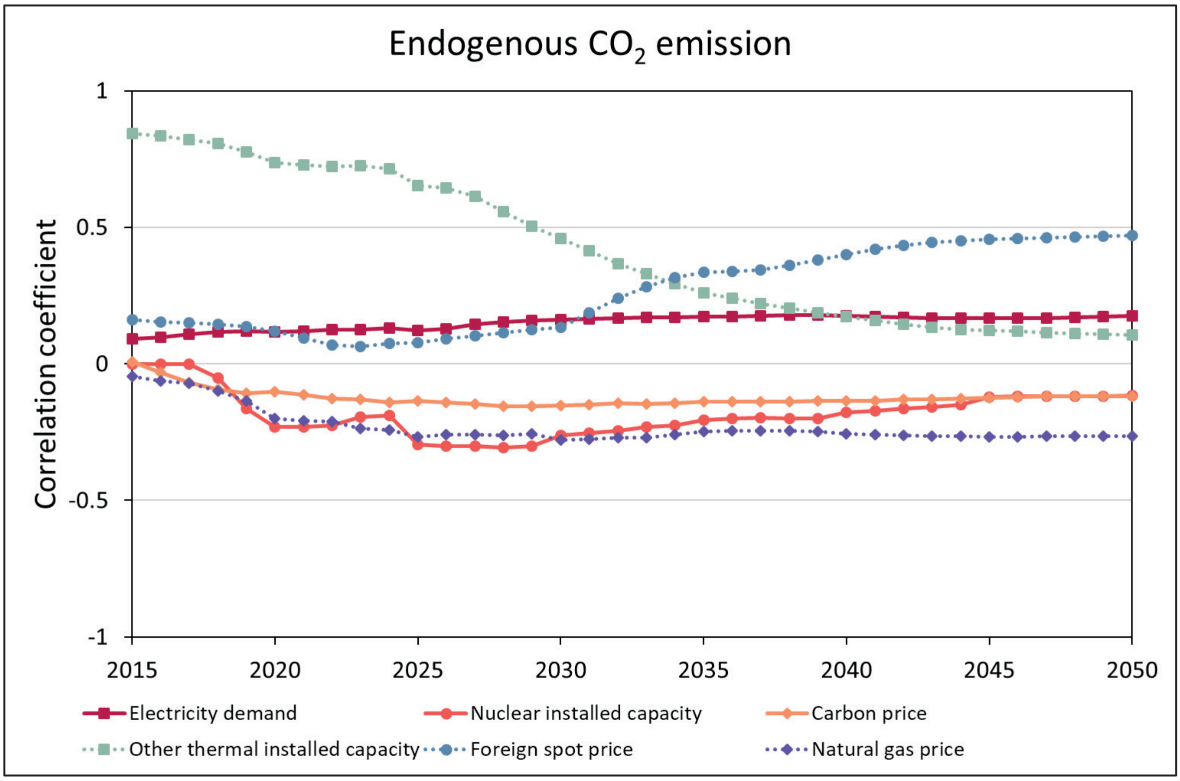

Figure 2.20 Correlation coefficients: endogenous CO_2 emission. Only six boundary conditions with the highest correlation coefficients are reported here.

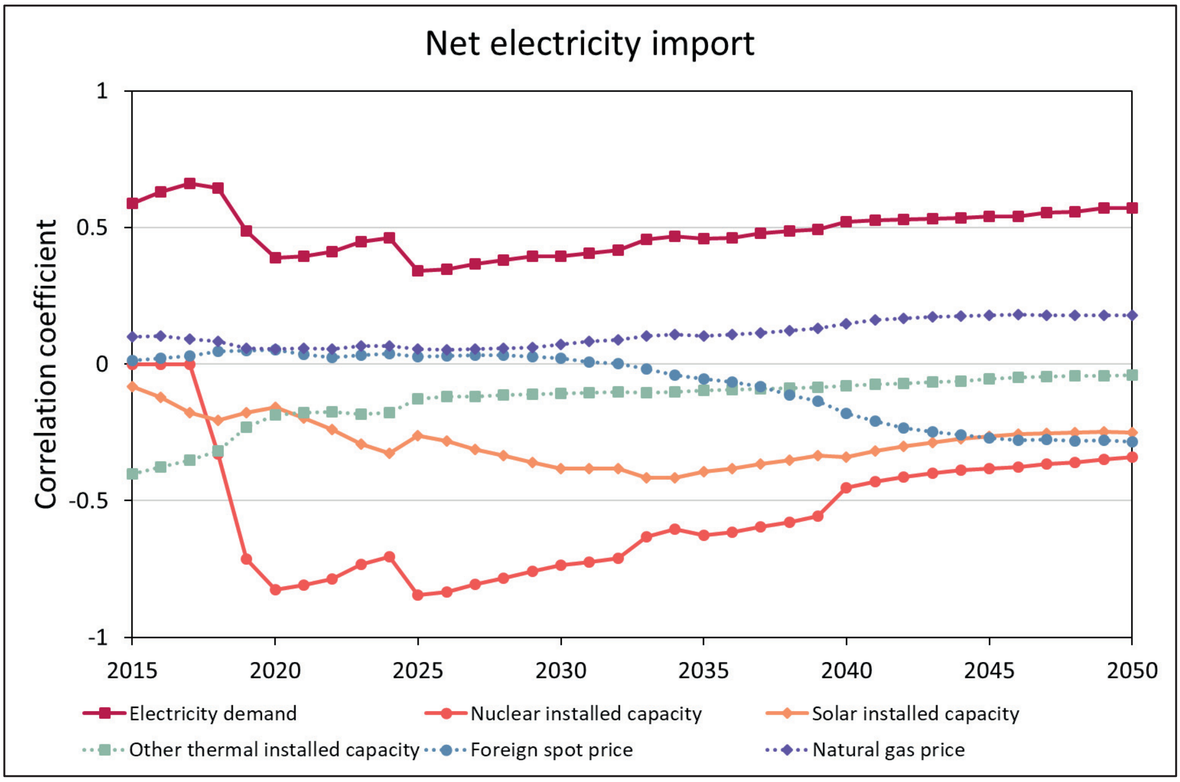

Figure 2.21 Correlation coefficients: net import. Only six boundary conditions with the highest correlation coefficients are reported here.

2.5 Conclusion and discussion

Since the conception of the Energy Strategy 2050 the Swiss energy transition has been a topic of much debate and has resulted in a large number of scenario studies to explore the transition towards a more renewable energy system. However, quantitative results of future energy system developments often deviate greatly between models, caused by differences in underlying assumptions, input values and modeling approaches (Kann & Weyant, 2000). A recent meta-analysis of Swiss energy transition scenario studies confirms a significant variation of quantitative results and approaches used (Densing et al., 2016). Comparison of these scenario study results requires that differences in modeling methodologies and assumptions are accounted for. However, the meta-analysis of Densing et al. (2016) uses scenario model outputs to determine a representative reduced set of scenarios.

The focus on this chapter is to demonstrate the use of computer simulation as a method in meta-analyses of quantitative sustainability transition scenarios, applied to the Swiss energy transition. In this Chapter 7 scenario studies are considered: SFOE (Prognos AG, 2012); VSE (Pöyry, 2012); ETHZ (Andersson et al., 2011); Greenpeace (Teske & Heiligtag, 2013); PSI-ELC (Kannan & Turton, 2011, 2012, 2013); PSI-SYS; UNIL (Weidmann, 2013). This means that the Cleantech (Barmettler et al., 2013) and SCS (SCS, 2013) models were excluded from the meta-analysis in this chapter, in favor of including the UNIL System Dynamics model. A total of 41 scenarios were selected from the 7 scenario studies, excluding scenarios that allow for reinvestments in nuclear energy. All selected scenarios are expert generated plausible scenarios, without any probability distributions available for the boundary conditions. The large amount of identified boundary conditions makes it unpractical to determine all joint probability distributions. Therefore, the set of boundary conditions should be reduced to the most important ones by means of a sensitivity and uncertainty analysis before engaging in such an exercise (Pruyt, 2013; Webster et al., 2002). The analysis can be applied to the available expert generated scenarios for the Swiss energy transition if all scenario parameters are implemented in a single model.

Thus, this chapter complements the meta-analysis of Densing et al. (2016) by exploring the uncertainty of Swiss scenarios by using a System Dynamics model. This chapter presented the design and implementation of a system dynamics model (EPFL-MIR) for the Swiss electricity market which contains detailed endogenous investment pipelines for a large number of technologies, as well as bounded rational actors. This allows us to model investment cycles (Ford, 1999, 2001; Kadoya et al., 2005) in a liberalized hydro-dominated market (Hammons et al., 2002) which is going through a nuclear phase-out (Osorio & van Ackere, 2016). While System Dynamics is a different method than used in most selected scenario studies, this approach has two distinct advantages: (1) it allows for a consistent comparison of underlying assumptions, data and scenarios, and (2) it allows for more realistic base assumptions (e.g. bounded rationality). An uncertainty analysis was performed on the System Dynamics model for all exogenous scenario parameter (boundary conditions) ranges reported in the expert scenarios (Pruyt, 2013). The uncertainty analysis was used to explore the full uncertainty space obtained from the Swiss scenario studies (Pruyt, 2013), generate insights in the range of plausible model outcomes (Bishop et al., 2007), and to filter out less influential boundary conditions (DeCarolis et al., 2017).

The first key finding is that the confidence intervals obtained from the EPFL-MIR model are much larger than the range of model outputs found in Swiss transition scenarios with predefined sets of boundary condition values. Relying on scenarios with predefined sets of boundary conditions, and often limited treatment of uncertainty (Densing et al., 2016), can lead to an underestimation of uncertainty, as well as an underestimation of the influence of boundary conditions. Similarly, reducing complexity by selecting a representative set of scenarios can contribute to a further underestimation of uncertainty and the influence of boundary conditions, as the range of underlying boundary condition values might be reduced simultaneously. The meta-analysis approach presented in this chapter does not run this risk as it considers all boundary conditions (model inputs), rather than model outputs.

The second key finding is that Switzerland can develop a long-term dependency on high levels of electricity imports, much higher than reported in other models, such as the UNIL System Dynamics model. Relaxing the import constraints imposed by most optimization models included in this meta-analysis, reveals a market tendency towards import reliance. While net exports can be observed throughout the model horizon, this only occurs in slightly more than 12.5% of the runs.

The third key finding is the identification of two subsets of boundary conditions to which the model is most sensitive. The first subset contains the following energy policy related boundary conditions: nuclear phase-out, electricity demand and RES deployment (solar PV in particular). The second subset contains uncertain boundary conditions: foreign spot price, carbon price, natural gas price, and other thermal installed capacity. Their importance was determined through a process of uncertainty analysis using the full set and range of boundary conditions in a Latin Hypercube Sample (McKay et al., 1979) design, visual inspection of confidence intervals and statistical screening (Ford & Flynn, 2005; Taylor et al., 2010).

The primary methodological contribution is the use of System Dynamics as a method in a meta-analysis of sustainability transition scenario studies. By implementing the underlying boundary conditions of all analyzed scenarios in one model an uncertainty analysis could be performed on a larger uncertainty space, increasing its analytical strength. This approach also demonstrates how a simulation model can be used to reduce the complexity of future analyses, by selecting a subset of most important boundary conditions, rather than adding to the existing complexity by presenting yet another model (conflicting) and quantitative outcomes.

The primary practical contribution is the exploration of boundary conditions which can be used as potential policy levers by policy-makers and firms in the Swiss energy transition, knowing that these boundary conditions will influence the system the most. Furthermore, by exploring a larger uncertainty space a better understanding of the range of possible model outcomes is given to policy-makers, allowing them to make better informed decisions without underestimating the uncertainty of the Swiss energy transition. Finally, the exercise of implementing a large set of Swiss transition scenarios in one model provided deeper insights in the assumptions and data driving model behavior.

A strength of the methodological contribution is its generalizability. While the results of the meta-analysis presented in this chapter are specific to the Swiss energy transition, the approach can be generalized to other sustainability transitions with readily available quantitative scenario studies.

There are a number of limitations to the EPFL-MIR model and analysis presented in this chapter. The first limitation is that the system boundaries are chosen in such a way that the neighboring countries are treated as exogenous, including investments in transmission capacity. Due to this limitation there is no feedback from the Swiss market to the foreign markets. While the Swiss market is relatively small compared to the German, Italian and French markets, it is likely that the endogenous investments in transmission capacity would more accurately capture impacts on electricity flows and spot prices between these countries. Furthermore, a high influence of foreign spot prices was found in the uncertainty analysis. However, due to its model boundaries the EPFL-MIR model is a single market model with simplified import and export dynamics. Finally, relatively little information is given on the boundary condition values for electricity demand in the Swiss scenario studies. To address this limitation further research could be done to extend the EPFL-MIR model to a multi-region model, such as the VSE model (Pöyry, 2012).

The second limitation is that demand profiles are currently static and based on historical values. However, such profiles are likely to change as a result of the adoption of e-mobility, heat pumps and demand response. While this assumption is common among the reviewed models, it is not a very realistic assumption and can lead to large differences in the dispatch models. However, determining dynamic demand profiles can be challenging due to the influence of other technologies and processes, such as demand-side management and price elasticities (Weidmann, 2013). Further research could add these important behavioral aspects to a currently technology dominated set of models.

Additional future research opportunities are identified as follows:

- The selection of most important boundary conditions presented in this chapter contains two sub-sets. For the non-political boundary conditions, the next step in the analysis would be to perform an estimation of their probability distributions together with experts (natural gas price and carbon price). Other non-political boundary conditions (foreign spot prices, solar installed capacity[15], and other thermal installed capacities) should be endogenized as they are not independent. For the political boundary conditions (nuclear installed capacity and electricity demand) a different approach is proposed in Chapter 5 of this thesis, which endogenizes the boundary condition in a policy making process. The approach combines theoretical knowledge of transitions in sociotechnical systems, agent-based modeling and simulation, and a formalization of power, agency and politics.
- Further work needs to be done on exploring the transition pathways and boundary conditions under which the system is showing different behavior, or branching points (de Haan, Rogers, Brown, & Deletic,

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[15] Making the solar installed capacity part of the internal model structure implies introducing another political boundary conditions: renewable energy targets and promotion mechanisms.

2016). Advanced behavior space generation and clustering techniques can be used to identify groups of runs and underlying boundary conditions (Guivarch, Rozenberg, & Schweizer, 2016; Islam & Pruyt, 2016; Kwakkel, Auping, & Pruyt, 2013; Pruyt & Islam, 2015).

3 Mixed-methods in sustainability research: a comprehensive literature review and process model

Preprint version of the article currently under review at the *Environmental Innovation and Societal Transitions* journal.

Abstract

While simulation is a useful method to study complex long-term sustainability transitions, the number of transition studies using simulation is limited, as the field is dominated by the use of qualitative case studies. Furthermore, the majority of simulation models are not based on frameworks. This has recently been recognized by transition scholars advocating mixed-methods research with various levels of integration of case studies, frameworks and simulation methods. However, a specific model to aid the development of mixed-methods research designs involving simulation and transition frameworks is still missing. In this article, a mixed-methods process model is developed, based on mixed-methods research design literature, and a comprehensive literature review of the sustainability transitions research field. The model addresses the theoretical and conceptual compatibility of relevant transition frameworks and simulation methods. Furthermore, the model facilitates the design and reporting of coherent mixed-methods research designs, which strike a well-informed balance between qualitative and quantitative insights.

Keywords: literature review, mixed-methods, process model, simulation, sustainability, transitions

3.1 Introduction

Sustainability transitions research is a relatively young field that has gained significant momentum in recent years[16], resulting in a vast amount of case studies. Many of these studies draw on popular frameworks, such as the Multi-Level Perspective (MLP), Transition Management (TM), Strategic Niche Management (SNM),

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[16] This trend is observed in earlier reviews (Chappin, 2011; Markard et al., 2012), and has since then continued (see Figure 3.1, Section 3.3.1).

and Technological Innovation Systems (TIS). Together, these frameworks provide a rich set of concepts to describe sustainability transitions in a detailed yet nuanced manner that covers technological, social, and institutional factors (Turnheim et al., 2015).

Nonetheless, theoretical and practical shortcomings are surfacing as the research field matures and is being critically assessed. First, most studies are qualitative case studies focusing on the early stages of contemporary or historical transitions (Holtz, 2011). It is difficult, if not impossible, to explore future phases in sustainability transitions with such qualitative methods, due to the inherent complexity and uncertainty of transitions. Second, computer simulation and other quantitative methods are rarely used in transition studies. Simulation is often the only tool available to capture the complex behaviors of a system going through a transition process (Axelrod, 1997), as well as transitions in complex systems emerging from micro-level mechanisms (Squazzoni, 2008; Timmermans, 2008; Timmermans et al., 2008). Third, reviews of available simulation models show that most models do not share the same conceptual and theoretical foundation, and that most simulation models do not adopt existing frameworks (Holtz, 2011; Li et al., 2015). Therefore, what we observe in sustainability transition studies is the traditional dichotomy of qualitative and quantitative methods, and few efforts towards integrating methods in transition research (Papachristos, 2014). This is a missed opportunity, as the utilization of qualitative and quantitative methods in a mixed-methods research design provides a more comprehensive and nuanced understanding of the studied phenomenon (Geels, Berkhout, et al., 2016; Papachristos, 2014; Turnheim et al., 2015).

Turnheim et al. (2015) acknowledge the importance of combining qualitative and quantitative methods and propose an approach to flexibly integrate simulation, socio-technical analysis, and initiative-based learning. Geels, Berkhout & van Vuuren (2016) similarly suggest the bridging of integrated assessment models, socio-technical transition analysis and practice-based action research in a sequential fashion, arguing against full integration on the grounds of differences in philosophies of science and ontological assumptions. In contrast, Papachristos (2014) suggested an integrative approach combining middle-range (quantitative) models and (qualitative) case study analysis. Papachristos & Adamides (2016) implemented this approach by studying the food/nutrition system though use of the MLP, a case study, and system dynamics simulation. A commonality between these contributions is that they propose and implement various mixed-methods research designs.

While the discussion on mixed-methods research and pragmatism is certainly not new (Doyle, Brady, & Byrne, 2009; Johnson & Onwuegbuzie, 2004), mixed-methods research designs have received little attention in sustainability transitions research. This is especially true for mixed-methods research combining simulation methods[17], case studies and transition frameworks, as shown in Section 3.3.2 of this chapter. The definition of mixed-methods research by Johnson, Onwuegbuzie & Turner (2007, p. 123) is used in this chapter: “Mixed methods research

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[17] Simulation *methods* is used throughout this chapter, as it best describes the relationship between simulation and other methods in a mixed-methods research design. Alternative terminologies are simulation *approaches* and simulation *paradigms* (Kelly et al., 2013).

is the type of research in which a researcher or team of researchers combines elements of qualitative and quantitative research approaches (e.g., use of qualitative and quantitative viewpoints, data collection, analysis, inference techniques) for the broad purposes of breadth and depth of understanding and corroboration". With regards to simulation, efforts in transition research are mainly focused on what (Greene, Caracelli, & Graham, 1989, p. 259) describe as *development*, where the outcomes of one method are used to develop, inform and implement the other (simulation) method. For example, recent studies primarily focused on sequential mixed-methods designs where qualitative methods are used to inform, design and parameterize simulation models (e.g. Auvinen, Ruutu, Tuominen, Ahlqvist, & Oksanen, 2015; Keeler, Wiek, White, & Sampson, 2015; Papachristos & Adamides, 2016; Rosales-Carreón & García-Díaz, 2015). Other efforts focus on the conceptualization and implementation of frameworks in various simulation methods (Bergman et al., 2008; DeCarolis et al., 2017; Li & Strachan, 2017; Lopolito, Morone, & Taylor, 2013; Papachristos, 2011; Schilperoord, Rotmans, & Bergman, 2008; Walrave & Raven, 2016), which is an important step towards further facilitating the use of simulation in sustainability transition studies in general (Holtz et al., 2015). However, a model to aid the development of mixed-methods research designs involving simulation and transition frameworks is still missing.

The contribution of this article is the development of a mixed-methods process model for sustainability transitions research, focusing on research designs involving simulation and transition frameworks. The process model addresses the theoretical and conceptual compatibility of relevant transition frameworks and simulation methods. Furthermore, the process model facilitates the design and reporting of coherent mixed-methods research designs, which strikes a well-informed balance between qualitative and quantitative insights. The development of the process model draws from more general mixed-methods literature (Collins et al., 2006; Heyvaert et al., 2013; Johnson & Onwuegbuzie, 2004; Onwuegbuzie & Leech, 2005, 2006), as well as a comprehensive literature review of sustainability transitions studies to ensure its specificity.

The remainder of the article is structured as follows. Section 3.2 presents the research design, detailing the structured literature review and a general mixed-methods process model. Section 3.3 presents results of the literature review, paying specific attention to the use of simulation methods and transition frameworks. Section 3.4 introduces the process model which is specifically developed to facilitate the design of mixed-methods research involving simulation methods and transition frameworks. Section 3.5 concludes the chapter with a discussion and directions for further research.

3.2 Research design

A specific process model for mixed-methods in sustainability transitions research is developed in this chapter. The model builds on the structured literature review detailed in Section 3.2.1, and a general process model described in Section 3.2.2. The process model is based on mixed-methods research design literature (Collins et al., 2006; Heyvaert et al., 2013; Johnson & Onwuegbuzie, 2004; Onwuegbuzie & Leech, 2005, 2006). In Section 3.2.3 attention is drawn to missing linkages in the general process model, which limit its usefulness for sustainability transitions research involving simulation and frameworks. Furthermore, it is detailed how the structured literature review addresses missing linkages between data gathering, model conceptualization, model validation, data analysis and transition frameworks.

3.2.1 Structured literature review

Sustainability transitions research has gained significant momentum, reaching more than a hundred publications a year in 2010 and 2011 (Markard et al., 2012). In recent years the literature has been expanding at such a rapid pace that a full review of the research field has become impractical. Therefore, a carefully scoped structured literature review is presented in this chapter. The review only includes peer-reviewed journal articles in the *Elsevier Scopus* and *Thomson Reuters Web of Science* databases. While this approach excludes books, book chapters and dissertations, the body of literature is broad and voluminous enough to develop an understanding of developments. The following characteristics are inventoried for each reviewed paper:

- **Research method(s).** All research methods which are reported to be used by the authors of a paper are assigned to that paper, no inference is made from the text. Consequently, a paper can have multiple or no research methods assigned to it.
- **Adopted framework**. All frameworks which are reported to be used by the authors of a paper are assigned to that paper. Consequently, a paper can have multiple or no frameworks assigned to it.
- **Research paradigm**. Johnson, Onwuegbuzie & Turner (2007, p. 124) distinguish three major research paradigms: qualitative, quantitative, and mixed-methods. Logically, a paper can only be assigned one research paradigm. In principle, papers are classified based on the paradigm reported by the authors of the paper. However, when this information is not available, the research paradigm is inferred from the research methods, and the type of data used. To avoid subjectivity, no inference is made for papers that do not report any methods, as was found to be common for papers making a theoretical contribution to the field. These papers have been classified as: not classified.
- **Time horizon**. Based on the studied time horizon of the transition under consideration, as reported by the authors, a paper is either classified as historical or future. If a paper covers both a historical and future period of the transition, then the paper is classified according to its emphasis on either the historical or future period. The subjective nature of this inference is limited by basing the classification on keywords indicating time, as well as dates. In some cases, such as papers focusing on theoretical contributions, no transition is studied, and the time horizon is therefore not applicable.
- **Research purpose.** Papers are classified according to the three research purposes described in (Yin, 2009): exploratory, explanatory, and descriptive. Exploratory research primarily aims to develop new questions, hypotheses, and theories (Dubé & Paré, 2003, p. 605; Kothari, 2004, p. 35; Yin, 2009, p. 9). Explanatory research is primarily aimed at causal investigations (Kothari, 2004, p. 39; Yin, 2009, p. 9), and theory testing (Dubé & Paré, 2003, p. 605). Descriptive research primarily aims to describe a phenomenon by reporting its observed state and rate of change, as well as related events, or making predictions (Kothari, 2004, p. 37; Yin, 2009, p. 9), without a theoretical interpretation (Dubé & Paré, 2003, p. 604). The classification is based on the research purpose reported by the authors of the paper.

The research question is used to infer the research purpose in case a research purpose is not provided, or in case more than one research purpose is reported in the paper.

The search parameters and operators for both databases are given in Tables 3.1 and 3.2 respectively. Reviews by Chappin (2011), Markard et al. (2012) and Fischer & Newig (2016) only use the Scopus database, potentially excluding relevant publications. However, the reviews by Chappin (2011) and Markard et al. (2012) were augmented based on their expert knowledge, by manually adding papers. The number of results per keyword (Table 3.2) are not indicative of the total body of literature, as there is significant overlap in results between databases and keyword searches. There is a slight difference in search fields between Scopus and Web of Science. Scopus allows a keyword search in the title, abstract and keywords. Web of Science's topic field also covers Web of Science-assigned keywords (Keywords Plus®) in addition to the title, abstract and author-assigned keywords.

Publications returned by both databases are merged and sorted by their publication year and author. The first step is to remove duplicates based on matching titles. Total of 1529 unique publications were included in the review at the end of this step. In the second step the selection was narrowed down based on the title, abstract and keywords of the publication. This is a subjective step and results will inevitably differ from one researcher to another. The criterion for inclusion is whether the publication fits the definition of sustainability transitions research as used by Markard et al. (2012, p. 959): "… all scientific articles that are concerned with the analysis of the institutional, organizational, technical, social, and political aspects of far-reaching changes in existing socio-technical systems (e.g., transportation and energy supply), which are related to more sustainable or environmentally friendly modes of production and consumption. Sustainability transitions research includes empirical studies, as well as conceptual and methodological contributions". A large number of papers do not match this definition as they refer to other types of transitions, such as: transition economies in economic journals, patient transitions in medical journals, and education-to-workforce transitions in management journals. Excluding journals from the keyword searches, because they focus on other types of transitions, would only be possible in some cases, as relevant articles are published in a wide variety of journals. Consequently, a significant number of articles is excluded in this step, resulting in a selection of 570 articles for further analysis. The exclusion of such a large share of papers is in-line with other reviews of the sustainability transitions literature (Chappin, 2011; Fischer & Newig, 2016; Markard et al., 2012).

Table 3.1 Field search parameters.

Field search parameters	Scopus	Web of Science
Years	All years; until 2016	1900 until 2016
Field search	Title, abstract, keywords	Topic (searches: title, abstract, author keywords, Keywords Plus®)
Document type	Article; Article in Press	Article

Table 3.2 Keyword search operators.

Search operators	Number of results Scopus	Number of results Web of Science	Operators included in other reviews[18]
"socio-technical transition"	147	40	A; B
"sociotechnical transition"	50	25	A
"societal transition"	119	44	A
"sustainab* transition"	419	107	C
"infrastructure transition"	26	11	
"transition management"	366	214	A; B; C
"multi level perspective"	271	163	B
"strategic niche management"	115	158	B
"innovation system" AND transition	218	103	B[19]
"system of innovation" AND transition	29	5	
"transition governance"	26	9	
Total (excl. overlap)	1400	779 (129 unique)[20]	

3.2.2 General mixed-methods process model

Recalling the definition of mixed-methods research by Johnson et al. (2007, p. 123), it should be noted that mixing can occur within a study or between studies in a research program (Creswell, 2009, p. 205; Johnson et al., 2007, p. 123). Furthermore, many different mixed-method research designs have been classified and reformulated throughout the years (Johnson & Onwuegbuzie, 2004). Leech & Onwuegbuzie (2009) identify eight typologies, whereas Heyvaert, Maes, & Onghena (2013) identify eighteen typologies. However, the identified typologies are all based on three interrelated design dimensions (Creswell & Plano Clark, 2007):

1. **Temporal: In what order are the methods performed?** Qualitative and quantitative methods can be used in a sequential or concurrent design. Selected methods do not dictate a sequential or concurrent design, as this is generally determined by the research purpose and research question. An exception would be modelling and simulation, which is inherently a sequential process. However, other methods can be performed in parallel to the simulation method.
2. **Integration: How are data and results integrated?** Depending on the order in which methods are performed, various options are available. For concurrent research designs the data could be combined during analysis, with the caveat that not all analytical tools can deal with mixed data types. Alternatively, data can be combined during interpretation to avoid such analytical complications. Data output of one method can be used as an input for another method in sequential designs.

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[18] A = (Chappin, 2011), B = (Markard et al., 2012), C = (Fischer & Newig, 2016)

[19] The exact key-word used by (Markard et al., 2012) is "technological innovation system".

[20] The Scopus database is more comprehensive than the Web of Science database for the search operators in Table 3.2. However, since neither database is complete there is added value in considering both, resulting in 129 additional unique publications.

3. **Emphasis: Which method is more important (to answer the research question)?** Importance of qualitative and quantitative methods in the research design is independent of the order in which the methods are performed. Importance is also independent of the way in which data and results are used, meaning that a case study providing conceptual and data input for a simulation model does not necessarily make the qualitative case study less important. Equal status of methods is also possible, which allows for triangulation by various qualitative and quantitative methods.

Johnson & Onwuegbuzie (2004) developed a general mixed-methods process model, based on their review of existing mixed-methods typologies and design dimensions. Comparison of this process model to later publications on the topic (Collins et al., 2006; Heyvaert et al., 2013; Onwuegbuzie & Leech, 2005, 2006) reveals a number of largely similar steps, which have been grouped as follows[21]: (1) Determine the research problem and purpose; (2) Define the research question; (3) Select the mixed-method design and methods; (4) Collect data; (5) Analyze data; (6) Interpret data; (7) legitimate the data; (8) Draw conclusions and reporting. While the mixed-methods definition by Johnson et al. (2007, p. 123) also encompasses *viewpoints* and *techniques*, the process model developed in Johnson & Onwuegbuzie (2004) places more emphasis on *data* by including seven additional data analysis steps (Onwuegbuzie & Teddlie, 2003). As a result of this emphasis, it is not clear how viewpoints (e.g. using transition frameworks as a theoretical lens), simulation methods, and data are linked.

3.2.3 Towards a specific mixed-methods process model for sustainability transitions

Simulation does not fit well in the general mixed-methods process model, as simulation is itself a process which can use either data type (qualitative and quantitative), while also producing quantitative data (Boero & Squazzoni, 2005; Dilaver, 2015; Sætra, 2017). Consequently, the data collection and data analysis steps have to be linked to the use and output of data by simulation models at three specific points. First, qualitative and quantitative data can be used for model conceptualization and parameterization (Boero & Squazzoni, 2005; Dilaver, 2015; Pruyt, 2013). Verhoog, Ghorbani, & Dijkema (2016, p. 79) identify two related approaches to model conceptualization and model parameterization: replication of *empirical observations* (e.g. Keeler et al., 2015; Papachristos & Adamides, 2016; Rosales-Carreón & García-Díaz, 2015; Sopha, Klöckner, & Hertwich, 2013); and involving stakeholders in an iterative *participatory modelling process*, in order to elicit and increase their knowledge of the studied phenomenon (Hare, Letcher, & Jakeman, 2003; Voinov & Bousquet, 2010). Participatory modelling is closely related to the participatory methodologies mentioned under *initiative-based learning* by Turnheim et al. (2015) and *practice-based action research* by Geels et al. (2016). Second, empirical data can also be used for model validation (Boero & Squazzoni, 2005; Gilbert & Troitzsch, 2005), but might not always be available (Louie & Carley, 2008). Boero & Squazzoni (2005, p. 7) argue for the use of readily available

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[21] All steps are detailed in Section 3.4 as part of the full process model, including steps for simulation and transition frameworks.

data gathering methods, such as interviews, case-studies, surveys, and participatory approaches. Third, simulation models produce their own sets of data, which will have to be analyzed, interpreted and legitimized.

As this linkage depends on the modelling and simulation process, the structured literature review in Section 3.3.1 is used to identify relevant simulation methods. The literature review will also uncover common data gathering methods in sustainability transition studies, which can be used for the conceptualization, parameterization and validation of simulation models. The literature review also draws attention to the research paradigm and time horizon of studies, as this has implications for the data that is collected.

Boero & Squazzoni (2005, p. 2) draw attention to the links between empirical data, model conceptualization, and model validation in a circular process, with the overall goal of empirically testing theoretical mechanisms underlying the simulation model. In relation to agent-based modelling (ABM), Boero & Squazzoni (2005, p. 3) go on to suggest the integration of ABM with qualitative, quantitative and participatory methods in a “creative bricolage”. Thus, the process model presented in Section 3.4 of this chapter provides a structure for the development of such a bricolage. Furthermore, the link between simulation methods and transition theories, relevant for sustainability transitions research, should be made explicit. The structured literature review in Section 3.3.1 also addresses the use of transition frameworks in relation to various methods used in the literature.

The link between transition frameworks and simulation has already received attention at the conceptual and practical level. While mid-range frameworks, such as the MLP, help structure the analysis by providing a limited set of concepts and mechanisms, the frameworks remain at a high level of abstraction (Halbe et al., 2015). Indeed, contributions related to the discussion of mixing methods in sustainability transitions research have primarily focused on conceptualizing and implementing transition frameworks in simulation models, at a high level of abstraction. As part of the MATISSE project, Haxeltine et al. (2008) extended the MLP with the empowered niche concept to conceptualize the transformation of niches and regimes. By drawing on historical transitions, the extended MLP is translated into a conceptual framework for transition modelling. The framework provides a set of mechanisms and aggregate behavior at the niche and regime levels, allowing for models to be created that focus on structural change and the dynamics of the system, rather than the agency of individual actors in the system. As a result, the conceptual framework remains at a high level of abstraction. Bergman et al. (2008) and Schilperoord, Rotmans & Bergman (2008) realized the importance of including individual agents in their models, and extended the conceptual framework of Haxeltine et al. (2008) with a support canvas of agents. However, the regime is still an aggregation, and the only individual support agents included in the simulation are abstract homogeneous consumers.

Other contributions have focused their efforts on the implementation of simulation models that are informed by a socio-technical perspective. Li, Trutnevyte & Strachan (2015) provided a review of such models focusing on energy transitions. From this review, the model by Köhler et al. (2009) is the only model based on a transition framework, since it implements the conceptual framework by Haxeltine et al. (2008) in an agent-based model to study sustainable mobility, using a transition framework. Interestingly, the agent-based model by Köhler et al.

(2009) has a SD structure with aggregate agents to represent the niches, regime, and simple consumer agents. Ulli-Beer et al. (2013), Li & Strachan (2017) and Papachristos (2011) also used SD to implement the MLP. McDowall (2014) uses socio-technical storylines informed by the MLP and a MARKAL optimization model in a sequential design. While such models are useful to provide new insights in the dynamics of transition pathways, part of the narrative strength and explanatory power of the MLP is lost, due to a lacking representation of agents and their agency. Lopolito et al. (2013) observed that ABM implementations of the MLP primarily focus on the structures of the system (such as niche and regime interactions), rather than individuals. Therefore, Lopolito et al. (2013) developed an ABM to capture the detailed mechanisms in niches, building on SNM. However, their implementation only considers one type of homogeneous actor to reduce model complexity. While this is a common approach in simulation, it does not adequately represent the underlying theoretical framework (SNM), for which stakeholder heterogeneity is important. Walrave & Raven (2016) also focused on the aggregate structures rather than individuals. However, the authors explicitly took into account the conceptual and theoretical compatibility of SD and TIS, feedback structures of innovation systems known as “motors of change” (Hekkert et al., 2007), and transition pathways (Geels & Schot, 2007). Regime and landscape interactions are used to contextualize the innovation system, according to the contexts as defined by Bergek et al. (2015). Thus, referring back to the observations by Halbe et al. (2015), we still observe a high level of abstraction with regards to the conceptualization and implementation of transition frameworks in simulation methods.

3.3 Methods used in sustainability transitions research

The results of the structured literature review are presented in Section 3.3.1. The review draws attention to the methods used in sustainability transitions studies, in relation to the research purpose, research paradigm, and time horizon. Section 3.3.2 provides an overview of common frameworks and simulation methods and addresses the link and compatibility between both. Results are only reported from 2001 to 2016, in order to increase the legibility of the figures. Given the low number of publications prior to 2001, this does not impact the findings.

3.3.1 Results of the structured literature review

Four developments in sustainability transitions research are identified. First, qualitative research paradigms have dominated sustainability transitions research since its inception and continue to do so (Figure 3.1). The analysis confirms earlier claims by Holtz (2011) regarding the dominance of case studies used to provide in-depth narratives of historical transitions. Qualitative case studies played an instrumental role in the development and communication of the MLP (Geels, 2002) and TM (Rotmans et al., 2001). The use of qualitative case studies persisted during early applications of the MLP (e.g. Geels, 2005a, 2005b), SNM (e.g. Truffer, Metzner, & Hoogma, 2002; Weber, 2003) and TM (e.g.: Van der Brugge, Rotmans, & Loorbach, 2005). The most common method during this period (2001-2007) is the qualitative case study, with data gathered primarily through desktop research and interviews. It was not until 2008 that the first simulation studies emerged (Bergman et al., 2008; de Haan, 2008; Tabara et al., 2008; Timmermans, 2008; Yücel & Meza, 2008). Since 2008 there has only been a slight uptake in quantitative and mixed-methods research paradigms. The number of simulation studies has remained relatively low in absolute numbers, while the number of qualitative case studies has consistently increased (Figure 3.2). Simulation approaches are used in about 34% of the quantitative and mixed-method studies. Social Network Analysis (SNA) has also found its introduction in sustainability transition studies, representing about 9% of all quantitative and mixed-methods studies. SNA is most commonly used in combination with SNM (e.g. Caniëls & Romijn, 2008) and the MLP (e.g. Lachman, 2014), but has also been applied in combination with TIS (e.g. Binz, Truffer, & Coenen, 2014). Historical Event Analysis is a popular quantitative method in combination with the functions of innovation systems, representing about 7% of the quantitative and mixed-methods studies. A popular method for gathering quantitative data is the survey, used in about 22% of the quantitative and mixed-methods studies. Thus, it can be concluded that use of a wide range of readily available data gathering methods has already been established in the sustainability transitions research domain, which can be used for modelling and simulation (Boero & Squazzoni, 2005).

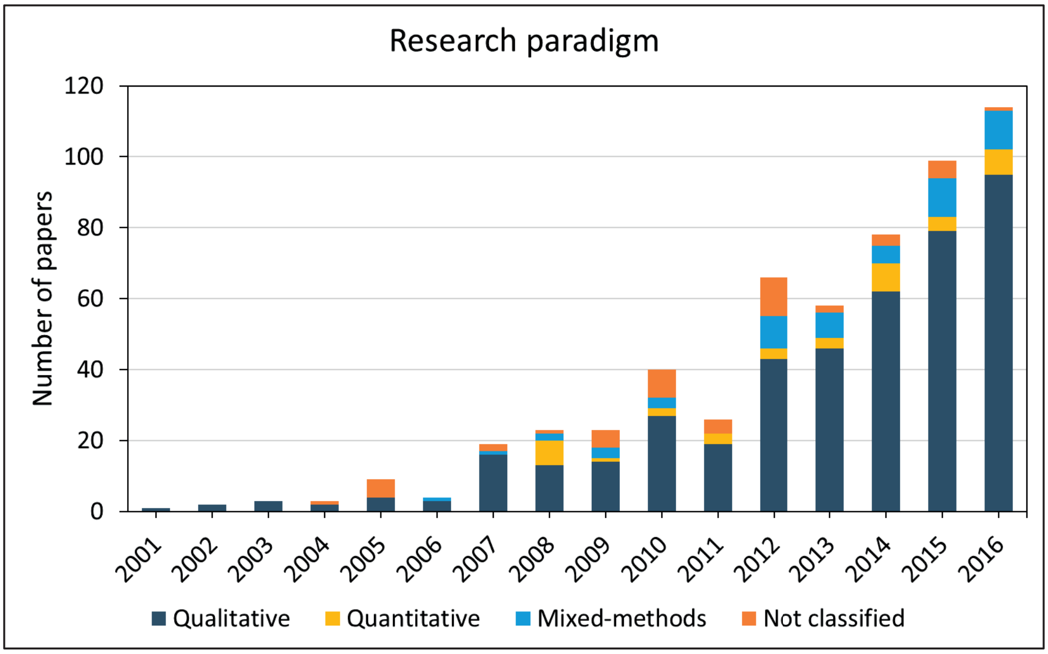

Figure 3.1 Research paradigms. The category "not classified" contains papers which do not report their research paradigm or research methods, as is common for papers making a theoretical contribution. No inference was made to avoid subjectivity.

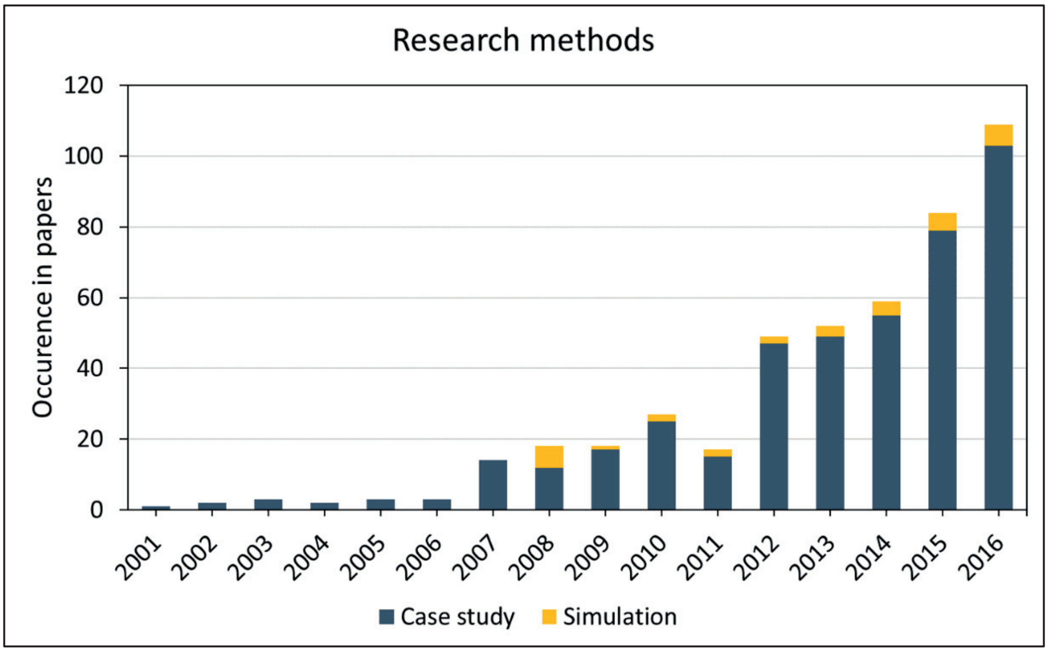

Figure 3.2 Research methods. Case study and simulation methods can occur in a single mixed-method study, which is why the occurrence in papers is reported, rather than the number of papers.

Second, most publications have a historical time horizon, meaning that they either study completed historical transitions or historical data of contemporary transitions (Figure 3.3). There has been relatively little change in this development since the similar observation by Holtz (2011). This development can be linked to the seminal work in sustainability transition studies, as well as the research paradigms and methods. As an illustration, early work on the MLP relied on selected historical transitions to develop and illustrate the framework, such as the transition from sail ships to steamships from 1780-1845 (Geels, 2002) or the transition from horse-drawn carriages to automobiles (Geels, 2005b). Historical transitions, especially completed transitions, provide crucial insights to develop theories on the various phases and pathways of transitions. Geels (2002, p. 1273) also noted that dynamics are different today than they were in previous centuries. However, the issue with studying contemporary transitions is that we cannot observe all phases of the transition. An example is the ongoing transition from centralized fossil-based energy systems to distributed renewable energy systems. The dominant qualitative research paradigm utilizing case studies, and data gathering through desktop research and interviews, is inherently incapable of studying future time horizons. Simulation and (qualitative) scenario development play a crucial role in studying future transitions. In particular, simulation can be used for policy-making and decision-making under uncertainty, enhancing system understanding, system design, and exploration (Holtz et al., 2015; Kelly et al., 2013).

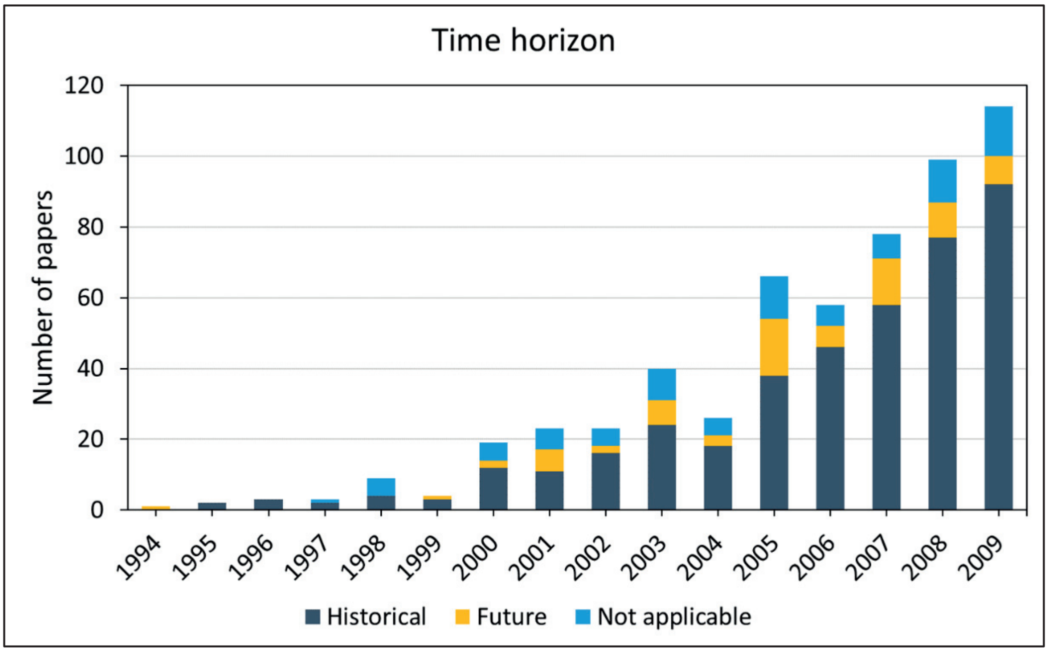

Figure 3.3 Time horizon. In some cases, such as papers focusing on theoretical contributions, no transition is studied and the time horizon is therefore not applicable.

Third, the primary research purpose of sustainability transition studies continues to be exploration (Figure 3.4). Research is increasingly focused on acquiring insights into historical transitions and novel cases through rich narratives. This becomes especially evident when considering both the time horizon and research purpose, as there are relatively few studies exploring future transitions. Computer simulation allows for the study of future transitions in complex socio-technical systems. However, even for the study of historical transitions there is an important argument to utilize quantitative methods: generalizability of results (Papachristos, 2014). For example, simulation can be used as a complementary method to qualitative case studies to increase the understanding of mechanisms underlying historical transitions (Papachristos, 2014). Similarly, simulation approaches have already been used to explain dynamics of existing transition frameworks in non-case-specific studies, such as the MLP (Papachristos, 2011), and SNM (de Haan, 2008). Furthermore, mixing methods would also allow for assumptions underlying frameworks to be tested and revised based on simulation findings (Papachristos, 2011).

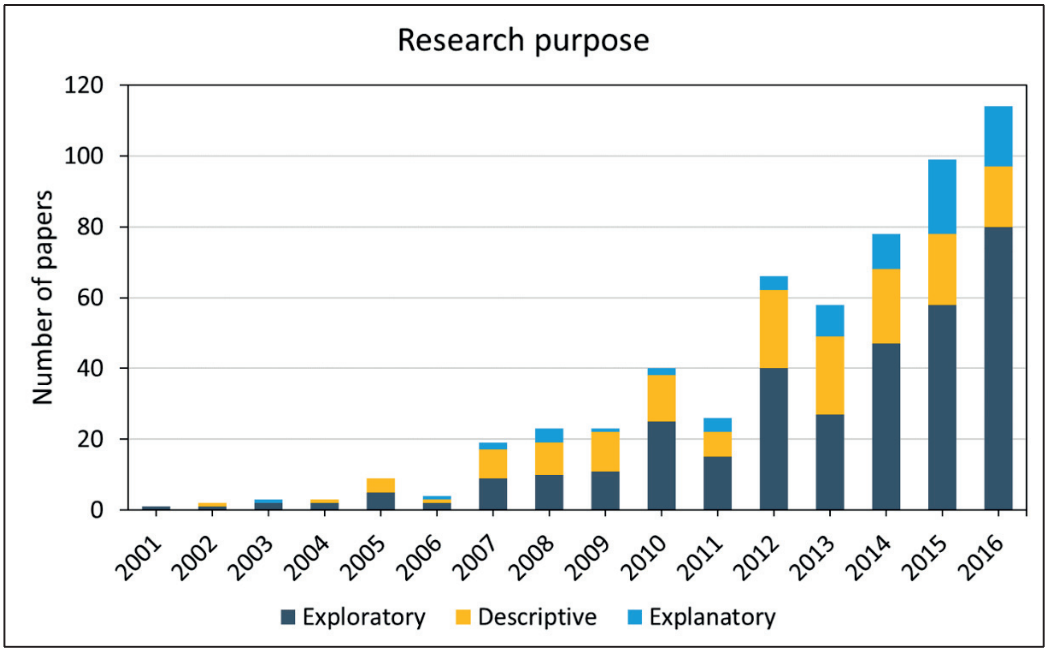

Figure 3.4 Research purpose.

Fourth, despite the steadily increasing absolute adoption of frameworks (Figure 3.5), mixed-methods studies are lagging behind in their adoption (33%) of on one of the four most common frameworks: MLP, TM, (Technological) Innovation Systems & SNM. This is especially pronounced for studies including simulation (23%), which is in line with earlier findings by (Chappin, 2011, p. 12). Overall, the MLP is the most used, and has been steadily increasing in popularity. While not all studies would benefit from adopting a framework, mid-range frameworks such as the MLP can greatly benefit simulation studies by providing a scope. However, conceptualizations of the MLP are not available for all modelling approaches, such as agent-based modelling and simulation (Section 3.2.3).

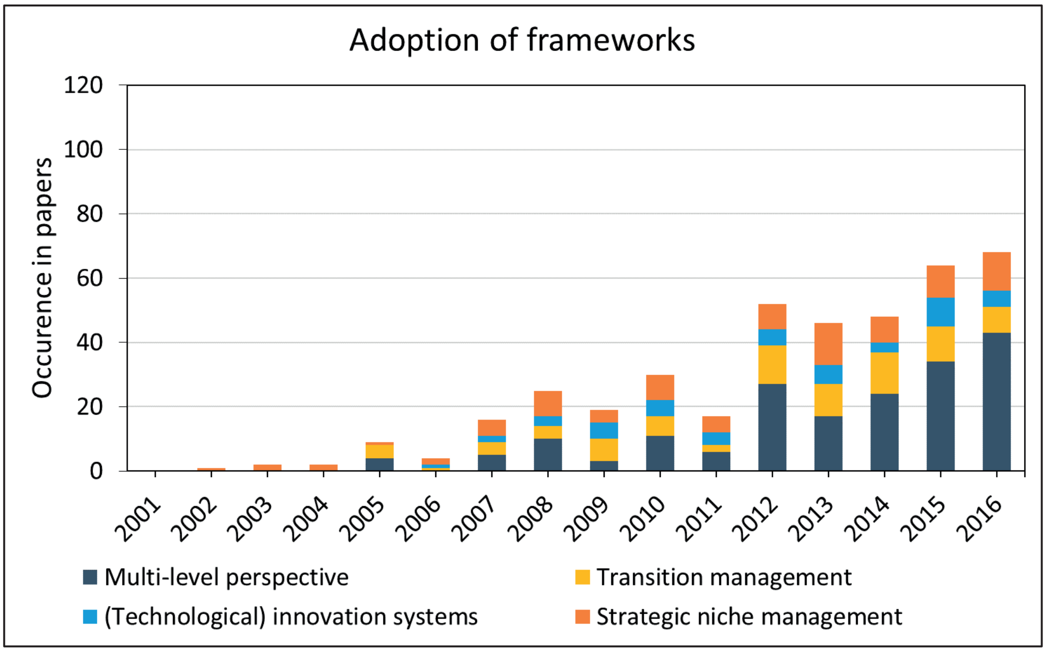

Figure 3.5 Adoption of frameworks. Multiple frameworks can be applied in one paper.

In conclusion, four closely related trends can be observed from the structured literature review: (1) the qualitative research paradigm still dominate the research field, (2) most publications have a historical time horizon, (3) exploration continues to be the primary research purpose, (4) there is a relatively low adoption of transition frameworks in mixed-methods studies using simulation methods. From the presented evidence it is not clear whether there is a bias in the selection of methods qualitative methods, which is driving the definition of the research question and research purpose, or vice versa. The objective of this chapter is not to determine where the bias exactly lies, but rather to propose a mixed-methods process model which addresses the linkages between simulation, frameworks and data gathering methods. Indeed, the dominance of exploratory qualitative studies focusing on historical transitions creates an opportunity for mixed-methods research (Table 3.3). The primary question that the process model addresses is "how to create a coherent mixed-methods research design for transition studies?", which is not a trivial question when it comes to combining frameworks and simulation methods.

Table 3.3 Comparison across qualitative, mixed-methods and quantitative studies.

	Total papers	Historical	Future	Exploratory	Descriptive	Explanatory	Used framework[22]
Qualitative	430	359 (83%)	41 (10%)	234 (54%)	144 (33%)	52 (12%)	143 (33%)
Mixed-methods	53	33 (62%)	18 (34%)	33 (62%)	8 (15%)	12 (23%)	15 (28%)
Quantitative	38	14 (37%)	15 (39%)	22 (58%)	4 (11%)	12 (32%)	8 (21%)

3.3.2 Overview of common methods used in sustainability research

This section zooms in on the methods used in sustainability transitions research, in order to address the linkages between simulation, frameworks and data in mixed-methods research designs. Table 3.4 presents the most common methods in relation to the research purpose and resign paradigm. What stands out from Table 3.4 is that case studies are already being used in a significant number of mixed-methods designs. Furthermore, standard data gathering methods (Boero & Squazzoni, 2005) are also being used in a significant number of mixed-methods studies.

However, simulation is being used in very few mixed-methods studies, even less so in combination with case studies and transition frameworks. Hereafter the focus will be on the most common simulation methods, agent-based modelling (ABM) and system dynamics (SD), and its link to common transition frameworks. The focus on ABM and SD also lays the foundation for addressing the linkage between data and simulation in the process model, which will be detailed in Section 3.4.2.

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[22] Only the main frameworks used in sustainability transitions research are considered: MLP, TM, SNM, and TIS. The absolute numbers as presented in Figure 3.5 can be deceptive, as it is becoming more common to apply multiple frameworks in one study.

Table 3.4 Frequency of methods used in sustainability transitions research. This overview is based on all studies included in the structured literature review, as reported by the authors of the studies. Methods with a low frequency (N < 5) are reported separately.

		Research purpose			Research paradigm		
Method	N	Exploratory	Descriptive	Explanatory	Qualitative	Quantitative	Mixed
Case study	431	230	142	59	382	7	42
Desktop research	294	158	89	47	265	4	25
Interview	266	148	72	46	242	0	24
Survey	37	21	9	7	17	6	14
Workshops	27	21	4	2	24	0	3
Participant observation	24	16	7	1	18	2	4
Scenario development	20	20	0	0	9	0	11
Agent-based modelling	12	8	0	4	0	11	1
Site visits	11	6	3	2	11	0	0
System Dynamics	10	7	0	3	1	6	3
Action research	9	6	3	0	9	0	0
Discourse analysis	9	3	6	0	9	0	0
Social Network Analysis	9	5	2	2	1	2	6
Focus-group	8	4	3	1	5	0	3
Historical Event Analysis	7	2	3	2	1	0	6
Backcasting	5	5	0	0	2	0	3
Content analysis	5	2	2	1	4	0	1
Foresighting	5	5	0	0	3	0	2

Methods (N < 5): AHP; Cluster analysis; Coding; Cost appraisal; Delphi; Econometrics; Equation Based Modelling; Equilibrium model; Ethnography; Event Structure Analysis; Factor analysis; Futures table; Gaming; GIS mapping; Grounded theory; Horizon scanning; Institutional Context Analysis; Key Word in Context; LCA; NK-model; Optimization; Partial Differential Equations; Participatory modelling; Patent analysis; PESTE analysis; Process tracing; Q methodology; Qualitative Comparative Analysis (QCA); Regression analysis; Roadmapping; Stakeholder analysis; Structural equations model; SWOT; Systems analysis; Trend analysis; Value network analysis; Visioning

Before addressing any linkage between frameworks and simulation methods, it is important to lay the foundation with two central theories in sustainability transitions research offering opposing analytical perspectives. All well-established frameworks build on one of these theories, resulting in an analytical dichotomy that is not often addressed. The first theory is complexity theory, illustrated here through the characteristics of Complex Adaptive Systems (CAS), as defined by (Holland, 1992, p. 19): aggregate behavior at the system level, evolving network structures, and adaptive social and technical elements. Related complexity theories on which popular transition frameworks build are complex systems theory (Kauffman, 1996) and large technical systems (Hughes, 1987; Nelson & Winter, 1982). The second theory is systems theory, which is illustrated here by the concept of technological systems (Carlsson & Stankiewicz, 1991, p. 111): “a network of agents interacting in the economic/industrial area under a particular institutional infrastructure (…) and involved in the generation, diffusion and utilization of technology”. While the definition of technological systems carries resemblance to that of CAS, it pays less attention to the agency of all system components and their ability to self-(dis)organize (Peter & Swilling, 2014). Rather, systems theory assumes that adaptive system properties and emergence are self-driven by stocks, flows, and non-linear feedback loops.

3.3.2.1 Overview of common frameworks

Frameworks are the analytical lenses that can connect qualitative and quantitative methods, provide structure, and scope analyses of sustainability transitions. Bottom-up frameworks are defined as frameworks focusing primarily on the influence of individual elements, while top-down frameworks aggregate individual elements and focus primarily on the influence of system structures. These frameworks are often combined with case studies, as they provide a strong narrative for transitions, while limiting the amount of factors to be considered (Papachristos, 2014). Similarly, frameworks could benefit the development of theoretically grounded parsimonious simulation models. The overview that follows is confined to the four most commonly used frameworks, as identified in Section 3.3.1: MLP, TM, SNM and TIS. Furthermore, familiarity with these core frameworks is assumed. Therefore, detailed descriptions of the frameworks are omitted in favor of references to seminal works. A summary of the overviews is given in Table 3.5.

SNM (Kemp et al., 1998) was developed as a prescriptive bottom-up framework to improve the early adoption of new technologies for sustainable development, but has more recently been used in ex-post analyses of niche development (Schot & Geels, 2008). SNM builds on the concepts of technological regimes (Dosi, 1982; Nelson & Winter, 1982), technological paradigms (Dosi, 1982), and large technical systems (Hughes, 1987). Furthermore, Elzen, Hoogma & Schot (1996) drew on lessons from, amongst others, socio-technical systems to define internal processes for successful development of a technological niche: (1) the articulation of expectations and vision; (2) the building of social networks; and (3) learning processes. While SNM draws from systems theories and complexity theories, it predominantly focuses on concepts from complexity theories. The focus on the emergence of social networks, and the role of individuals in particular, contribute to this conclusion. Due to the ex-post analytical nature of SNM, it is less suited to study ongoing transitions that we can, to a large extent, only study ex-ante. Furthermore, the inward focus of SNM causes it to pay limited attention to the influence of exogenous factors. These exogenous factors are often relegated to the landscape in other multi-level frameworks. This makes SNM less suitable to study transitions which are also exogenously driven, such as the nuclear phase-out in Switzerland, which is largely driven by the Fukushima nuclear disaster in 2011.

TM (Rotmans et al., 2001) is a mid-range transition framework that builds on the multi-level model (Rip & Kemp, 1998) and complex systems theory (Kauffman, 1996). Special attention is paid to experimentation, innovation, and learning taking place in niches, and the role of individuals in so-called transition arenas. Therefore, TM can be considered a bottom-up framework as well. In contrast to SNM, a landscape concept is included in TM, allowing exogenous variables to be considered more adequately. There are three important characteristics that differentiate TM from other frameworks. First, TM prescribes an important role to the policy elite and national government. This could be explained by the history of the framework, which originated from a Dutch governance experiment that had been maintained for 10 years since 2001 (Loorbach, 2010). Second, TM combines the process of visioning (long-term goals) with short-term policy-making, enabling adaptive governance. Third, the framework provides a process approach, facilitating the participation of diverse stakeholders in a complex transition process. The implication of these three unique features is that TM is primarily suited for exploratory studies of future transitions and participative processes, while it is less useful for explanatory purposes. This is corroborated by the findings in the literature review, summarized in Table 3.5.

MLP (Geels, 2002; Rip & Kemp, 1998; Schot, 1998) is a descriptive mid-range transition framework that has its theoretical foundations in the multi-level model (Kemp et al., 1998; Rip & Kemp, 1998), the concept of technological regimes (Nelson & Winter, 1982), and large technical systems (Hughes, 1987). The concept of technological regimes was extended (Rip & Kemp, 1998) to include rules as a social dimension. The MLP has a very intuitive rationale, which highlights the importance of the landscape (Markard & Truffer, 2008, p. 609): "Innovation and transition processes can be explained by the interplay of stabilizing mechanisms at the regime level and (regime-) destabilizing landscape pressures combined with the emergence of radical innovations at the niche level". While the MLP has been criticized for lacking agency (e.g. Smith, Stirling, & Berkhout, 2005) it is a bottom-up framework, and this critique has since been addressed by Geels & Schot (2007). At the same time, it is easy to see how it can be, and has indeed been, used as a top-down framework, focusing on system structures rather than individual elements (Papachristos, 2011; Ulli-Beer et al., 2013). MLP was developed using historical cases (Geels, 2002), and has since been applied to many historical and ongoing transitions.

Innovation system literature (Freeman, 2004; Lundvall, 1985) originated as a descriptive framework that has its theoretical foundations in grounded theory (Lundvall, 2007). Many concepts have been coined since then: National System of Innovation (Dosi, Teece, & Chytry, 1998; Freeman, 1987), Regional System of Innovation (e.g. Cooke, 1996; Edquist, 2004; Etzkowitz, 2002; Lundvall & Borrás, 2005), and Technological Innovation Systems (Bergek, Jacobsson, Carlsson, Lindmark, & Rickne, 2008; Hekkert, Harmsen, & de Jong, 2007). Due to the importance of technologies in sustainability transitions, TIS is popular amongst scholars. TIS builds on the concept of technological systems (Carlsson & Stankiewicz, 1991) and is mainly concerned with the structure and functions at a system level, rather than with the actions of individual agents. This top-down analytical perspective is reflected clearly in the identification and use of motors of change, which are feedback structures at the level of system functions (Hekkert, Suurs, et al., 2007). These feedback structures are important accelerators or inhibitors of change which are endogenous to innovation systems.

3.3.2.2 Overview of common simulation methods

Based on the structured literature review in Section 3.3.1, the following simulation methods are selected for further comparison: agent-based modelling (ABM) and System Dynamics (SD). The selection of ABM and SD is similar to earlier work focusing on transition dynamics (Yücel, 2010). In this section, it is illustrated how both simulation methods are positioned within sustainability transitions research, in particular in relation to transition frameworks. No hybrid methods are considered in the comparison, such as the agent-based systems dynamics models described in Peter & Swilling (2014). The comparison covers the conceptual foundation, analytical perspective, and research purpose. For a more detailed description of both simulation methods, see e.g. (Chappin, 2011; Kelly et al., 2013; Peter & Swilling, 2014; K. H. van Dam, Nikolic, & Lukszo, 2012). A summary of the overview is given in Table 3.5.

Agents are the principal components of ABMs, whose attributes give unique properties to the simulation method (Nwana, 1996; Woolridge & Jennings, 1995). First, agents autonomously react to their environment and anticipate future states of the system, which can lead to emergent system behavior (aggregate behavior), and is often more complex than is the sum of individual actions (Holland, 1992). Second, agents can communicate, interact and co-operate to evolve new network structures over time. Third, agents can learn from their own actions as well as those of other agents, allowing for continuous improvement and adaptation. These characteristics correspond well with the definition of Complex Adaptive Systems, illustrating why ABM is a bottom-up simulation method, fully capable of accurately representing the agency of individuals in sustainability transitions. Furthermore, ABM is both spatially and temporally explicit (Kelly et al., 2013), allowing spatial dynamics and transition pathways to be captured over long time periods. Since the concept of agents is easily understood by stakeholders, the method lends itself well to participatory processes with the purpose of increasing the understanding of sustainability transitions or exploring future transitions. Furthermore, assumptions underlying frameworks such as SNM, TM, and MLP can be challenged by attempting to replicate emergent system level behavior, using historical data and case studies to detail the micro-level mechanisms underlying transition processes.

SD provides an orthogonal analytical perspective to ABM, working on the key assumption that dynamic system behavior is driven primarily by its own structure (Pruyt, 2013). The structure of SD models is defined by stocks, flows, variables, and the links between these structural elements. Positive and negative links can be used to construct feedback loops at the system level, which stabilize or destabilize the system. SD is a top-down simulation method that has a high conceptual compatibility with systems theory (Sterman, 2000). The modelled elements are translated into differential equations to gain insights into the systems' responses to policy designs by means of virtual experimentation (Pruyt, 2013). Specifically, modelling in terms of system structure and feedback allows for a participatory approach, and a better understanding of the dynamics underlying sustainability transitions, as it is easily understood by stakeholders (Kelly et al., 2013). Furthermore, long-term simulation facilitates the exploration of transition pathways under various scenarios and policy options. Finally, SD can also be used in conjunction with case studies and TIS to provide an explanation of transition dynamics – for example, using macro-level mechanisms represented as feedback loops.

Table 3.5 provides an overview of three important characteristics for both ABM and SD. First, both simulation methods have different conceptual foundations, resulting in orthogonal yet complementary analytical perspectives. For the transition frameworks, a similar distinction can be noted between TIS and the other frameworks. The theoretical and analytical compatibility is highest when TIS and SD are combined, or when SNM, TM, and MLP are combined with ABM. Second, simulation is useful for studying both historical and future transitions. For example, the innovation systems literature mostly relies on content analysis (Hekkert et al., 2007), resulting in a historical account of the development of functions. SD would be well-suited to explore the future dynamics of functions of innovation systems. Third, simulation is generally reported to serve exploratory and explanatory purposes. While qualitative methods can be used for descriptive purposes and feed into simulation models, the ultimate research purpose will remain exploratory and explanatory. This highlights the importance of the sequence, weight and combination of methods in a mixed-methods research design.

Table 3.5 Overview of frameworks and simulation methods.

	Conceptual foundations	Analytical perspective	Primary research purposes (% based on literature review)[23]
Strategic niche management	Large technical systems and multi-level framework	Bottom-up: Individual elements	Exploratory (42%) Descriptive (42%) Explanatory (16%)
Transition management	Complex systems theory and multi-level framework	Bottom-up: Individual elements	Exploratory (63%) Descriptive (33%) Explanatory (4%)
Multi-level perspective	Large technical systems and multi-level framework	Bottom-up: Individual elements	Exploratory (63%) Descriptive (27%) Explanatory (11%)
Technological Innovation Systems	Technological systems and innovation systems	Top-down: System structures and functions	Exploratory (52%) Descriptive (40%) Explanatory (8%)
Agent-based modelling	Complexity theory	Bottom-up: Individual agents	Exploratory Explanatory
System dynamics	Systems theory	Top-down: System structure and feedback loops	Exploratory Explanatory

3.4 Towards a specific mixed-methods process model for transition research

The mixed-methods process model presented in this section builds on the process model by Johnson & Onwuegbuzie (2004), and later publications on the topic (Collins et al., 2006; Heyvaert et al., 2013; Onwuegbuzie & Leech, 2005, 2006), as introduced in Section 3.2.2. Novel to the process model presented in this section is that it incorporates the findings on transition frameworks and simulation methods discussed in Section 3.3. These additions can be found in steps 1 through 5 of Figure 3.6 and are detailed in Section 3.4.1. These steps primarily address the linkage and compatibility of transition frameworks and simulation methods in a coherent mixed-methods research design. Another addition to the process model is the simulation loop, focusing on the linkage between data gathering, simulation and data analysis. This loop consists of steps 7 through 11 in Figure 3.6, which are detailed in Section 3.4.2. The simulation loop was developed by reviewing literature on ABM and SD simulation model design.

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[23] Frequencies are too low for simulation methods to report meaningful statistics.

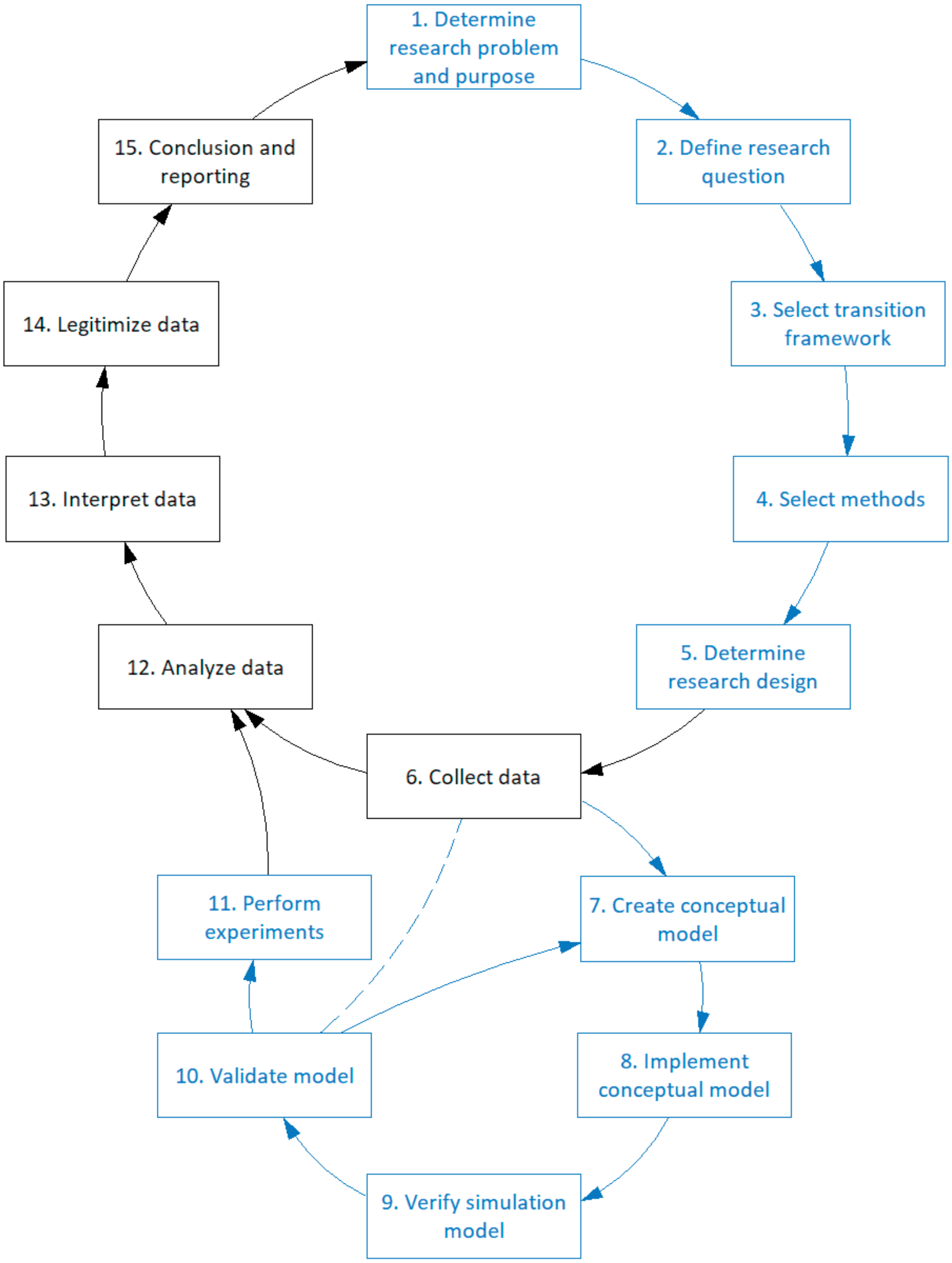

Figure 3.6 Specific mixed-methods process model for sustainability transitions research.

3.4.1 Incorporating transition frameworks and simulation methods in the design process

During step 1 the research problem and purpose are determined. This is an important step in scoping the research and forms the basis for the analytical perspective of the study. The research can fall into one of three categories (Dubé & Paré, 2003; Kothari, 2004; Yin, 2009): exploratory, explanatory, and descriptive. Being explicit about the research purpose at this stage is important for defining the research question (step 2) and research design (step 5). If clarity is lacking at this stage of the process, then it will be difficult during step 5 to determine an appropriate order, integration and emphasis of selected methods. Exploratory research is the dominant research purpose in sustainability transitions research, followed by descriptive research, and lastly explanatory research.

During step 2 the research question is defined. The research question further specifies the unit of analysis and can indicate the type of data which has to be acquired during the research. The unit of analysis is particularly important for the selection of a framework (step 3) and a simulation method (step 4), as it is closely related to the analytical perspective. Kelly et al. (2013, p. 176) present a decision tree for the selection of an appropriate modelling method, emphasizing the distinction between “aggregated effects” and “interactions between individuals” as a decision variable in simulation method selection. This distinction should be clear from the research problem and research question defined in steps 1 and 2.

During steps 3 and 4 frameworks and methods are selected. Table 3.6 can be used to select a framework and simulation method that is well-suited for the analytical perspective and research purpose. An important consideration when using a simulation method is the theoretical compatibility with the framework, as well as the fit with the research purpose. While hybrid frameworks (e.g. combining TIS and MLP (Markard & Truffer, 2008)) and hybrid simulation approaches (e.g. agent-based SD (Peter & Swilling, 2014)) are not considered, their position in the table could be determined based on the same characteristics. Frameworks provide transition scholars with a theoretical lens for mixed-method designs involving case studies and simulation. More specifically, frameworks facilitate the selection of factors, outcomes of interest, and mechanisms to scope the application of qualitative and quantitative methods in the research design (Creswell, 2013). Furthermore, frameworks allow for the integration of insights from case studies and simulation by ensuring that the analytical perspective and concepts used are consistent. Note that the use of a transition framework or simulation method is not prescribed and that the choice of qualitative and quantitative methods is left open, regardless of the emphasis the process model places on simulation. In fact, in the case of a descriptive research purpose it is not recommended to use any of the simulation methods, while transition frameworks and qualitative modelling (e.g. de Gooyert, Rouwette, van Kranenburg, Freeman, & van Breen, 2016) can still be useful. Table 3.4 can be used for the selection of common data gathering methods, as suggested by Boero & Squazzoni (2005). The overview in Table 3.4 is based on the structured literature review. As a result, the overview is representative of the current state of the sustainability transitions field, but not exhaustive. While most research methods do not prescribe a research paradigm, it can be observed from Table 3.4 that certain methods do have a strong association with the qualitative, quantitative or mixed-method research paradigm.

During step 5 three interrelated dimensions of the research design are considered (Creswell & Plano Clark, 2007):

1. **Temporal:** Are the qualitative and quantitative methods performed sequentially or concurrently? Which method is performed first? Methods selected during step 4 of the process model do not dictate a dominant position in the mixed-methods research design, nor do they mandate a sequential or

concurrent design. Simulation is an exception as it is inherently a sequential process (Section 3.4.2). A design can contain more than two methods in a sequential or parallel design, as illustrated by two out of the four studies reviewed in Section 3.4.3.

2. **Integration:** Are data and results integrated during analysis (step 12) or interpretation (step 13)? Methods selected during step 4 can impose constraints on the research design in terms of integration, if the method is only able to handle qualitative or quantitative data.
3. **Emphasis:** The emphasis on qualitative or quantitative methods is strongly determined by the importance of that method for answering the research question. Thus, importance is independent of the temporal and integration design dimensions. Methods can also have an equal status.

The analysis and interpretation of the data in steps 12 and 13 depend on the methods selected, which will not be covered in detail here. Further information on the legitimization of the data can be found in (Onwuegbuzie & Teddlie, 2003). Concluding and reporting in step 14 is deemed to be self-explanatory.

Table 3.6 Framework and simulation method selection based on the analytical perspective and research purpose. It should be noted that frameworks marked with (*) are only partially compatible with the analytical perspective. More specifically, SNM, TM, and MLP can only be used at the system structure level, while the individual agents will have to be aggregated to match a top-down analytical perspective.

	Analytical perspective	
Research purpose	Top-down	Bottom-up
Exploratory	TIS and SD SNM* and SD TM* and SD MLP* and SD	SNM and ABM TM and ABM MLP and ABM
Descriptive	TIS SNM* TM* MLP*	SNM TM MLP
Explanatory	TIS and SD SNM* and SD TM* and SD MLP* and SD	SNM and ABM TM and ABM MLP and ABM

3.4.2 Adding the simulation loop

The simulation loop is based on ABM and SD model design literature, as these simulation methods were selected in the structured literature review in Section 3.3.2. An overview of the simulation process descriptions is given in Table 3.7. The various steps were grouped into aggregate steps on the left-hand column of the table, identifying five unique steps for the simulation loop, and three steps which are overlapping with the process model as presented in the mixed-methods literature (Collins et al., 2006; Heyvaert et al., 2013; Johnson & Onwuegbuzie, 2004; Onwuegbuzie & Leech, 2005, 2006). The overlapping steps form potential starting points at which data gathering, simulation and data analysis are linked. The first aggregated step in Table 3.7 overlaps with step 1 in the process model and is therefore not included again. Hereafter steps 7 through 11 of the simulation loop are detailed, including relevant feedback loops and its linkages to data collection (step 6) and data analysis (step 12) in Figure 3.6.

During step 7 a conceptual model is created. The conceptual model is closely related to the research problem, research purpose and research question (steps 1 and 2), as it defines the boundary of studied system, important variables and mechanisms to be simulated (Pruyt, 2013). For SD models this involves formulating dynamic hypotheses, which explains how the systems' structure is driving certain dynamic behavior (Sterman, 2000). For ABM this involves formulating the dynamics of the system by detailing what actions agents take and which states they can have (Nikolic, van Dam, & Kasmire, 2012). Thus, a conceptual model can be understood as defined by Robinson (2004, p. 65): "The conceptual model is a non-software specific description of the simulation model that is to be developed, describing the objectives, inputs, outputs, contents, assumptions and simplifications of the model." It is through this definition that the linkage to data collection becomes apparent. A certain level of knowledge has to be acquired of the system to be studied, in order to be able to formulate a simplification of that system. As an illustration, all four studies reviewed in Section 3.4.3 use a sequential research design in which a data gathering method (e.g. desktop research, survey, or interviews) precedes the development of a conceptual model (Auvinen et al., 2015; Keeler et al., 2015; Papachristos & Adamides, 2016; Rosales-Carreón & García-Díaz, 2015).

During steps 8 through 10 the conceptual model is implemented in software and tested. Several modeling environments are available for the implementation of ABM and SD models, and these do not necessarily involve programming. After the model has been implemented, verification and validation tests are performed on the model. The distinction is made between verification, which tests whether the conceptual model is implemented correctly in the software, and validation, which tests whether the simulation model corresponds with reality (Gilbert & Troitzsch, 2005, p. 23). This distinction uncovers the link with (empirical) data collection for validation purposes, which requires information on the observed system. This data linkage is indicated by a dashed line in Figure 3.6. There is a feedback loop in the process model, involving steps 7 through 10, as conceptual modelling, model implementation and model testing are inherently iterative processes (Robinson, 2004).

During step 11 the simulation model is used to perform (virtual) experiments. This step can generate large amounts of quantitative data, which will have to be analyzed. In the process model this model data output is placed parallel to step 6, where both qualitative and quantitative data can be gathered by other methods. Both step 11 and 6 feed directly into step 12, during which the data is analyzed. The types of data, selected data analysis methods (step 4), as well as the research design (step 5), all determine whether the data is mixed during data analysis (step 12) or interpretation (step 13).

Finally, the model use step in Table 3.6 overlaps with steps 13 through 15 of the process model and is therefore not included.

Table 3.7 Aggregate simulation loop steps and underlying modelling and simulation literature.

	ABM		SD	
Aggregated steps	(van Dam et al., 2012, p. 74)	(Grimm & Railsback, 2005, p. 27)	(Forrester, 1994, p. 245)	(Sterman, 2000, p. 86)
Determine research problem	Problem formulation and actor identification	Formulate the question		Problem articulation
Conceptualize model	System identification and decomposition Concept formalization Model formalization	Assemble hypotheses Choose model structure	Describe the system	Formulation of dynamic hypothesis
Implement model	Software implementation	Implement the model	Convert description to level and rate equations	Formulation of a simulation model
Verify simulation model	Model verification			Testing
Validate simulation results	Model validation[24]			
Perform experiments	Experimentation	Analyze the model	Simulate the model	
Data analysis	Data analysis			
Model use	Model use	Communicate the model	Design alternative policies and structures Educate and debate Implement changes in policies and structure	Policy design and evaluation

3.4.3 Using the process model

Four recent studies are discussed hereafter to illustrate the use and added-value of the process model. The findings are summarized in Table 3.8. All studies have a mixed-methods design including a simulation method. The first study (Auvinen et al., 2015) focuses on the question how strategic decision-making in complex socio-technical systems can be supported. More specifically, the study focuses on decision-making on the topic of emission-free urban passenger transport in Helsinki by 2050. The study has an exploratory research purpose, which matches the long time-horizon considered. A wide-range of methods are selected, which are performed sequentially in the following order: (theoretical) case study, vision building, conceptual modelling, roadmapping, system dynamics simulation. The MLP is used as the underlying theoretical framework, which would raise a red flag when using the process model and warrants a discussion on the implications of this combination. Caution is advised when combining system dynamics simulation and the MLP as a theoretical lens, especially when data collected using one method is used as an input for the next method. Indeed, the causal loop diagram presented in the study shows a focus on aggregate concepts. More weight is given to the qualitative methods. The study reports on a theoretical case and does not report the data collected, verification or validation of the model.

The second study (Keeler et al., 2015) focuses on the long-term impacts of regional water governance regimes. This is also an exploratory study. Unlike the other studies, no framework is used. The methods are used sequentially, as follows: desktop research (case study), survey, scenario analysis, system dynamics simulation. Data from one method is used in the next step of the sequential research design. While the research focus, and

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[24] This step is originally positioned after experimentation and data analysis in (van Dam et al., 2012, p. 74).

a time-horizon until 2080, would suggest a higher importance for the quantitative method, the focus is rather on the qualitative methods that facilitate learning and the process. All steps of the process model, with the exception of validation of the simulation model and legitimation of the data, are reported in the study itself. A reference is provided by the authors to the WaterSim 5.0 model that has been used for further documentation.

The third study (Papachristos & Adamides, 2016) addresses the question how we can cope methodologically with sustainability transitions concerning multi system interactions. The study explores the functional foods sector with a time-horizon until 2040. Similarly to the study by Auvinen et al. (2015), caution is advised as the MLP is used as a theoretical foundation in combination with system dynamics simulation. In a sequential design a qualitative case-study is used to conceptualize the system dynamics model, focusing clearly on structures and aggregate concepts. The weight of the qualitative and quantitative methods is equal in this study. While validation is addressed, no comments are made on the verification of the model.

Finally, the fourth study (Rosales-Carreón & García-Díaz, 2015) addresses the question in which way actors perceive barriers that hamper the transition towards the construction of near-Zero Energy Buildings in the Netherlands, and how this knowledge is disseminated. This is an exploratory study without a clear time-horizon. Combined use of the sectoral innovation systems framework and agent-based simulation raises concerns with regards to the data collection and model implementation in a sequential design. Desktop research and semi-structured interviews are used as inputs for the agent-based model. The methods are reported to have an equal status. No details on the verification and validation of the agent-based model are provided in the study.

Overall, these four studies have a well-informed mixed-methods design when analyzed. However, the choices for the research design are not always clearly articulated, beyond the choice and order of the methods. In all selected studies the quantitative methods followed the qualitative methods in a sequential design, and data gathered using the qualitative methods served as an input for the simulation. Other research designs could also be imagined using the process model, such as a concurrent design for triangulation, or a qualitative method being used in a sequential design to explain findings in a simulation study. Furthermore, the implications of combining bottom-up simulation models with top-down transition frameworks, or conversely, is not discussed in any of the studies. Use of the mixed-methods process model would draw attention to this research design choice. Finally, by strictly following the process model improvements can be achieved with regards to the documentation of data collection, verification and validation.

Table 3.8 Illustration of added-value of the process model. Only mixed-methods studies using ABM or SD are considered.

Process-model step	(Auvinen et al., 2015)	(Keeler et al., 2015)	(Papachristos & Adamides, 2016)	(Rosales-Carreón & García-Díaz, 2015)
Define research question	How can strategic decision-making in complex socio-technical systems, such as urban passenger transportation in Helsinki, be supported?	What is the long-term impacts of regional water governance regimes in metropolitan Phoenix, Arizona?	how we can cope methodologically with sustainability transitions concerning multi system interactions, such as the functional foods sector?	How do actors perceive barriers that hamper the transition towards the construction of near-Zero Energy Buildings in the Netherlands?
Define research purpose	Exploratory	Exploratory	Exploratory	Exploratory
Select transition framework	MLP	-	MLP	Sectoral Innovation Systems
Select methods	System Dynamics; Vision building; Modeling	System Dynamics; Survey; Scenario analysis; Desktop research (case study)	System Dynamics; Case study	ABM; Desktop research; Interviews
Determine research design	Sequential design: ▪ Case study ▪ Vision building ▪ Conceptual modeling ▪ Roadmapping System Dynamics Weight: qualitative Mixing: during analysis	Sequential design: ▪ Desktop research Survey ▪ Scenario analysis ▪ System Dynamics Weight: qualitative Mixing: during analysis	Sequential design: ▪ Case study ▪ System Dynamics Weight: equal Mixing: during analysis	Sequential design: ▪ Desktop research & interviews ▪ Agent-based simulation Weight: equal Mixing: during analysis
Collect data	Not reported: theoretical case	Desktop research & Survey	Case study	Desktop research & interviews
Create conceptual model	Causal loop diagram	System analysis	Causal loop diagram	System diagram & incidence matrix
Implement conceptual model	Yes, using System Dynamics	Yes, using WaterSim 5.0	Yes, using System Dynamics	Yes, using agent-based modelling
Verify simulation model	Not reported	Yes, consistency analysis	Not reported	Not reported
Validate simulation model	Not reported	Not reported	Yes	Not reported
Perform experiments	Yes	Yes, WaterSim 5.0	Yes	Yes
Analyze data	Yes	Yes	Yes	Yes
Interpret data	Yes	Yes	Yes	Yes
Legitimize data	Yes, includes feedback processes after the interpretation of results.	No, but the potential to use the approach in an iterative participatory process is discussed.	Partially, as the validity of mechanisms is assessed through the SD model.	Yes, includes expert discussion and feedback for qualitative and quantitative results.
Conclusion and reporting	Yes	Yes	Yes	Yes

3.5 Discussion and conclusion

In this article, a mixed-methods process model for sustainability transition studies has been elaborated, which provides an answer to the call for various levels of integrating case studies, frameworks and simulation methods (Geels, Berkhout, et al., 2016; Papachristos, 2014; Turnheim et al., 2015). The presented process model aids the development of mixed-methods research designs involving transition frameworks and simulation models. The process model builds on established general mixed-methods research literature (Collins et al., 2006; Heyvaert et al., 2013; Johnson & Onwuegbuzie, 2004; Onwuegbuzie & Leech, 2005, 2006), and incorporates results from a structured literature review of sustainability transitions literature. In doing so, attention is drawn to missing linkages in the general process model, which limit its usefulness for sustainability transitions research involving simulation and transition frameworks. The specific process model presented in this article addresses the missing linkages between data gathering, model conceptualization, model validation, data analysis and transition frameworks.

Turnheim et al. (2015) stated that a loose integration of methods will improve the analysis of transition dynamics, transition pathways, and public and private governance strategies. In comparison to a loose integration, use of the mixed-methods process model as presented in this article brings the following five additional advantages for transition scholars who seek to combine transition frameworks and simulation methods. First, the framework functions as a theoretical lens to scope the research and provides a set of concepts ensuring comparability of results across case studies and simulation models within the same research design. The comparability of results is not guaranteed when methods and studies are loosely integrated, and even less so when methods are performed separately as suggested by Geels et al. (2016). Therefore, a mixed-methods research design is more likely to provide comprehensive policy relevant insights regarding sustainability transitions across all methods used than a loose integration of methods could. Second, new mixed-methods research designs can be imagined using the process model, going beyond sequential designs where simulation follows a case study and data collection. Alternative designs include: concurrent design for triangulation, and qualitative method being used in a sequential design to explain findings in a simulation study. Third, the application of frameworks provides a theoretical foundation for simulation models in sustainability transitions research, allowing modelers to build on established knowledge in the transitions field. Fourth, introducing simulation into research designs that also feature case studies and frameworks allows for a broader range of research purposes to be addressed in new ways. For example, in explanatory research, hypotheses defined using case studies can be tested using simulation, allowing frameworks to be systematically challenged and refined (Yücel, 2010). Additionally, mixed-methods designs can be used for informed explorations of future transitions, and to gain a deeper understanding of historical transitions and their underlying dynamics. Fifth, the mixed-methods process model ensures the theoretical and conceptual compatibility of the selected methods or informs the researcher of implications when the compatibility is compromised. While bottom-up frameworks can be, and have been, combined with top-down simulation methods, a discussion on the implications is often missing as indicated in Section 3.4.3. By strictly following the process model, improvements can be achieved with regards to the documentation of research designs, data collection, verification, validation and data legitimation.

The use of mixed-methods designs is not without its challenges. First, formalizations of frameworks are not yet widely addressed in the literature. Formalizations so far have mainly focused on System Dynamics, limiting the use of Agent-Based Modelling in mixed-methods designs. Formalized frameworks also improve the comparability between case studies as they offer consistency in the selection, use, and definition of concepts. This has previously been a concern with regards to the unsystematic use of the MLP in case studies (Genus & Coles, 2008). Second, mixed-methods research imposes considerable resource requirements in terms of time, costs, and knowledge. There are relatively few researchers who command both qualitative and quantitative methods, and even fewer who have experience in mixing methods. Therefore, regardless of the research design, it is likely that a team of researchers is required to successfully perform a mixed-methods study (Ivankova, Creswell, & Stick, 2006; Johnson & Onwuegbuzie, 2004), which comes at a premium, potentially limiting the feasibility of the study. Third, using formalized frameworks for case studies can take away the flexibility and depth of the qualitative data gathered. For this reason, not all transition studies using simulation can or should follow a mixed-methods design. The advantages and disadvantages should be considered carefully on a case-by-case basis.

In light of the above discussion and the challenges in particular, the following areas for future research are encouraged:

1. In this article, a dichotomy between bottom-up and top-down analytical perspectives is used to classify frameworks and simulation methods, not focusing on hybrid methods. Hybrid frameworks and hybrid simulation models can be used to address novel research questions at the nexus of top-down and bottom-up analytical perspectives. While such a combination can potentially avoid the implications of theoretical and conceptual incompatibility, it is not straightforward to combine multiple social and spatial scales in simulation models (Rounsevell, Robinson, & Murray-Rust, 2012). Further research is necessary to explore the advantages and disadvantages of hybrid frameworks and simulation models in sustainability transitions research.
2. In order to effectively create ABMs informed by transition frameworks, the concepts of these frameworks still have to be operationalized at a lower level of abstraction. Efforts so far have mainly focused on system structures. Conceptual compatibility is important for the operationalization of transition frameworks to simulation methods, which is guaranteed when using the mixed-methods process model. Future research should focus on the operationalization of SNM, TM, and MLP at a low level of abstraction.
3. The use of simulation in sustainability transition studies, and the incorporation in a mixed-methods design as presented in this article, are encouraged to address new research questions. In particular, studies focusing on future transitions and the refinement of existing frameworks are necessary to further advance this field of research.

4 Formalizing the multi-level perspective with concepts of power, agency and politics

Abstract

In sustainability transitions research the use of formal modeling and simulation is hindered by a lack of formalized transition frameworks. Current efforts rely on abstract formalizations to simulate niche and regime dynamics, disregarding the micro-level mechanisms such as power, agency and politics. This article presents a formalization of the multi-level perspective (MLP) framework at the level of agents to better address the role of individuals in sustainability transitions, as well as to internalize policy-making. The presented formalization refines and extends the closely related concepts of power, agency and politics as they are currently used in the MLP. These contributions further increase the use of modelling and simulation informed by transition frameworks. Furthermore, the formalization of key MLP concepts allows for a better understanding of the real complexity and inertia underlying sustainability transitions. Finally, a low level of abstraction of formalized concepts facilitates a structured and transparent discussion to further improve the framework.

Keywords: agency, agent-based modelling, politics, power, multi-level perspective, simulation, sustainability transitions

4.1 Introduction

Sustainability transitions are often politically driven (Meadowcroft, 2009), responding to external shocks and internal system dynamics. Transition pathways are difficult to anticipate due to the unpredictable nature of external shocks, such as the Fukushima Daiichi disaster driving nuclear phase-out decisions in Europe, and the complexity of underlying social, technical and institutional factors. More specifically, Geels et al. (2016) found that transitions may shift between pathways, not least due to shifts in key stakeholder’s interests and power distributions (Loorbach, 2010; Voß & Bornemann, 2011). Indeed, the political struggle for power underlying sustainability transitions, such as the Energiewende in Germany (Hoppmann et al., 2014; Jacobsson & Lauber, 2006), is far from linear.

A vast number of theoretical contributions has emerged on the concept of politics in transitions (e.g. Fuenfschilling & Truffer, 2016; Hoffman & Loeber, 2016; Jhagroe, 2016; Raven, Kern, Verhees, & Smith, 2016; Voß & Bornemann, 2011), as well as the related concepts of power (e.g. Avelino & Rotmans, 2009; Avelino & Wittmayer, 2016; Geels, 2014) and agency (e.g. Fischer & Newig, 2016; Geels & Schot, 2007; Rosenbloom, Berton, & Meadowcroft, 2016). However, these theoretical contributions have not carried over to modeling and simulation studies. This is a missed opportunity as computer simulation is likely the only tool that allows us to study the role of micro-level politics in a complex system in transition (Squazzoni, 2008). In particular, agent-based modeling and simulation (ABMS) allows for the representation of autonomous agents to simulate such micro-level politics in sustainability transitions. The majority of transition simulation models are not based on transition frameworks such as the Multi-Level Perspective (MLP), hindered by a lack of formalized transition frameworks. Indeed, current efforts to formalize the MLP remain at a high level of abstraction, focusing on the dynamics of niches and regimes (e.g. Haxeltine et al., 2008; Papachristos, 2011; Walrave & Raven, 2016), rather than individuals.

Thus, the challenge of formalization remains and raises critical questions, such as: How exactly do the politics play out at the level of individual stakeholders? How is policy, power and agency endogenously determined? A number of studies in the field of political science focus specifically on these questions, combining game theory, formal models (e.g. Thomson, Stokman, Achen, & König, 2006) and computer simulation (e.g. Abdollahian, Baranick, Efird, & Kugler, 2006; de Mesquita, 2011). These approaches resonate well with the bottom-up analytical approach of the MLP and ABMS as they focus on the role of individuals and micro-level mechanisms underlying political power struggles, such as bargaining and coalition forming. However, in order to (consistently) translate the MLP into computer code, its concepts have to be formalized at a low level of abstraction.

In this article, two contributions are made to the sustainability transitions literature in general and the MLP in particular. The first contribution is a comprehensive review of the concepts of politics, power and agency. The review also incorporates contributions from other fields, such as political science. The three concepts are integrated in a single dynamic framework, which is based on the MLP and puts these concepts center-stage in sustainability transitions. Policy-making, institutional emergence and technological change are internalized through the concepts of politics, power and agency. Thus, the formalized MLP allows for the agency of (incumbent) actors in sustainability transitions to be better addressed (Späth, Rohracher, & Von Radecki, 2016). Furthermore, the formalized framework addresses the impact of co-evolving technical, social and institutional system structures on the overall system (in)stability, both at the level of the governed and governing (policy-making) system (Vasileiadou & Safarzyńska, 2010).

The second contribution is the formalization of the MLP at the level of agents. Formalization facilitates the increased use of modelling and simulation studies informed by sustainability transition frameworks. Simulation studies allow for rigorous hypothesis testing (Yücel, 2010) with regards to the MLP. Hypothesis testing is important to gain more confidence in newly introduced mechanisms, such as: policy-making informed by the political struggle for power in a dynamic population of agents with shifting interests and power. Similarly, a low level of abstraction of formalized concepts facilitates a structured application in qualitative case studies, promoting the comparison of case studies, as well as a transparent discussion to further improve the MLP.

This chapter is structured as follows. In Section 4.2 the MAIA meta-model is introduced, which will be used to formalize the MLP concepts for ABMS. In Section 4.3 the social, technological and institutional structures of the MLP are conceptualized. In Section 4.4 the concepts of power, agency and politics are elaborated based on a comprehensive literature review and contextualized in the structures of the MLP through the formalization using the MAIA meta-model. In Section 4.5 the chapter is concluded with a discussion.

4.2 Formalizing the MLP at the agent level

In order to create simulation models informed by transition frameworks, it is necessary to formalize the concepts of transition frameworks at the right level of abstraction. For system level formalizations of the MLP we can rely on frameworks developed by Haxeltine et al. (2008) and Papachristos (2011). However, a formalized framework with a low level of abstraction is currently not available for ABMS (Halbe et al., 2015). Use of Modelling Agent systems based on Institutional Analysis (MAIA) (Ghorbani, 2013) is recommended for the formalization of the MLP to a low level of abstraction. MAIA extends and formalizes concepts of the Institutional Analysis and Development framework (IAD) (Ostrom, 2005), and has a high theoretical and conceptual compatibility with ABMS and transition frameworks based on complexity theories, such as the MLP[25]. Key characteristics of complexity theory, as described for complex adaptive systems by (Holland, 1992): aggregate behavior at the system level, evolving network structures, and adaptive social and technical elements. Individual system elements play a central role in complexity theory and are represented as autonomous agents in ABMS.

There are three additional reasons for using MAIA. First, model input can be gathered in various ways, including case studies, and always poses the challenge of data selection (Andersen, Richardson, & Vennix, 1997, p. 196): which data is recorded and which data is discarded? This challenge can be partially overcome by the use of transition frameworks, as these inform the researcher of the relevant variables and mechanisms. MAIA can also aid with the collection and structuring of qualitative and quantitative data by making the variables operational (Ghorbani, Dijkema, & Schrauwen, 2015). Thus, MAIA can be utilized in the qualitative, quantitative and mixed-methods research designs. Second, the importance of participatory modelling approaches has been demonstrated (Peter & Swilling, 2014), but lacks a theoretical and methodological foundation (Halbe et al., 2015). MAIA has been successfully applied in participatory model development (Verhoog et al., 2016), due to its common language for domain and modelling experts, online applications for flexible low-cost collaboration and concepts to define and observe collective outcomes of interest. Third, MAIA supports multi-domain and multi-disciplinary model development, allowing domain experts and modelers to conceptualize a wide variety of socio-

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[25] The MLP (Geels, 2002; Rip & Kemp, 1998) builds on the concept of large technical systems (Hughes, 1987; Nelson & Winter, 1982).

technical and socio-ecological models. See (Ghorbani, 2013), (Verhoog et al., 2016) and (Ghorbani et al., 2015) for a number of cases where MAIA was successfully applied to study complex systems.

The MAIA meta-model consists of five interrelated structures that serve three specific purposes (Ghorbani, Bots, Dignum, & Dijkema, 2013). First, the Social Structure translates social entities to agents with attributes and decision criteria. All relevant stakeholder properties and internal decision processes are formalized, allowing for the implementation of complex and heterogeneous agents. The Institutional Structure provides a dynamic set of concepts to assign roles, objectives, and institutional rules to the agents. Institutions such as social norms and regulations are constructed using the ADICO grammar of institutions (Crawford & Ostrom, 1995), specifying to whom the institution applies (Attribute), the Deontic type, action or set of actions (aIm), Condition under which the institution holds and the sanction (Or else). Not all ADICO elements have to be used when defining an institution, as there might not be a sanction for (not) performing certain actions (Ghorbani, 2013). Such a rich grammar allows for endogenous institutional emergence (Ghorbani & Bravo, 2016) through institutionalization, deinstitutionalization and the introduction of new formal and informal institutions. The Physical Structure is used to conceptualize the technical dimension of the system. The physical assets are owned and operated by agents within the agent-based model. These three structures are used to describe the social, technical, institutional, and economical state of the system under transition. The Operational Structure is used to model and understand the actions of agents. The actions of the involved agents are key in this structure and determine the dynamics of the system, highlighting the bottom-up analytical perspective of MAIA. The Evaluative Structure can be used to visualize transition pathways under a wide range of assumptions, scenarios and uncertainties. This allows for specific policy interventions to be traced to explore their impact on transition pathways, system behavior, and system performance. Furthermore, the Evaluative Structure can be used for explanatory purposes by observing and visualizing model parameters over many runs.

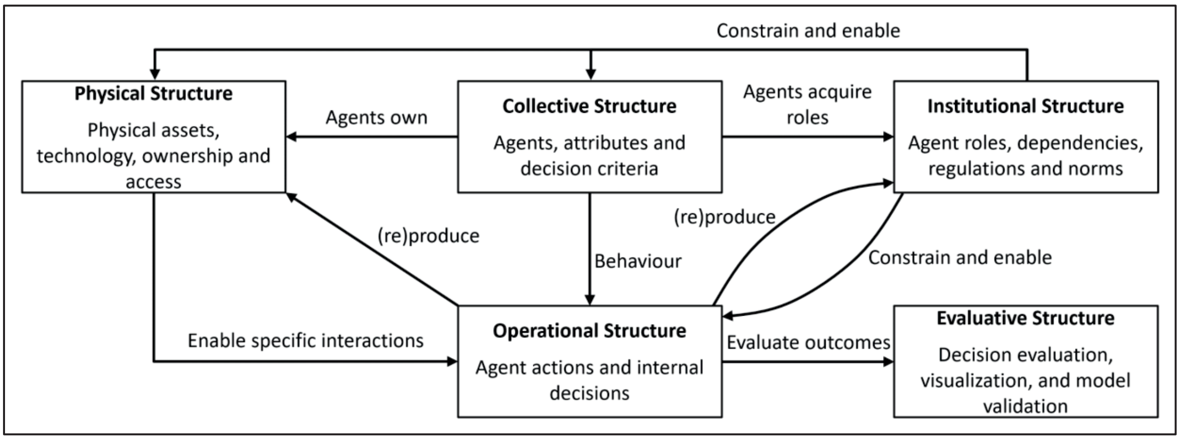

Figure 4.1 MAIA meta-model. Adapted from (Ghorbani, 2013).

The formalization of the MLP using MAIA for implementation in ABMS is positioned at the center of the position paper by Holtz et al. (2015) and the commentary by McDowall & Geels (2017). With this chapter I do not aim to add additional arguments to the discussion. Rather, I would emphasize the benefits and challenges put forward in both papers and propose a way to advance the use of modelling and simulation in sustainability transition studies. More specifically, formalization of MLP concepts will uncover a number of hidden assumptions and promote openness with regards to assumptions underlying models. Furthermore, ABMS is not positioned to replace narrative approaches, but rather to complement them. I am empathic to the idea that narrative approaches are better suited to describe qualitative dimensions such as institutions and power struggle using processual descriptions. However, when one wishes to explore future transition pathways involving such dimensions, then simulation models building on rich qualitative descriptions become indispensable due to the required computational power to explore the inherent complexity in the system's transition pathways.

4.3 Conceptualizing the structures of the MLP

The niche and regime concepts are central to the narrative of the MLP framework, as summarized by (Markard & Truffer, 2008, p. 609): "Innovation and transition processes can be explained by the interplay of stabilizing mechanisms at the regime level and (regime-) destabilizing landscape pressures combined with the emergence of radical innovations at the niche level". These concepts are in fact aggregate constructs at the system level which are composed of many individual elements and micro-level actions. As a result, critics have claimed that the niche and regime are ill-defined (Genus & Coles, 2008). In order to drill down to the level of individuals we have to acknowledge that individuals are part of these aggregate level constructs and that they influence and are influenced by system level constructs such as niches and regimes. Most of the literature formalizing the MLP has focused on these system level structures (Haxeltine et al., 2008; Papachristos, 2011). First, the current literature was reviewed to determine a comprehensive conceptualization of niches, regimes and the landscape, as well as the micro- and system-level level mechanisms driving sustainability transitions. Second, the conceptualization is formalized using the MAIA meta-model.

Geels (2002) defines a sociotechnical regime based on the concept of technological regime as defined by (Rip & Kemp, 1998, p. 340): "A technological regime is the rule-set or grammar embedded in a complex of engineering practices, production process technologies, product characteristics, skills and procedures, ways of handling relevant artefacts and persons, ways of defining problems; all of them embedded in institutions and infrastructures." Socio-technological regimes are thought to be stable due to the network of stakeholders which is (re)producing the social, institutional and physical structures in the regime (Geels, 2002), resulting in a set of institutions constraining and enabling the population of stakeholders. This conceptualization carries close resemblance to the duality of structures as described by (Giddens, 1984). Technology is defined as having no power by itself (Geels, 2002), something which will be contested in Section 4.4. Consistent with the earlier definitions of sociotechnical regimes, Haxeltine et al. (2008) present a top-down conceptual framework in which regimes are conceptualized as being made up of actors and their practices, physical assets, rules, regulation and norms. Since the agents are aggregated in this conceptual framework their individual agency is lost in the translation to system level structures. Avelino & Rotmans (2009) instead present a framework in which attention is paid to the power of individual agents. However, the types of power which agents can exercise are determined by their role as a regime or niche actor. Only niche actors can have innovative power for example, which is not a very useful restriction of assigning power to agents as regime actors can also engage in innovative activities. A more detailed discussion on (types of) power will be given in Section 4.4. The regime is often assumed to be responsible for producing incremental innovations (Geels, 2002). Adoption of niche innovation by the regime happens gradually, either by complementing existing technologies in the regime, or by capturing part of the market growth. Regimes can also gradually reconfigure themselves, driven by endogenous responses to internal and external pressure (e.g. from the landscape). Existing institutions and infrastructure play a crucial role in the selection of technologies.

The niche is more dynamic and is conceptualized as being the breeding place for radical innovations through learning processes (Schot, 1998), shielded from the selection mechanisms of the regime. Haxeltine et al. (2008) conceptualize the niche and regime as consisting of the same social and institutional structures. A differentiating factor is that the regime is assumed to have better developed structures compared to the niche, implying the regime (as an aggregate sub-system) has more power than the niche. Furthermore, the regime has a well-developed physical infrastructure, to which the niche is also assumed to have access. Think for example of the introduction of distributed electricity generation sources, such as solar photovoltaic panels, in established electricity distribution networks. Haxeltine et al. (2008) furthermore present the concept of empowered niche, which is somewhere in between a niche and regime in terms of structural strength. Underlying the conceptual framework of Haxeltine et al. (2008) conceptual framework is the assumption that niches and regimes are in direct competition, and that there can only be one regime at a given moment. This limits the ability of modelers to explore multi-regime dynamics. Therefore, the conceptualization presented in this chapter will not be restricted to a single regime. Concrete threshold numbers for moving from niches to empowered niches and regimes are not given, although Geels & Schot (2007) proposed 5% market share as a threshold for niches to be (partially) transferred to the regime. This threshold number is used by Papachristos (2011) for the development of a System Dynamics (SD) model of the MLP. However, in the SD model niches do not have the ability to establish rules (institutions) and align their activities (actions), which limits the niche's capacity to build structures. Lopolito, Morone, & Taylor (2013) focus specifically on the emergence of technological niches. Departing from the assumption that most niches emerge from a window of opportunity created by regulatory, social or technological changes in the landscape, regime or other niches (Hoogma, 2000). Raven et al. (2016) additionally propose that niches can be constructed by technology advocates in passive geographical or social contexts in which there is an opportunity for a new technology. Experiments are at the core of niche dynamics, as experiments allow for the development of new social networks required to realize the experiment, generation and diffusion of knowledge within these networks, as well as the articulation and reinforcement of expectations regarding new technologies (Geels, 2007; Lopolito et al., 2013). The expectations of the new technologies linked to the experiments are unique per agent and transmit through the social networks, based on the performance of the experiments, socially embedding the new technology (Kemp et al., 1998). As the social network develops it is able to attract more powerful agents to join the network, further enhancing the stability of the network (Geels & Raven, 2006; Lopolito et al., 2013). This is a reinforcing set of feedback loops within the niche, which help to strengthen or weaken the niche's structure (Geels, 2007; Geels & Raven, 2006). However, Lopolito et al. (2013) do not address how the niche can compete with, and potentially overthrow the regime.

Geels (2004) builds on this conceptualization by drawing on the duality of structures (Giddens, 1984), stating that the actions of actors are not only enabled and constrained by institutions, but also by technologies, infrastructures and social networks. These social and physical structures are (re)produced by actors and are often difficult to change, which leads to incremental changes along a certain pathway. These incremental developments are also termed “path dependency” and “lock-in”. The (re)production of structures is realized by actors engaged in a dynamic game, for which the rules are defined through formal and informal institutions. As a result, the rules of the game can change over time, leading to a dynamic conceptualization of institutions. Additionally, social networks and physical infrastructures are also dynamic. Different actors hold different levels of power in these games and engage in power struggles and coalition forming, but the concept of power is not clearly defined by Geels (2004).

As formal (regulative) and informal (normative) institutions are (re)produced the institutional framework becomes clearer and stronger (Geels, 2004), called institutionalization. The level of institutionalization plays an important role in the distinction between niches and regimes. Geels (2004) suggests that niches have a lower level of institutionalization than regimes. However, the threshold between niche and regime is not clear and is rather an arbitrary qualitative description of “strong” and “weak”, “incremental” and “radical”. It also begs the question: what if something is developed in the R&D department of a big firm, such as Alphabet working on autonomous driving. Would we then classify this as a niche within a company which is well-established within a regime? Could companies then be part of both the regime and niche? Perhaps the aggregation of large organizations under one banner is not precise enough in such a situation. Indeed, Geels et al. (2016) draw on the concept of ambidextrous organizations which are not only engaged in incremental innovation (exploitation), but also radical innovation (exploration) simultaneously (March, 1991). Such a conceptualization gives more agency to the regime agents. The aggregated agent concept of the MAIA meta-model could help in this case. The focal firm could be represented as an aggregate of many departments or projects within the firms’ boundaries. Each department would then be a separate agent with unique characteristics and dynamics. Furthermore, physical infrastructure and social networks become stronger when they are (re)produced as well, which could be an additional differentiator between niches and regimes.

Landscapes on the other hand are defined as gradients which cannot be changed at will over the course of the studied transition. Institutions which can be attributed to the landscape include customs, traditions, norms and religion, as they are expected to take between 100 and 1000 years to change (Williamson, 1998), and can thus be considered relatively stable over the course of a multi-decade transition. The landscape is defined as exogenous to, and more rigid than, the regime. However, this is contradictory with the statement that sociotechnical regimes may contribute to landscape changes (Geels, 2002, p. 1262), which implies feedback structures exist between the two levels and that landscapes cannot be exogenous by definition. In this chapter and conceptualization, the landscape as a structure is not considered as exogenous, but mainly contain factors which are exogenous to the studied system. Andrews-Speed (2016) also refers to the deep societal institutions identified by Williamson (1998), but also considers physical, natural and demographic phenomena as being part of the landscape. Van Driel & Schot (2005) further add the category of external shocks (e.g. nuclear disaster, war, oil crisis) to the landscape concept. Walrave & Raven (2016) assume in their system dynamics model that landscape pressures will impact regimes for an arbitrary 60 months, reducing the regime's resistance by 15%, essentially representing a window of opportunity.

The conceptual framework developed by Haxeltine et al. (2008) and the subsequent simulation model implementations by Bergman et al. (2008) and Schilperoord, Rotmans, & Bergman (2008) capture important transition dynamics at the system level. Practices, defined as routinized actions of agents (Reckwitz, 2002), play a central role in the framework and models, as it determines the support, growth and decline of niches and regimes. Practices are translated into resources which become available for the niche or regime to grow or maintain its physical or institutional structures. However, the transformation between niches, empowered niches and regimes is based on a simple threshold effect. Agents and their practices are implemented as a support canvas in the models by Bergman et al. (2008) and Schilperoord et al. (2008), allowing for agents to change their practices over time by responding to their environment. While this might work for generic two-dimensional practices as implemented in the models, things quickly become complicated when multiple dimensions are considered. The conceptualization is unique as it allows for the translation of support for niches and regime into technological and institutional structures, which then constrain and enable the agents within the niches and regime. However, individual agents within the niches and regime are not represented in the conceptual framework or simulation models, rather the regime and niches are implemented as aggregate agents. Mechanisms for the merging of niches, or the absorption of niches by regimes, are conceptualized as system level mechanisms, rather than specifying the role of individual agents in these processes. As a result, micro-level mechanisms such as power, agency and politics are not given much attention at a conceptual level. Späth et al. (2016) use a case-study of the Stuttgart E-mobility region to illustrate the agency of incumbent agents to engage in niche activities as a strategical move. Conversely, various agents and networks of agents engage in lobbying activities to mobilize niche protection measures (Ulmanen, Verbong, & Raven, 2009). Such examples highlight the importance to critically review the conceptualization of agency in the MLP, in order to address the question how individual agents or networks of agents can influence sustainability transitions.

4.4 Formalizing power, agency and politics for the MLP

Earlier criticism on the lack of power, agency and politics in sustainability transition frameworks (e.g. Meadowcroft, 2009; Shove & Walker, 2007; Smith, Stirling, & Berkhout, 2005) have sparked a burgeoning literature, resulting in a rich collage of conceptualizations of power, agency and politics. Contributions typically focus on the identification of various types of power (e.g. Avelino & Rotmans, 2009; Avelino & Wittmayer, 2016; Geels, 2014) and agency (e.g. Fischer & Newig, 2016; Geels & Schot, 2007; Rosenbloom et al., 2016). Similarly, Avelino, Grin, Pel, & Jhagroe (2016) point out the multi-dimensional nature and complexity of politics in sustainability transitions, a topic to receive much attention lately (e.g. Fuenfschilling & Truffer, 2016; Hoffman & Loeber, 2016; Jhagroe, 2016; Raven et al., 2016; Voß & Bornemann, 2011). Incorporating such rich conceptualizations in a mid-range framework, such as the MLP, raises concerns with regards to the usefulness of such an extended framework. While the level of detail in the conceptualizations is important to gain a deeper understanding of the concepts and their role in sustainability transitions, their integration in the MLP 'as-is' places a high cumulative burden on the researcher employing the extended framework. This raises questions of feasibility for performing the study, as well as interpretation of results when multiple types of power, agency and politics are co-evolving. More fruitful is an approach akin to Verhoog & Finger (2016), who aim to provide a parsimonious conceptualization based on the power relationships between actors, institutions and technology. However, micro-level mechanisms underlying the concepts remain obscure in their conceptual framework.

This section is based on a review of the sustainability transitions literature to identify the common elements of the concepts and underlying mechanisms of power, agency and politics. The objective is to provide a parsimonious conceptualization of the three concepts and their underlying mechanisms, rather than a comprehensive overview of recent contributions to the literature.

4.4.1 Refining the concept of power

Existing conceptualizations of power focus primarily on the typology of power and assigning identified types of power to agents in the niche and regime levels of the MLP. One of the earliest attempts to provide a framework to study power in sustainability transitions is by Avelino & Rotmans (2009, p. 550), who define power as "the ability of actors to mobilize resources to achieve a certain goal". System structures, such as laws and infrastructure, cannot have power in this agent-centric definition of power. In fact, the definition of power proposed by Avelino & Rotmans (2009) bears closes resemblance to the definition of agency by Giddens (1984, p. 14): "the ability to take action and make a difference over a course of events" and the definition of power-to by Weber (1978, p. 53): "the probability that one actor within a social relationship will be in a position to carry out his own will despite resistance." Subscribing to such a definition of power results in a conceptual view in which physical and institutional structures can only be power-neutral, and can only exercise power when mobilized by agents (Avelino & Rotmans, 2009; Avelino & Wittmayer, 2016; Geels, 2002). However, others have also included institutional factors as being capable of holding power. Grin (2010) defines structural power at the level of the landscape, making it an exogenous force on the system. Geels (2014) and Kern (2011) propose a more dynamic conceptualization of institutional power, or rules of the game, by not relegating it to the landscape.

However, when the definition of power is extended to include power-over, as defined by Dahl (1957, p. 203) "A has power over B to the extent that he can get B to do something that B would not otherwise do", then the concept of power can be extended beyond actors. Geels (2004), drawing on Giddens (1984), already addressed the constraining and enabling nature of social (e.g. network of agents), institutional (e.g. rules) and physical (e.g. infrastructure) structures early on in the development of the MLP. While the constraining and enabling features were not explicitly conceptualized as power, we will show its rather closely related to the concepts of power. Indeed, Verhoog & Finger (2016) conceptualize technology (e.g. physical infrastructure), institutions and agents as three system elements which can have power-over other system elements.

First, agents can hold power-over other agents, whether they are in their social network or not. These power relationships are bi-directional, relative and dynamic, resulting in complex networks of relationships when many agents in evolving social networks are concerned. Geels (2014) identifies two principal ways in which agents exercise power over other agents. Agents can directly mobilize their resources to influence the behavior of other agents. This relates to the idea that resources are not power-laden until they are used. However, the threat of having the ability to utilize certain resources might be enough to influence the behavior of other agents, meaning that the resources passively exercise power-over other agents. The idea of resource mobilization does imply that an agent needs to possess the resources first and must then also be motivated to use these resources towards a certain goal. These components are not always articulated clearly in conceptualizations of power, but it will be argued in Section 4.5 that this is crucial for the conceptualization of politics in terms of power-struggles. Agents can also influence the behavior of other agents through the use of discourse. Discourse plays an important role in the establishment, dissemination and reinforcement of expectations of technologies within a community of agents (Geels & Raven, 2006). Unique characteristics of agents determine their power relative to one another, but is also determined by the broader social, institutional, and technological environment. Agents also hold power-over technologies through ownership, which can be an important pre-requisite for engaging in certain practices (actions). Technologies can also be used to indirectly influence other agents, technologies or institutions.

Second, technologies play a role in reinforcing practices through the materialization of institutions (Fuenfschilling & Truffer, 2016) and thus contribute to the stability of regimes, or the emergence of new niches. The presence or absence of technologies shapes the set of feasible options in the system in terms of new technologies, institutions and stakeholders, thus holding power-over these entities (Fuenfschilling & Truffer, 2016). This leads to a co-evolutionary relationship between institutions and new technologies, which is modulated by agents (Finger, Groenewegen, & Künneke, 2005; Fuenfschilling & Truffer, 2016). Capital intensive infrastructures, such as electricity and natural gas distribution networks, have properties that result in natural monopolies. As a result, other technologies cannot directly compete with these technologies, limiting the feasible solution space for technologies. For this reason, regulation is required to make sure owners of the infrastructure systems are not collecting monopolistic rents. On the other hand, the existence of a well-developed electricity distribution grid also allows for the introduction of complementary technologies, such as solar photovoltaic panels and local battery storage solutions. Another example is the development of a new technology which enables new business models, which might be obstructed by existing institutions, requiring institutional adjustments to unleash the full potential of the new technology. Such an adjustment of institutions is more likely, and less radical, when a fit-and-conform strategy is adopted, rather than a stretch-and-conform strategy (Smith & Raven, 2012). Once established, infrastructures add significant stability to the regimes and are often continuously reproduced through maintenance and incremental improvements. Even in non-monopolistic situations significant stocks of technology can lead to barriers to entry for market entrants (Grünewald, Cockerill, Contestabile, & Pearson, 2012).

Third, formal and informal institutions hold power-over stakeholders by constraining and enabling certain actions through (social) sanctions (Fuenfschilling & Truffer, 2016; Geels, 2014). Institutions define the rules of the game, and agents (re)produce these institutions through the play of the game, in which rules are used or followed in the actions of the agents. The play of the game, and reproduction of institutions, drives the institutionalization in niches and regimes (Williamson, 1998). The higher the level of institutionalization, the more difficult it is to change the institutions, meaning that the game becomes more difficult to change when it has been played for a long time. Introducing new rules which are not compatible with the current rules of the game might be difficult and ineffective, as it needs to lead to a change in behavior in order to be institutionalized. Institutions can also exclude certain technologies and agents from entering the market, for example by setting standards, granting exclusive production rights through patents or requiring licenses to operate. Markets are considered as a special institution, or set of rules of the game, which structure the behavior of the players in that market through incentives (Williamson, 1985, 1996) and selection mechanisms (Nelson & Winter, 1982). Mechanisms of inclusion and exclusion need not be formalized in laws or regulations but can also be based on practices within a community. Furthermore, institutions often hold significant power-over some agents, depending on their role in the system, rather than all agents in the society. Finally, institutions provide a way for agents to (indirectly) exercise power-over other system elements, even when they lose their own power (e.g. politicians whose term ended). The same obviously holds for infrastructure (technology) as well, once things are built they typically last, and exercise power-over other system elements, for a very long time.

4.4.2 Formalizing the concept of power

In sum, the conceptualization of power proposed here focuses on the power of A over B (Avelino & Rotmans, 2011), extending earlier conceptualizations by focusing explicitly on the power of agents, institutions and technology (Fuenfschilling & Truffer, 2016). It should be noted that power as defined here is always relational (Geels & Schot, 2007; Tyfield, 2014). Readers are referred to Chapter 6 of Ghorbani (2013) for the formal specification of the MAIA concepts introduced hereafter (in italics).

Agents are central in the formalization of power, but are clearly embedded in the social, institutional and physical context. A rich set of unique attributes can be used to define a heterogeneous population of agents, representing anything from small niche start-ups to large established regime players, and from individual household members to high ranking politicians. First, agents have an array of *properties* to describe attributes such as their income, skills and their expectation of a certain technology. Second, agents can have *personal values*, such as their environmental consciousness, which can impact their expectations of technologies. Third, agents acquire *information* through learning from experiments (e.g. technological performance), markets, other agents, or various other sources. Fourth, agents are embedded in the physical context through the *physical components*. These components can be, but are not necessarily, owned by the agent. Physical components give a certain *affordance* to the agent, which is a set of actions which can be performed as a result of (having access to) the physical component. Conversely, not having access to certain physical components can limit the set of actions available to the agent. Fifth, agents are embedded in the institutional context through their *role*.

Acquiring a role can depend on the ownership of a certain physical component, or the acquisition of a certain physical component can depend on the role of the agent. Other *entry conditions* for agents to acquire a role can also be specified and can be based on any of the attributes. Furthermore, agents use decision criterion under certain *conditions*, taking into consideration an array of *aspects* and a *threshold* value. While this might appear as a relatively simple way to model decisions, it can in fact be used to construct complicated utility functions which consider a diverse set of aspects. We will see in Section 4.4.4 that this is essential for the modeling and simulation of politics in sustainability transitions. The *decision criterion* can thus also be used to take into consideration the passive power-over effects of *physical components*, *agents* or *institutions*. For example, when there are χ *physicalComponents* ۷, then *Agent A* will not perform *action* α. The *decision criterion* also allows for bounded rationality to be modeled, as agents might have incomplete *information* over the array of aspects or might rely on simple heuristics. Finally, the *composite agent* class can for example be used to represent a network of agents involved in a niche experiment. Importantly, individual agents, their roles and physical components are retained when using the composite agent class. This allows for modeling and simulating the impact of a resourceful agent (e.g. in terms of money or infrastructure) joining the innovation network. Such networks can also be used to exchange information between the different agents. These networks are specified using the *social connection*.

Physical components are owned by agents. Agents can *own* any number of physical components, including none, as indicated by the notation *0…**. This class can be used to implement single physical assets, or complete infrastructure networks, using a node and link implementation. First, an array of *properties* (e.g. price, performance and location) can be used to implement a wide range of physical components. Second, the components might be *open* or *closed* (Boolean) to certain agents. This is especially important for modeling network industries, such as electricity networks, or the access that niche agents have to regime infrastructure. Third, the *composition* can be used to define more complicated technologies, consisting of a number of physical components. Analogous to the *compositeAgent* class the individual *physicalComponents* and their attributes are retained. Fourth, the *physical connection* can be used to define the *begin* and *end nodes* of the *link*. Consequently, the physical component class can be used to implement both nodes (e.g. power plants) and links (e.g. transmission lines) of the *Physical Structure*. Furthermore, *affordance* describes the set of actions that agents, who have access to, or ownership over the asset, can perform.

InstitutionalStatements can be used to implement a wide range of institutions using the ADICO grammar of institutions, such as *shared strategies*, *norms* or *rules* (Ghorbani, 2013). First, all *InstitutionalStatements* are applicable to at least one *role*, but a role can be governed by many *InstitutionalStatements*. This is described by the *attribute* of the *InstitutionalStatement*. Second, the *deontic type* describes if a certain action is prohibited (e.g. forbidden), obliged (e.g. must) or permitted (e.g. may). Third, the *aIm* describes the *action*, or *plan* as will be defined later, to which the institution pertains. Fourth, the *condition* describes the geographical, temporal or other conditions under which the institution holds. Thus, allowing for example for a geographical differentiation of institutions to capture the different laws in two adjacent municipalities or countries. Fifth, the *sanction* is captured with the *or_else* statement and can describe both social and formal sanctions imposed on agents that do not comply with the rule. This also implies that there should be some sort of monitoring and policing structure in place to enforce the rules, this can for example be done by the agents in the social network, but also by a regulator or other competent authority. The result is a statement, such as the following: “Car drivers (*Attribute*) are forbidden (*Deontic*) to exceed 30km/h (*aIm*) in residential areas (*Condition*) or they are fined (*Or_else*).” Just because there is a sanction does not mean that the *agent* will necessarily comply with the institution. Models which expect full compliance with rules might have quite predictable results, allowing for little to no innovation and deviation from the status quo.

It should be noted that the part of the formalization presented here does not focus on the (re)creation of physical and institutional structures, as this is done through agency (power-to). Instead, the focus is on the power-over as a result of the existence of these physical, social and institutional (Arts & Tatenhove, 2004; Grin, Rotmans, & Schot, 2011). This also means that a definition of power-over is static. In order for the system to be dynamic it needs to contain a definition of agency.

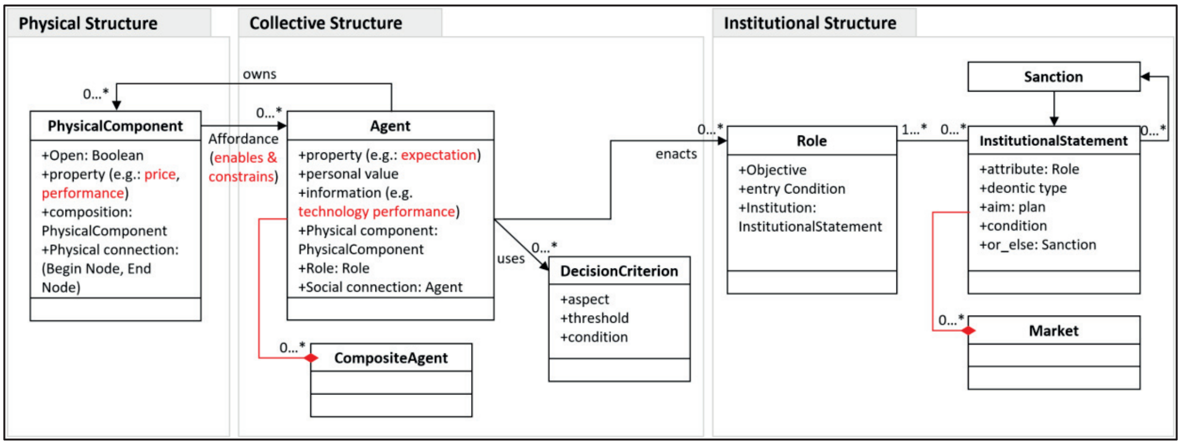

Figure 4.2 Physical, Collective and Institutional Structures of MAIA used to formalize power as part of the MLP. Text and arrows in red indicate a relation to MLP specific examples in the text of this sub-section. Source: created by the author, based on the MAIA concepts (Ghorbani et al., 2013).

4.4.3 Refining the concept of agency

The conceptualization of power as power-over directly relates to the concept of agency, recalling the definition by (Giddens, 1984, p. 14): “the ability to take action and make a difference over a course of events”. Thus, agency is the power-to take actions, embedded in the context of power relations (power-over) with other agents, institutions and technologies. Central to the definition is the assumption that agency can only be held by agents. Thus, agents are key to the endogenous development and technological and institutional structures in socio-technical systems. Fuenfschilling & Truffer (2016) draw attention to the role of agents and agency in the creation, change and maintenance of institutions in regimes. Lawrence & Suddaby (2006) focus on the role of practices to create new rules with sanctions as enforcement mechanisms, increasing support for those rules and associated practices (actions).

Geels & Schot (2007) identify a broad set of actions which agents can perform, as defined by formal, cognitive and normative rules which constitute the rules of the game. This definition of agency is consistent with other definitions in the sense that only agents can have agency. However, the definition does not account for the power of technology over agents, and rather refers to institutions and the duality of structures theory (Giddens, 1984) by means of a rule-based model of agency Geels & Schot (2007). Verhoog & Finger (2016, p. 111) relate this rule-based model to the institutional layers identified by Williamson (1998, p. 26) as follows: (1) formal rules of the game (e.g. laws) are produced through rule-creation and rule-alteration, and (2) reproduced through rule-using and rule-following as part of the play of the game. The game thus consists of a set of actions by agents, such as investments in physical assets or voting as part of a political process, in the context of existing institutions. However, with the formalization of power-over, as presented in Section 4.4.2, this context is extended to include technologies (physical components).

It is important to note that this conceptualization does not attribute any agency to the niche, regime or landscape (Fischer & Newig, 2016), but rather to the individual agents which might be part of a niche or regime. Fischer & Newig (2016) found in their review of the literature that more efforts are focused on assigning specific actors to the niche and regime. Such an exercise will not be attempted here, meaning that the agent class can be part of a niche, regime or both.

4.4.4 Formalizing the concept of agency

In sum, the formalization of the concept of agency (power-to) builds on the formalization of power-over, as presented in Section 4.4.2 and Figure 4.2, and extends common definitions in the literature by explicitly including the technological context. An overview of the formalized concepts is given in Figure 4.3. Again, due to space limitations, readers are referred to Chapter 6 of Ghorbani (2013) for the formal specification of the MAIA concepts introduced hereafter (in italics).

The actions of *Agents*, denoted as *Entity Action*, are central to the formalization of agency, as *Agents* are the only entities that can have the power-to do something. Does this then mean that *PhysicalComponents*, such as an oil refinery, do not do anything? Not exactly, as the operational aspects of these *PhysicalComponents* are captured in their *properties*. However, the actual operation of *PhysicalComponents* is through the *EntityAction*. For this reason, the *EntityAction* always needs an *Agent* as the *Performer* of the action. It is not necessary for the *Agent* to perform a certain *Role*, but this might be one of the *preConditions* for performing the action. Other *preConditions* that test the feasibility of the action to be performed can depend on *institutionalStatements*, *Agent properties* or *PhysicalComponents*. This formalization allows for detailed feasibility checks to be built into the simulation model, capturing the power *PhysicalComponents*, *Agents* and *InstitutionalStatements* have over other agents. Furthermore, while these aspects might not be a direct requirement for the *preCondition*, they might be taken into consideration by the *Agent* through the *DecisionCriterion* as described in Section 4.4.2. Finally, when the action is performed there is an outcome on the system state, as defined by the *postCondition*. This could be the construction of a power plant, or the hiring of a new employee.

Entity Actions only represent a single action by an *Agent*, but multiple *Entity Actions* can be used in a specific order to create more complicated actions. *Plans* can be defined using a single *EntityAction* (*Atomic Plan*), combining multiple *EntityActions* in given order (*Sequential Plan*), randomly selecting an action from a set of *EntityActions* (*Alternative Plan*) or by iterating an action until a certain condition is met (*Loop Plan*). A *Plan* could for example contain all *Entity Actions* related to a political voting procedure. Multiple related *Plans* are grouped together in an *Action Situation*, which could for example contain all *Plans* related to the political procedure to establish a new law, including the agenda setting, lobbying and formal voting process. Finally, all *Action Situations* are stored as a list in one single *Action Arena* per simulation.

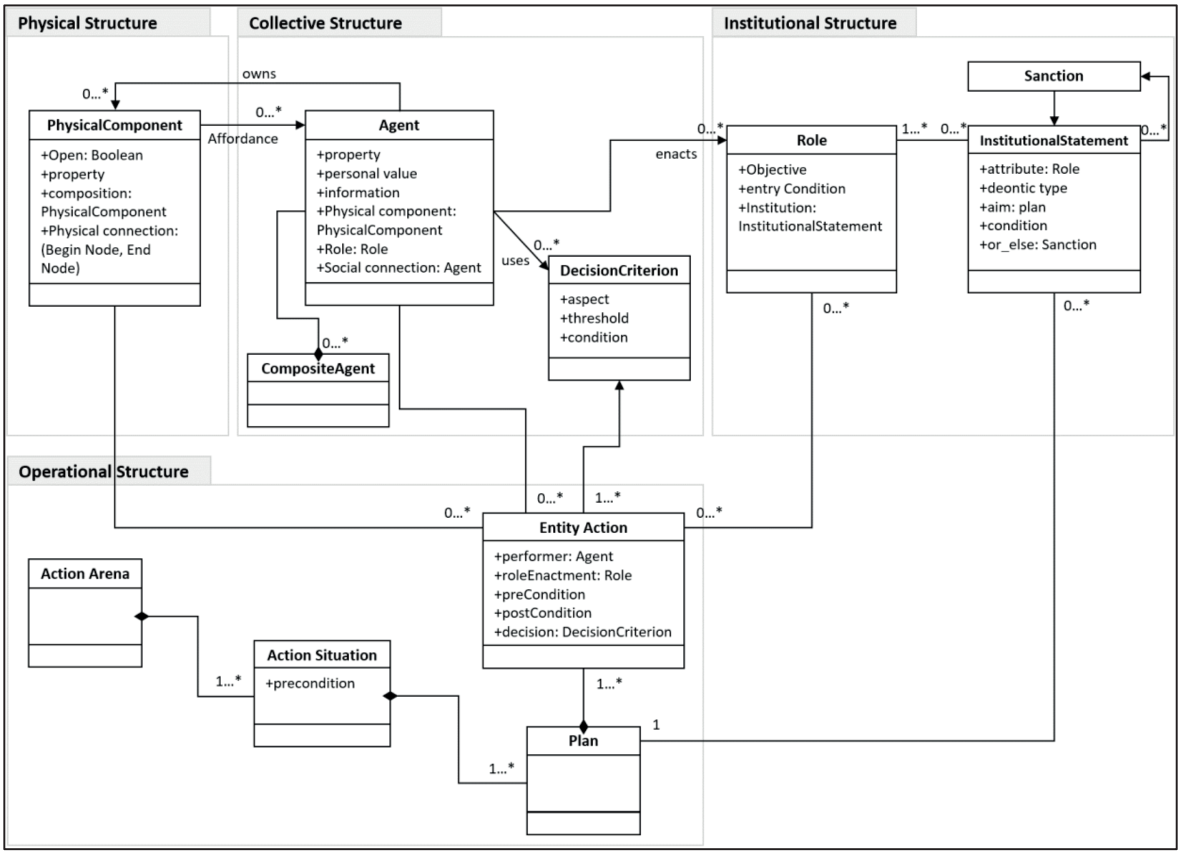

Figure 4.3 Operational structure of MAIA used to formalize agency as part of the MLP. The concept of agency is contextualized by the Physical, Collective and Institutional Structures. Source: created by the author, based on the MAIA concepts (Ghorbani et al., 2013).

4.4.5 Refining the concept of politics

As hinted in Section 4.4.4, politics can be defined as a type of agency in which Agents engage in order to maintain or change the rules of the game (institutions). By explicitly incorporating the concept of politics in the MLP two contributions are made to the MLP literature: (1) a political layer is added to the MLP, and (2) history is added to the political system by embedding the politics in a broader socio-technical system in which lock-in, institutions and technologies play an important role. The conceptualization presented here, as well as the formalization presented in Section 4.4.6, bring together the fields of sustainability transition studies, political science and ABMS.

More concretely, politics can be understood as the power-struggles of agents to influence policy-making, where policies are a type of formal institution. An important nuance in this definition is that Agents at best influence the political process of policy-making, and that such efforts do not necessarily result in new policies. Political efforts can also be aimed at maintaining the current policies, also called the status quo (Tsebelis, 2000). Indeed, (Thelen, 2003) and (Mahoney & Thelen, 2009) noted that there are various rates at which institutions change, differentiating between endogenous incremental change and rapid disruptive change due to external shocks. This suggests that there are some mechanisms underlying the power-struggles of policy-making that can significantly influence the rate and scope of policy-change. Common mechanisms identified in the literature are blockage and coalition forming (Hess, 2013, p. 849), veto power (Geels, Kern, et al., 2016; Tsebelis, 2000) and other actions. However, such mechanisms do not capture the informal aspects of politics, such as lobbying and the role of discourse (Rosenbloom et al., 2016). These informal mechanisms are aimed at influencing the position of individual agents vis-à-vis policies in the interest of the influencing agent, also called advocacy (Lawrence & Suddaby, 2006). Fuenfschilling & Truffer (2016) highlight the importance of considering individual agents, rather than aggregated structures such as the regime, as positions of agents within the regime are both dynamic and conflictual.

In order to accurately model politics the advocacy phase should be separated from the formal decision-making phase (Stokman & Van den Bos, 1992; Stokman & Zeggelink, 1996). This separation allows for voting power to be disentangled from other sources of power, providing insights in the influence agents without formal decision-making power can have on policy-outcomes. Such models are called mixed models, which are less common than models considering uniquely agents with formal decision-making power (Schneider, Steunenberg, & Widgrén, 2006). During the advocacy phase agents are only assumed to be self-interested when using their power, i.e. influencing the position of other agents to move closer to their preferred position. Additionally, agents will only mobilize their resources for advocacy purposes if they are interested in the policy issue, denoted as saliency. Schneider et al. (2006) found that models which incorporate the saliency of agents on policy dimensions are more accurate in predicting policy-outcomes. These three agent properties (position, power and saliency) are common in political science models (Bueno de Mesquita, 2011; Nunberg, Barma, Abdollahian, Perlman, & Green, 2010; Stokman & Zeggelink, 1996; Wise, Lester, & Efird, 2015). During the voting phase only agents with formal voting power are included, casting their votes based on the outcomes of the advocacy phase. It is furthermore assumed that agents engage in strategic behavior to optimize their advocacy actions, including “trading” positions on different policy issues (Wise et al., 2015). For example, agent *A* will adjust its position on policy issue *X*, in exchange for an adjustment of agent *B* on policy issue *Y*. Any analysis including multiple policy dimensions, and the ability of agents to exchange positions between policy dimensions, greatly increases the complexity of the underlying model. Such complexity and strategic behavior can be modeled and simulated using a combination of cooperative game theoretical models and ABMS, such as the model developed at KAPSARC[26] (Wise et al., 2015). Trading between policy dimensions cannot be done in the model developed by Bueno de Mesquita (2011), or any of the follow-up models that tried to uncover the black-box assumptions of the model (Eftekhari & Rahimi, 2014; Scholz, Calbert, & Smith, 2011).

Related to the formal decision-making process the concept of veto power is introduced (Tsebelis, 2000). An agent has veto power when a policy decision can be blocked by that agent, regardless of the power of the agents or coalitions supporting that policy. Veto power is closely related to the formal rules of the game, such as the voting rule (e.g. simple majority, qualified majority and unanimity), or veto powers assigned to European Member Status or a head of state. The formal rules of the game can be different for each policy issue and thus require a detailed understanding of the rules of the game currently in place. Veto theory provides an explanation for the rate and scope of policy changes. Tsebelis (2000) and Tsebelis & Chang (2004) show that policy change is more likely to be slow and incremental under the following conditions: (1) there is a large difference in positions between veto players, (2) there are many veto players and (3) there is a high majority voting threshold. The risk-taking behavior of agents with positions far removed from the status quo plays an important role, as these agents are willing to take the risk of not reaching agreement on an (incremental) policy change in favor of finding a more radical policy change much closer to their position. Finally, there is the role of narratives and discourse in setting the policy agenda (Hermwille, 2016). Defining the set of policy options to be chosen from is very advantageous, as the agents can try to exclude options that are outside the range of policy options they would be willing to accept. However, all agents can engage in advocacy actions to influence the narratives and discourses around a policy issue.

4.4.6 Formalizing the concept of politics

In sum, the formalization of the concept of politics builds on the formalization of power-to, as presented in Section 4.4.4 and Figure 4.3. The formalization also builds on existing ABMS which draw primarily from game theory and political science (Bueno de Mesquita, 2011; Eftekhari & Rahimi, 2014; Nunberg et al., 2010; Scholz et al., 2011; Wise et al., 2015). However, these models often neglect the existing technological and institutional environment, outside of the formal rules of the game of the policy decision-making process, in which the agents operate. In this Section the algorithm of the Preana model, as described in Eftekhari & Rahimi (2014), is extended to include a formal policy decision-making process in addition to the informal advocacy phase. Furthermore, the agenda setting process is included and the algorithm is linked to the broader socio-technical system. As a result, the algorithm can now take the information directly from the agents, institutions and technologies in the simulation model. Finally, the algorithm is adjusted to support multiple policy continua, as Preana is a non-cooperative bargaining model, agents cannot exchange positions between policy continua. An overview of the formalized concepts is given in Figure 4 and the extended flowchart is given in Figure 4.5.

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[26] KAPSARC's Toolkit for building collective decision-making models (KTAB) software is available at the following website, under a standard MIT License: https://github.com/KAPSARC/KTAB

Policy options are defined along a linear axis called a *policy continuum* (Bueno de Mesquita, 2011; Wise et al., 2015), which is ideal for defining continuous policy options such as CO_2 emission savings by year 2050. However, discrete policy options should be ordered in the same way by all *Agents*, which can be challenging for multi-dimensional policy options. Multiple policy continua can be defined in the simulation model, keeping in mind that this significantly increases data requirements. The first step in the algorithm is to determine the *policy continua*, by finding the range of *Positions* over the population of relevant *Agents* for each policy dimension. *Agents* take into consideration their social, technological and institutional context when determining their ideal *Position*, based on their *expectations* of their *utility* to be gained from the policy outcome in the socio-technical context. The second step is to calculate the most likely outcome, which is the median voter theory in most models (e.g. de Mesquita, 2011; Eftekhari & Rahimi, 2014; Nunberg et al., 2010). KAPSARC's KTAB model allows for other implementations, such as the Central Position Theorem (Wise et al., 2015). The third step is to calculate the *expected utility* for each *Agent*. In the fourth step all *Agents* evaluate if they can make an offer to another *Agent* to change the *Position* of that agent, based on the current most likely outcome, their *initial Position*, *current Position*, *saliency* and *power*. If this is possible the *Agent* will make an offer during the fifth step to the other *Agent*. In the seventh step *Agents* evaluate their offers and select one or reject all offers. The making and choosing of offers is a very strategic process, in which *Agents* go through a lot of scenarios, based on their expected pay-off (contribution to their *Utility*), expected *Power* and pay-off of other *Agents*. This is why game theoretic models, as described in more detail in Wise, Lester, & Efird (2015) are useful references for determining complex *DecisionCriterion* used in these steps. In the eight step the *Positions* of all *Agents* are updated. Afterwards the most likely outcome is calculated again, and this loop is repeated until no offers can be made, at which point the advocacy phase is finished. Other stop criterion could also be included, such as a maximum number of iterations. The formal voting process is typically performed by a smaller subset of *Agents*, and their *Power* is determined by their number of votes and veto power. Formal voting power is assigned based on the *Role* of the *Agent* and by the rules of the game (*InstitutionalStatement*), as well as the voting threshold. If the threshold is passed, then the selected policy will replace the status quo. If the threshold is not passed, or if veto power is exercised, then the status quo is maintained.

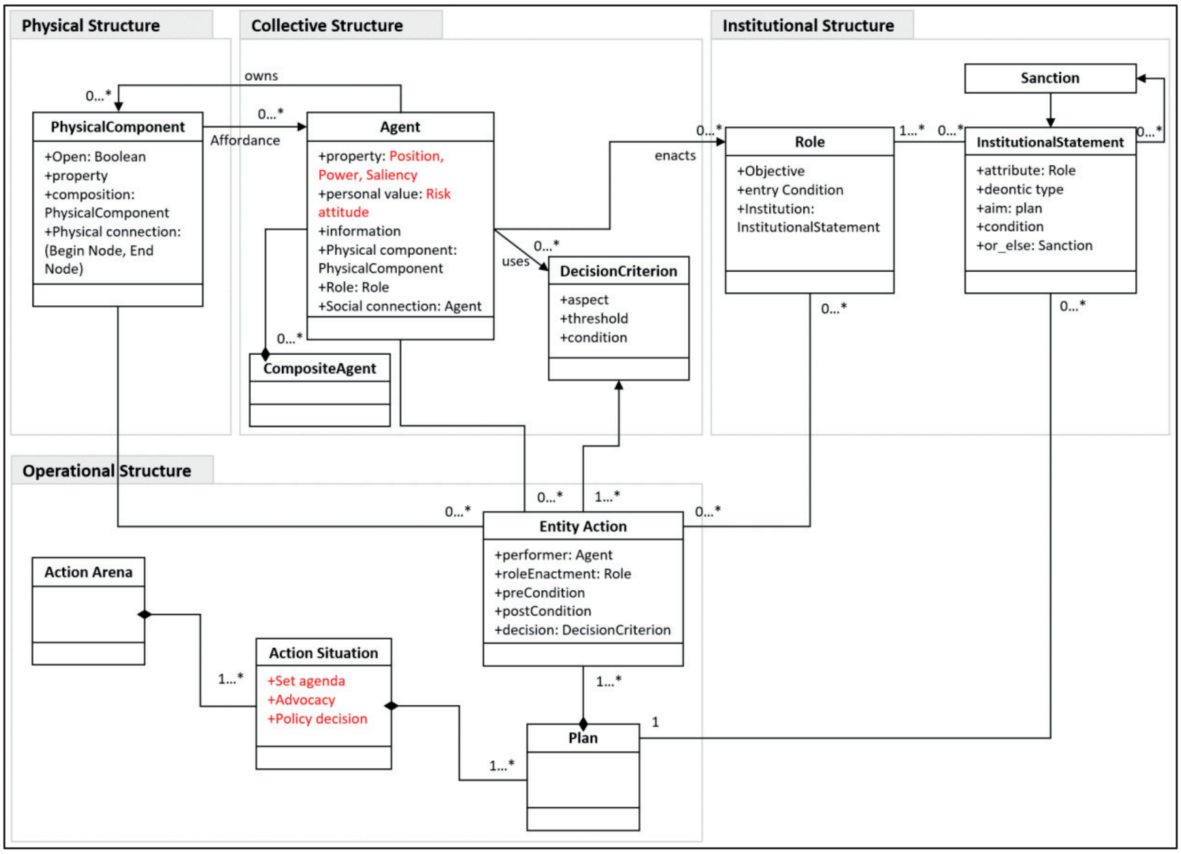

Figure 4.4 Operational structure of MAIA used to formalize politics as part of the MLP. Text in red indicates a relation to politics specific concepts. Source: created by the author, based on the MAIA concepts (Ghorbani et al., 2013).

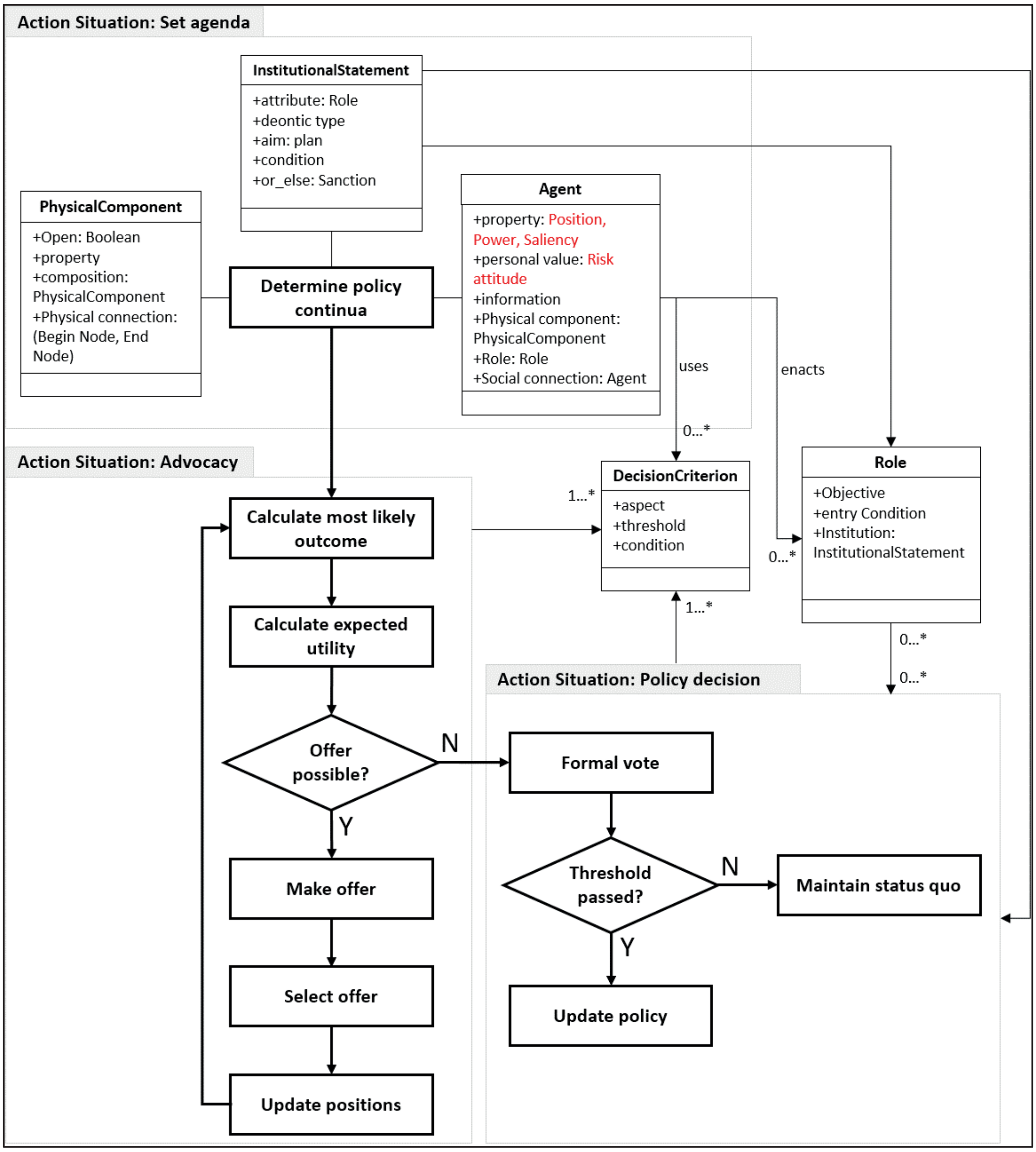

Figure 4.5 Flow-chart for the Action Situations related to politics. The most relevant UML classes are also added to the Figure to show the role of technology, institutions and agents. Text in red indicates a relation to politics specific concepts. Source: created by the author, based on the MAIA concepts (Ghorbani et al., 2013) and PREANA (Eftekhari & Rahimi, 2014).

4.5 Discussion and conclusion

In this article, two contributions are made to the sustainability transitions literature in general and the MLP in particular. The first contribution is a comprehensive review of the concepts of politics, power and agency. The review also incorporates contributions from other fields, such as political science. The three concepts are integrated in a single dynamic framework, which is based on the MLP and puts these concepts center-stage in sustainability transitions. Policy-making, institutional emergence and technological change are internalized through the concepts of politics, power and agency. Thus, the formalized MLP allows for the agency of (incumbent) actors in sustainability transitions to be better addressed (Späth et al., 2016). Furthermore, the formalized framework addresses the impact of co-evolving technical, social and institutional system structures on the overall system's (in)stability, both at the level of the governed and governing (policy-making) system (Vasileiadou & Safarzyńska, 2010).

The second contribution is the formalization of the MLP at the level of agents. Formalization facilitates the increased use of modelling and simulation studies informed by sustainability transition frameworks. Simulation studies allow for rigorous hypothesis testing (Yücel, 2010) with regards to the MLP. Hypothesis testing is important to gain more confidence in newly introduced mechanisms, such as: policy-making informed by the political struggle for power in a dynamic population of agents with shifting interests and power. Similarly, a low level of abstraction of formalized concepts facilitates a structured application in qualitative case studies (Ghorbani et al., 2015), promoting the comparison of case studies, as well as a transparent discussion to further improve the MLP. By explicitly incorporating the concept of politics in the MLP two contributions are made to the MLP literature: (1) a political layer is added to the MLP, and (2) temporality is added to the political system by embedding the politics in a broader socio-technical system in which lock-in, institutions and technologies play an important role. The present formalization brings together the fields of sustainability transition studies, political science and ABMS. The result is a dynamic definition of the concept of politics in a social, institutional and technological context. Policy-making directly follows from the political struggle for power and formal decision-making, which dynamically changes over time as stakeholder's interest and power shifts.

Niches and regimes are implicitly included in the formalization, as they are composed of the various MAIA building blocks, but by themselves do nothing (i.e. the niche and regime do not have any power or agency). Rather, it is a selection of agents, institutions and technologies with a certain level of structuration which are labeled as a niche or regime. Landscapes are conceptualized as a collection of external variables. As such, the niche, regime and landscape concepts are useful narrative devices, and play an important role during data analysis and interpretation (Steps 11 through 13 in the mixed-methods process model, Figure 3.6, Section 3.4). The data gathered from the simulation model should be treated similarly as empirical data gathered by directly observing the real system. Thus, patterns of social, technical and institutional structuration in simulation outputs can lead to the identification of niches and regimes, which emerge and change over time.

The implementation of the formalized MLP in ABMS is not without its challenges. First, there are few existing models to build on, leading to high initial development costs of the model. Such an exercise also requires a multidisciplinary set of skills, especially when the model is applied to a real case. Second, data requirements can prove to be a limiting factor for the modeling and simulation of the political dimension of the model. Access to experts is not guaranteed, which might lead to low quality input data and unreliable simulation results. While techniques exist to deal with uncertainty, such as sensitivity analysis, the impact of low quality data might completely negate the added value of considering the political dimension. Ideally, policy uncertainty is reduced by a more accurate understanding and representation of likely future policy-scenarios. Third, modeling and simulating discourses remains a challenge. While historical and current discourses can be studied in great detail and used to instantiate the simulation model, the current formalization does not offer a theoretical foundation to simulate the evolution of discourse over multiple decades.

In light of the above discussion and the challenges in particular, the following areas for future research are encouraged:

1. More work on discourse is needed to incorporate the concept and its underlying mechanisms in the formalized MLP. A theoretical foundation for the mechanisms is crucial in this case.
2. The formalized framework should be implemented to bring ABMS and MLP closer in a simulation study, lowering the barrier for future transition scholars. Such models can facilitate the ongoing discussions to improve the MLP and its formalization, for example through the rigorous testing of hypotheses which are based on the MLP conceptualization or rich case studies.
3. Similarly, linking the KTAB model (Wise et al., 2015) to socio-technical ABMS for use in sustainability transition studies can lower the barrier to include politics in future simulation studies. It is suggested to continue these efforts in an open-source fashion, providing full insight in the underlying assumptions. Model documentation plays a crucial role in these efforts.

5 Conclusion and discussion

In this chapter a critical reflection is provided on the contributions, findings and shortcomings of the individual papers in this thesis, placing the work in the broader context of politically driven contemporary sustainability transitions. This is followed by a discussion on potential future research.

5.1 Critical reflection on Chapter 2 (paper 1)

A recent meta-analysis of Swiss energy transition scenario studies highlighted a significant variation of quantitative results, assumptions and modeling approaches (Densing et al., 2016). Comparison of these scenario study results requires that differences in modeling methodologies and assumptions are accounted for. However, the meta-analysis of Densing et al. (2016) uses scenario model outputs to determine a representative reduced set of scenarios.

This chapters complements the meta-analysis of Densing et al. (2016) by exploring the uncertainty of Swiss scenarios by using a System Dynamics model. This chapter presented the design and implementation of a system dynamics model (EPFL-MIR) for the Swiss electricity market. A uncertainty analysis was performed on the System Dynamics model for all boundary condition ranges reported in the selected expert scenarios (Pruyt, 2013). The uncertainty analysis was used to explore the full uncertainty space obtained from the Swiss scenario studies (Pruyt, 2013), generate insights in the range of plausible model outcomes (Bishop et al., 2007), and to filter out less influential boundary conditions (DeCarolis et al., 2017). Based on the uncertainty analysis the following key findings were obtained:

- The confidence intervals obtained from the EPFL-MIR model are much larger than the range of model outputs found in Swiss transition scenarios with predefined sets of boundary condition values. The larger confidence intervals are inherent to the uncertainty analysis approach, as it contains many runs with boundary condition combinations not included in the Swiss scenario studies. However, relying on scenarios with a limited predefined set of boundary conditions, and often limited treatment of uncertainty (Densing et al., 2016), can lead to an underestimation of uncertainty, as well as an underestimation of the influence of certain boundary conditions. Similarly, reducing complexity by selecting a representative set of scenarios can contribute to a further underestimation of uncertainty and the influence of boundary conditions, as the range of underlying boundary condition values might be reduced simultaneously. The meta-analysis approach presented in this thesis does not run this risk as it considers all boundary conditions (model inputs), rather than model outputs.

- Switzerland can develop a long-term dependency on high levels of electricity imports, much higher than reported in other models, such as the UNIL System Dynamics model. Relaxing the import constraints imposed by most optimization models included in this meta-analysis, reveals a market tendency towards import reliance.
- Two subsets of boundary conditions are identified to which the model is most sensitive. The first subset contains the following energy policy related boundary conditions: nuclear phase-out, electricity demand and RES deployment (solar PV in particular). The second subset contains uncertain boundary conditions: foreign spot price, carbon price, natural gas price, and other thermal installed capacity.

The primary methodological contribution is the use of System Dynamics as a method in a meta-analysis of sustainability transition scenario studies. By implementing the underlying boundary conditions of all analyzed scenarios in one model an uncertainty analysis could be performed on a larger uncertainty space, increasing its analytical strength. This approach also demonstrates how a simulation model can be used to reduce the complexity of future analyses, by filtering unimportant boundary conditions.

The primary practical contribution is the exploration of boundary conditions which can be used as potential policy levers by policy-makers and firms in the Swiss energy transition. Furthermore, by exploring a larger uncertainty space a better understanding of the range of possible model outcomes is given to policy-makers, allowing them to make better informed decisions without underestimating the uncertainty of the Swiss energy transition. Finally, the exercise of implementing a large set of Swiss transition scenarios in one model provided deeper insights in the assumptions and data driving model behavior.

A strength of the methodological contribution is its generalizability. While the results of the meta-analysis presented in this chapter are specific to the Swiss energy transition, the approach can be generalized to other sustainability transitions with readily available quantitative scenario studies.

There are a number of limitations to the EPFL-MIR model and analysis presented in this chapter. The first limitation is that the system boundaries are chosen in such a way that the neighboring countries are treated as exogenous, including investments in transmission capacity. Due to this limitation there is no feedback from the Swiss market to the foreign markets. While the Swiss market is relatively small compared to the German, Italian and French markets, it is likely that the endogenous investments in transmission capacity would more accurately capture impacts on electricity flows and spot prices between these countries. Furthermore, a high influence of foreign spot prices was found in the uncertainty analysis. However, due to its model boundaries the EPFL-MIR model is a single market model with simplified import and export dynamics. Finally, relatively little information is given on the boundary condition values for electricity demand in the Swiss scenario studies. To address this limitation further research could be done to extend the EPFL-MIR model to a multi-region model, such as the VSE model (Pöyry, 2012).

The second limitation is that demand profiles are currently static and based on historical values. However, such profiles are likely to change as a result of the adoption of e-mobility, heat pumps and demand response. While this assumption is common among the reviewed models, it is not a very realistic assumption and can lead to large differences in the dispatch models. However, determining dynamic demand profiles can be challenging due to the influence of other technologies and processes, such as demand-side management and price elasticities (Weidmann, 2013). Further research could add these important behavioral aspects to a currently technology dominated set of models.

Critically reflecting on the age of the models and data which are used as an input for the EPFL-MIR model raises questions regarding the policy relevance of the findings, as well as the position of the model within the current policy debate. First, since the models have been released, the energy system has not changed significantly in Switzerland. Therefore, the EPFL-MIR model is not considered to be outdated in terms of its structure. However, the policy debate has shifted significantly since 2012, in particular since the popular vote on the Swiss Energy Strategy 2050 on 21 May 2017. For example, the implementation of the measures voted by the Swiss population is expected to steer the system towards the demand scenario in which electricity demand more or less stabilizes. Other topics, such as the liberalization of the electricity market is still a relevant question for Switzerland today, and the EPFL-MIR model is particularly well-equiped to explore transition pathways in a fully liberalized market. Recently, system adequacy (Demiray et al., 2017) and capacity remuneration mechanisms (Betz, Cludius, & Riesz, 2015) have received increased attention in Switzerland, in response to developments in neighbouring countries. The EPFL-MIR model would have to be extended in order to address these new policy questions. The meta-analysis approach used in this chapter is inherently “slow”, as it depends on the publication of an ensemble of other models. Such models might not be (immediately) available. Thus, it is not desirable to use a meta-analysis approach to provide quick answers to current policy questions. The EPFL-MIR model, however, could be extended like any other model, offering a solid basis drawing from major Swiss scenario studies and easily updated (public) data.

5.2 Critical reflection on Chapter 3 (paper 2)

In this chapter a mixed-methods process model for sustainability transition studies has been elaborated, which provides an answer to the call for various levels of integrating case studies, frameworks and simulation methods (Geels, Berkhout, et al., 2016; Papachristos, 2014; Turnheim et al., 2015). The presented process model aids the development of mixed-methods research designs involving transition frameworks and simulation models. The process model builds on established general mixed-methods research literature (Collins et al., 2006; Heyvaert et al., 2013; Johnson & Onwuegbuzie, 2004; Onwuegbuzie & Leech, 2005, 2006), and incorporates results from a structured literature review of sustainability transitions literature. In doing so, attention is drawn to missing linkages in the general process model, which limit its usefulness for sustainability transitions research involving simulation and transition frameworks. In comparison to a loose integration, use of the mixed-methods process model as presented in this article brings the following five additional advantages for transition scholars:

1. The transition framework functions as a theoretical lens to scope the research and provides a set of concepts ensuring comparability of results across case studies and simulation models within the same research design. The comparability of results is not guaranteed when methods and studies are loosely integrated, and even less so when methods are performed separately as suggested by Geels et al. (2016). Therefore, a mixed-methods research design is more likely to provide comprehensive policy relevant insights regarding sustainability transitions across all methods used than a loose integration of methods could.
2. New mixed-methods research designs can be imagined using the process model, going beyond sequential designs where simulation follows a case study and data collection. Alternative designs include: concurrent design for triangulation, and qualitative method being used in a sequential design to explain findings in a simulation study.
3. The application of frameworks provides a theoretical foundation for simulation models in sustainability transitions research, allowing modelers to build on established knowledge in the transitions field.
4. Introducing simulation into research designs that also feature case studies and frameworks allows for a broader range of research purposes to be addressed in new ways. For example, in explanatory research, hypotheses defined using case studies can be tested using simulation, allowing frameworks to be systematically challenged and refined (Yücel, 2010). Additionally, mixed-methods designs can be used for informed explorations of future transitions, and to gain a deeper understanding of historical transitions and their underlying dynamics.
5. The mixed-methods process model ensures the theoretical and conceptual compatibility of the selected methods or informs the researcher of implications when the compatibility is compromised. While bottom-up frameworks can be, and have been, combined with top-down simulation methods, a discussion on the implications is often missing as indicated in Section 3.4.3. By strictly following the process model, improvements can be achieved with regards to the documentation of research designs, data collection, verification, validation and data legitimation.

The use of mixed-methods designs is not without its challenges. First, formalizations of frameworks are not yet widely addressed in the literature. Formalizations so far have mainly focused on System Dynamics, limiting the use of Agent-Based Modelling in mixed-methods designs. Second, mixed-methods research imposes considerable resource requirements in terms of time, costs, and knowledge. There are relatively few researchers who command both qualitative and quantitative methods, and even fewer who have experience in mixing methods. Therefore, regardless of the research design, it is likely that a team of researchers is required to successfully perform a mixed-methods study (Ivankova et al., 2006; Johnson & Onwuegbuzie, 2004), which comes at a premium, potentially limiting the feasibility of the study. Third, using formalized frameworks for case studies can take away the flexibility and depth of the qualitative data gathered. For this reason, not all transition studies using simulation can or should follow a mixed-methods design. The advantages and disadvantages should be considered carefully on a case-by-case basis.

Critically reflecting on the structured literature review, which is the primary method used in this chapter, draws attention to the static nature of the method. Furthermore, while the low frequency of studies using simulation methods is a compelling argument to develop a mixed-methods framework, it also questions the relevance of a snapshot overview with low numbers of observations in some categories. Essentially, a comprehensive literature review covering hundreds of peer-reviewed publications only returns a handful of studies combining simulation methods, transition frameworks and qualitative methods. Based on such a limited dataset it is difficult to draw strong conclusions on the use of modeling and simulation in mixed-methods designs. Additionally, over time the utilization of methods, research paradigms (qualitative, quantitative and mixed), as well as the research purpose (exploratory, descriptive or explanatory) might shift. Therefore, established general mixed-methods and simulation literature was consulted, ensuring the relevance of the specific mixed-methods process model over time.

This future research suggestion in Chapter 3 (paper 2) is addressed in the Chapter 4 (paper 3): In order to effectively create ABMs informed by transition frameworks, the concepts of these frameworks still have to be operationalized at a lower level of abstraction. Efforts so far have mainly focused on system structures. Conceptual compatibility is important for the formalization of transition frameworks to simulation paradigms, which is guaranteed when using the mixed-methods process model. Future research should focus on the formalization of SNM, TM, and MLP to a low level of abstraction.

5.3 Critical reflection on Chapter 4 (paper 3)

In this article, two contributions are made to the sustainability transitions literature in general and the MLP in particular. The first contribution is a comprehensive review of the concepts of politics, power and agency. The review also incorporates contributions from other fields, such as political science. The three concepts are operationalized and formalized in a single dynamic framework, which is based on the MLP and puts these concepts center-stage in sustainability transitions. Policy-making, institutional emergence and technological change are internalized through the concepts of politics, power and agency. Thus, the formalized MLP allows for the agency of (incumbent) actors in sustainability transitions to be better addressed (Späth et al., 2016). Furthermore, the formalized framework addresses the impact of co-evolving technical, social and institutional system structures on the overall system (in)stability, both at the level of the governed and governing (policy-making) system (Vasileiadou & Safarzyńska, 2010).

The second contribution is the formalization of the MLP at the level of agents. Formalization facilitates the increased use of modelling and simulation studies informed by sustainability transition frameworks. Simulation studies allow for rigorous hypothesis testing (Yücel, 2010) with regards to the MLP. Hypothesis testing is important to gain more confidence in newly introduced mechanisms, such as: policy-making informed by the political struggle for power in a dynamic population of agents with shifting interests and power. Similarly, a low level of abstraction of formalized concepts facilitates a structured application in qualitative case studies (Ghorbani et al., 2015), promoting the comparison of case studies, as well as a transparent discussion to further improve the MLP. By explicitly incorporating the concept of politics in the MLP two contributions are made to the MLP literature: (1) a political layer is added to the MLP, and (2) temporality is added to the political system by embedding the politics in a broader socio-technical system in which lock-in, institutions and technologies play an important role. The present formalization brings together the fields of sustainability transition studies, political science and ABMS. The result is a dynamic definition of the concept of politics in a social, institutional and technological context. Policy-making directly follows from the political struggle for power and formal decision-making, which dynamically changes over time as stakeholder's interest and power shifts.

Niches and regimes are implicitly included in the formalization, as they are composed of the various MAIA building blocks, but by themselves do nothing (i.e. the niche and regime do not have any power or agency). Rather, it is a selection of agents, institutions and technologies with a certain level of structuration which are labeled as a niche or regime. Landscapes are conceptualized as a collection of external variables. As such, the niche, regime and landscape concepts are useful narrative devices, and play an important role during data analysis and interpretation (Steps 11 through 13 in the mixed-methods process model, Figure 3.6, Section 3.4). The data gathered from the simulation model should be treated similarly to empirical data gathered by directly observing the system. Thus, patterns of social, technical and institutional structuration in simulation outputs can lead to the identification of niches and regimes, which emerge and change over time. The formalized MLP in Chapter 4 does not prespecify a number of niches or regimes, but formalizes the underlying structuration mechanisms. This does not mean that a simulation model implementing the formalized MLP would not be capable of simulating the role of niches and regimes in sustainability transitions. In fact, the formalization allows for more flexibility, while respecting the original conceptualization of the MLP, and without resorting to threshold values as implemented in other conceptual models (Haxeltine et al., 2008).

However, the implementation of the formalized MLP in ABMS is not without its challenges. First, there are few existing models to build on, leading to high initial development costs of the model. Such an exercise also requires a multidisciplinary set of skills, especially when the model is applied to a real case. Second, data requirements can prove to be a limiting factor for the modeling and simulation of the political dimension of the model. Access to experts is not guaranteed, which might lead to low quality input data and unreliable simulation results. While techniques exist to deal with uncertainty, such as sensitivity analysis, the impact of low quality data might completely negate the added value of considering the political dimension. Ideally, policy uncertainty is reduced by a more accurate understanding and representation of likely future policy-scenarios. Third, modeling and simulating discourses remains a challenge. While historical and current discourses can be studied in great detail and used to instantiate the simulation model, the current formalization does not offer a theoretical foundation to simulate the evolution of discourse over multiple decades.

Thus, endogenously determining the political agenda for multiple decades is challenging in the least, and a clear mechanism was not conceptualized or formalized in Chapter 4. While more work is needed on this topic, it also questions the usefulness of the formalized MLP to be used over very long timeframes (multiple decades). Alternatively, efforts focusing on the earlier stages of transitions can greatly contribute to a reduction of uncertainty by ex-ante simulating a distribution of policy-outcomes. Based on the distribution of outcomes, and feedback with the system structures over time, likely future topics on the policy agenda could be determined endogenously. This of course becomes more difficult over longer time periods, and for transitions with ambiguous goals.

Finally, since the formalized MLP has not yet been implemented in a simulation model. Thus, there is currently no reflection on the usefulness of the parsimonious formalization as presented in Chapter 4. The formalized MLP should be used in a variety of cases to determine whether the formalization is useful, whether it has to be extended, or whether it could be complemented with qualitative methods in a mixed-methods design.

5.4 Future research

The following additional research opportunities identified in the three papers are closely connected:

- The selection of most important boundary conditions presented in Chapter 2 contains two sub-sets. For the non-political boundary conditions, the next step in the analysis would be to perform an estimation of their probability distributions together with experts. For the political boundary conditions, a different approach is proposed in Chapter 5 of this thesis, which endogenizes the boundary condition in a policy making process. The approach combines theoretical knowledge of transitions in sociotechnical systems, agent-based modeling and simulation, and a formalization of power, agency and politics.
- The use of simulation in sustainability transition studies, and the incorporation in a mixed-methods design as presented in this article, are encouraged to address new research questions. In particular, studies focusing on future transitions and the refinement of existing frameworks are necessary to advance this field of research further.
- The formalized framework should be implemented to bring ABMS and MLP closer in a simulation study, lowering the barrier for future transition scholars. Such models can facilitate the ongoing discussions to improve the MLP and its formalization, for example through the rigorous testing of hypotheses which are based on the MLP conceptualization or rich case studies.
- Similarly, linking the KAPSARC Toolkit for Behavioral Analysis (KTAB) (Wise et al., 2015) model to socio-technical ABMS for use in sustainability transition studies can lower the barrier to include politics in future simulation studies. It is suggested to continue these efforts in an open-source fashion, providing full insight in the underlying assumptions. Model documentation plays a crucial role in these efforts.

For illustrative purposes a mixed-methods research design is proposed, using the process model presented in Chapter 3 (paper 2). The research question is: What are the uncertainty distributions of the most influential boundary conditions used in Swiss energy transition scenario studies? The research purpose is exploratory. The selected methods are given in Figure 5.1. The research design has both a sequential and parallel phase. The meta-analysis is performed first to inventory the most influential boundary conditions used in Swiss energy transition scenarios. The results of this step are presented in Chapter 2 of this thesis. In the next phase both qualitative methods (expert interviews and focus groups) as well as quantitative methods (agent-based modeling) are used in parallel, looking at a different subset of boundary conditions. The probability distribution of the boundary conditions can be used in the simulation model when the experiments are performed, as this will influence the probability distribution of policy outcomes. The weight of the qualitative and quantitative methods is equal, and the data is mixed during analysis.

While this thesis presents an analysis of the Swiss energy transition, the methodological contributions can be generalized to other systems as well. The generalizability is guaranteed by building on the multi-level perspective, which has been extensively applied to various systems at varying levels of analysis. Furthermore, to ensure its generalizability, the mixed-methods process model draws on the broad sustainability transitions literature, general mixed-methods literature and simulation literature. The meta-analysis, as presented in this thesis using System Dynamics simulation, is more likely confined to sustainability transitions with an underlying infrastructure system. Regardless, the method could be applied to energy transitions in other countries and to different infrastructure systems such as water, transport and waste.

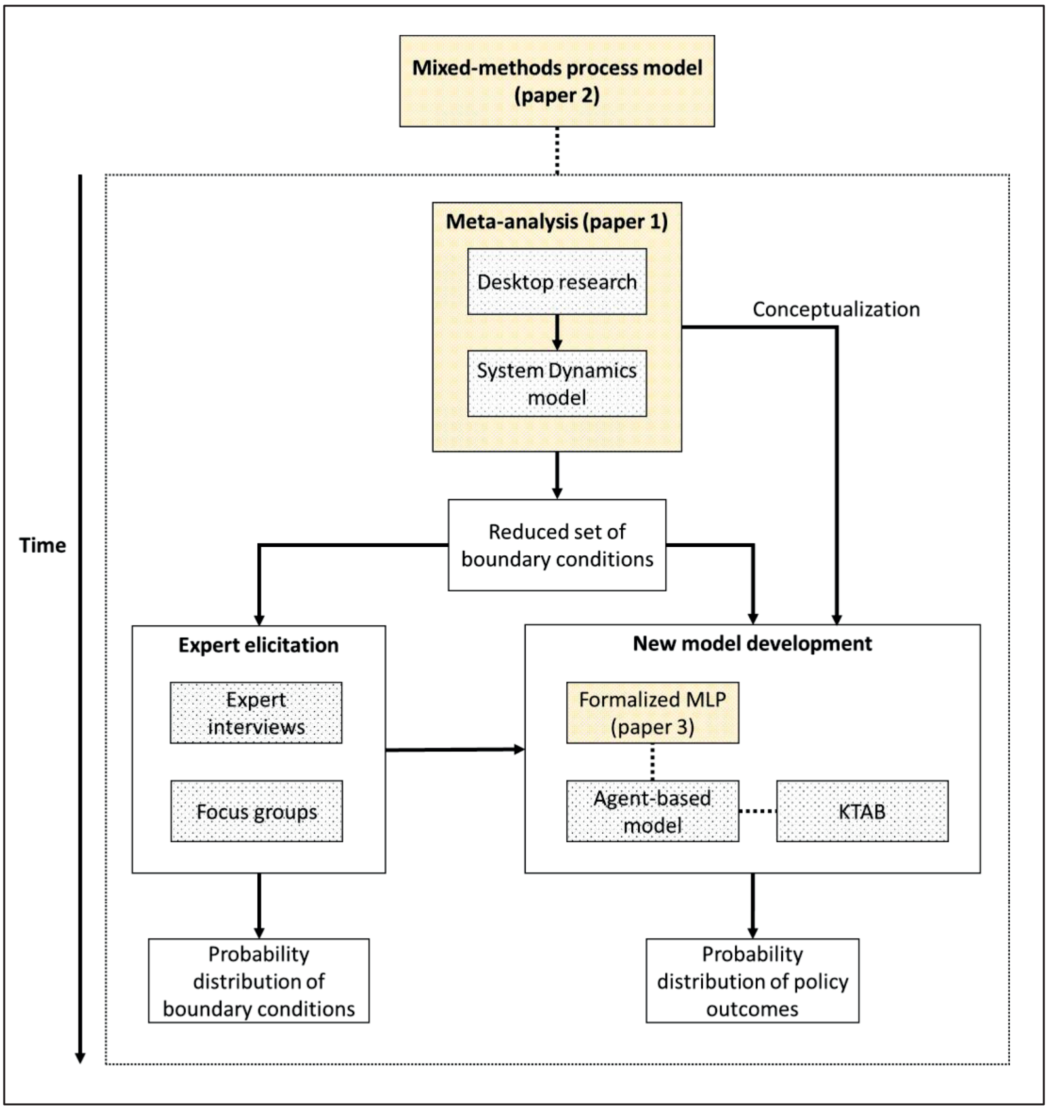

Figure 5.1 Example mixed-methods research design.

A. Appendix: model boundary conditions

Table A.1 Boundary conditions with annual values. Linear interpolation is used between reported values. In case necessary, the values reported in the scenario studies were converted to match the units reported in this table by the author.

Boundary condition	Unit	Unique boundary condition values	2015	2020	2025	2030	2035	2040	2045	2050
Yearly electricity demand	TWh	SFOE WWB	64.9	68.7		70.4	71.5	71.5		73.9
		SFOE NEP	63.4	65.8		62.9	62.2	60.1		57.9
		SFOE POM	63.6	66.0		64.8	65.0	64.4		65.7
		VSE Scenario 1	62.1	64.5	66.7		70.6			75.0
		VSE Scenario 2	62.2	64.3	65.8		67.4			67.7
		VSE Scenario 3	62.0	63.6	64.3		63.1			56.0
		Greenpeace [R]	61.1	62.0		61.1		63.0		63.0
		ETHZ Hoch	63.0	67.6			75.9			85.2
		ETHZ Mittel	61.6	64.8			69.4			73.1
		ETHZ Tief	60.2	62.0			61.1			61.1
Waste burning installed capacity	MW	SFOE	203	203	203	203	203	203	203	203
		Greenpeace	10	30		30		100		200
RES CHP installed capacity	MW	SFOE	249	164	152	90	37	2	1	1
		VSE	56	56	56	56	56	56	56	56
		GREENPEACE	276	427		769		871		942
Other thermal installed capacity	MW	SFOE	0	0	0	0	0	0	0	0
		PSI-ELC	522	522	522	522	522	522	522	522
		GREENPEACE	320	320		310		200		200
		UNIL	760	760	760	760	760	760	760	760
Available FR import contracts	MW	SFOE	2500	1500	1300	500		200	0	0
		VSE	2688	1920	1664	1407	640	0	0	0
Hydro reservoir installed capacity	MW	SFOE C-variant	8200							8485
		SFOE CE/E-variant	8200							9316
		VSE S1	8200	8200	8300		8400			8600
		VSE S2	8200	8300	8400		8600			8900
		VSE S3	8200	8300	8500		8700			9100
		UNIL	8420							8420
		GREENPEACE	8200							8080
Nuclear installed capacity	MW	40 years	3278	1190	0	0	0	0	0	0
		45 years	3278	2905	1190	0	0	0	0	0
		50 years	3278	2905	2175	1190	0	0	0	0
		60 years	3278	2905	2905	2175	2175	1190	0	0
		UNIL NUCind	3278	2905	2905	2540	2175	2175	2175	2175
	GW	SFOE C-variant	0.25	0.36		1.02	2.67	3.68		6.26

Boundary condition	Unit	Unique boundary condition values	2015	2020	2025	2030	2035	2040	2045	2050
Solar installed capacity		SFOE CE/E-variant	0.35	0.55		2.02	4.70	7.13		11.76
		VSE S1	0.10	0.20	0.30		0.90			3.70
		VSE S2	0.10	0.30	0.50		1.50			8.90
		VSE S3	0.20	0.30	0.60		2.10			14.90
		UNIL	0.76	4.11			13.54	-------ENDOGENOUS-------		
		GREENPEACE	0.70	3.40		15.00		17.00		19.00
		Others (market)	---------------------------------------ENDOGENOUS---------------------------------------							
Wind installed capacity	MW	SFOE C-variant	60	90		360		645		895
		SFOE CE/E-variant	210	420		925		1640		2700
		VSE S1	0	100	300		500			1200
		VSE S2	100	200	400		700			1900
		VSE S3	100	300	500		900			2500
		UNIL	60	279			919	-------ENDOGENOUS-------		
		GREENPEACE	400	600		2000		2200		2300
		Others (market)	---------------------------------------ENDOGENOUS---------------------------------------							
CHP initial installed capacity	MW	SFOE	525	380	270	180	95	0	0	0
		VSE; UNIL	0	0	0	0	0	0	0	0
		VSE (O4)	100	100	100	100	100	100	100	100
		VSE (O6); PSI-ELC	200	200	200	200	200	200	200	200
		GREENPEACE	400	500		500		300		100
Geothermal installed capacity	MW	VSE S1	0				0			200
		VSE S2/S3	0				100			400
		GREENPEACE	20	30		100		500		700
		Other	0	0	0	0	0	0	0	0
Pump installed capacity		VSE	1800	4000	4000		4000			4000
		UNIL	1500							3400
ROR installed capacity	MW	SFOE C-variant	3800				4520			4940
		SFOE CE/E-variant	3800				5200			6200
		VSE S1	3600	3700	3800		3800			4000
		VSE S2	3600	3800	3800		4000			4200
		VSE S3	3600	3800	4000		4200			4400
CCGT investment costs	CHF/kW	VSE; UNIL	1015			1015				1015
		PSI-ELC; PSI-SYS	1150			1050				1050
		ETHZ	1752			1752				1752
CCGT firing efficiency	%	VSE; UNIL	52.0	53.0	53.0		54.0			54.0
		PSI-ELC; PSI-SYS	58.0			63.0				65.0
		ETHZ	58.0	58.0	58.0	58.0	58.0	58.0	58.0	58.0
Natural gas price	CHF/MWh	VSE; UNIL	25.2	25.7	26.9		35.0			36.4
		PSI-ELC	44.5							67.0
		GREENPEACE	53.0	62.5	67.9			83.0		98.2
		PSI-SYS	32.4	39.6		46.8		46.8		50.4
Carbon price	CHF/ton	SFOE-POM	20.0	39.5		47.8	52.0	55.1		58.2
		SFOE-NEP	23.8	46.8		109.2	124.8	135.2		142.5
		VSE; UNIL	23.0	30.2	39.89		65.2			65.2
		GREENPEACE	13.8	23.8		37.5		52.5		71.3
Solar investment cost	CHF/kW	VSE; UNIL	3300	2600	2300		2000			1500
		PSI-ELC	4750			2850				1950

Boundary condition	Unit	Unique boundary condition values	2015	2020	2025	2030	2035	2040	2045	2050
		GREENPEACE	2166	1558		1209				981
		PSI-SYS	5588	4675	3763	2850	2625	2400	2175	1950
Solar FOM	CHF/kW	VSE; UNIL	33.0	26.0	23.0		20.0			15.0
		PSI-ELC; PSI-SYS	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
		GREENPEACE	36.3	20.0		13.8		13.8		13.8
Wind investment cost	CHF/kW	VSE	2100	2000	1900		1860			1770
		PSI-ELC	1950			1750				1750
		UNIL	2100	200	1900		1860			1770
		GREENPEACE	1406	1219		1209		1215		1270
		PSI-SYS	2050	1950	1850	1750	1750	1750		1750
Wind FOM	CHF/kW	VSE; UNIL	4.2	4.0	3.8		3.7			3.5
		PSI-ELC	3.6			2.8				2.8
		GREENPEACE	5.3	5.2		5.3		5.5		5.8
		PSI-SYS	4.0	3.6	3.2	2.8				2.8
Wind VOM	CHF/MWh	VSE; UNIL	0	0	0	0	0	0	0	0
		PSI-ELC	41.0			32.0				32.0
		PSI-SYS	46.0			32.0				32.0
CHP investment costs	CHF/kW	VSE; UNIL	2500							2500
		PSI-ELC	2560			2100				2100
		ETHZ	1099							1099
		PSI-SYS	1350			1260				1260
CHP VOM	CHF/MWh	VSE; UNIL	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0
		PSI-ELC	9.3			6.9				6.9
		ETHZ	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2
		PSI-SYS	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0
CHP firing efficiency	%	VSE; UNIL	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35
		PSI-ELC	32.0			42.0				42.0
		PSI-SYS	56.0			58.0				60.0
CHP heat income	CHF/MWh	VSE; UNIL	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
		PSI-ELC; PSI-SYS	--ENDOGENOUS--							
Spot price	CHF/MWh	BFE C/CE-variant	58.5	59.0		60.0	53.0	53.0		53.0
		BFE E-variant	58.5	59.0		76.0	107.0	113.0		134.0
		UNIL DE-AT	48.2	48.2	48.2	48.2	48.2	48.2	48.2	48.2
		UNIL FR	54.1	54.1	54.1	54.1	54.1	54.1	54.1	54.1
		UNIL IT	82.5	82.5	82.5	82.5	82.5	82.5	82.5	82.5
Total NTC	GW	UNIL	7.5	10.0	10.0	10.0	10.0	10.0	10.0	10.0

Table A.2 Boundary conditions with seasonal values. A step-function is used to implement the seasonal availability. In case necessary, the values reported in the scenario studies were converted to match the units reported in this table by the author.

Boundary condition	Unit	Unique boundary condition values	Winter	Spring	Summer	Fall
Nuclear seasonal availability	%	SFOE	87.0	87.0	87.0	87.0
		VSE	100.0	89.0	70.0	89.0
		PSI-ELC	95.0	68.0	68.0	95.0

Table A.3 Boundary conditions with constant values. In case necessary, the values reported in the scenario studies were converted to match the units reported in this table by the author.

Boundary condition	Unit	Unique boundary condition values	Value
CCGT initial installed capacity	MW	SFOE; PSI-ELC; Greenpeace	0
		VSE	400
		VSE (Option 4)	600
		UNIL	89
Transmission losses	%	SFOE; PSI-ELC; ETHZ	7.0
		UNIL	8.0
Nuclear price	CHF/MWh	VSE	9.2
		PSI-ELC	16.1
		UNIL	10.0
		ETHZ	10.1
CCGT switch	Dmnl	UNIL; PSI-ELC Gas-X; SFOE C&C/E-variants; VSE (S1, S2, O4, O5, O7); ETHZ; PSI-SYS	1
		Others	0
CCGT average size	MW	SFOE; PSI-ELC	550
		UNIL	600
		ETHZ	480
CCGT lead time	Year	VSE; UNIL; Greenpeace; ETHZ	2
		PSI-ELC	3
CCGT lifetime	Year	VSE; UNIL; ETHZ	30
		PSI-ELC; PSI-SYS	25
CCGT FOM	CHF/kW	VSE; UNIL	42.0
		PSI-ELC; PSI-SYS	8.0
CCGT VOM	CHF/MWh	VSE; UNIL	2.6
		PSI-ELC; PSI-SYS	24.1
		ETHZ	8.5
CO_2 content natural gas	tCO_2/MWh	SFOE; PSI-ELC	0.2
		VSE; UNIL	0.2
Hydro reinvestment	Dmnl	PSI-ELC	1
		Others	0
Hydro reservoir lead time	Year	VSE	10
		PSI-ELC	3
		GREENPEACE	2
Solar VOM	CHF/MWh	VSE; UNIL	0
		PSI-ELC	2.0
		PSI-SYS	2.2
Solar lifetime	Year	VSE; UNIL	20
		PSI-ELC; ETHZ	35
		PSI-SYS	40
Solar availability factor	%	VSE	11.0
Wind lifetime	Year	VSE; PSI-ELC; UNIL	20
		ETHZ	35
Wind availability factor	%	VSE; UNIL	18.0
		PSI-ELC;PSI-SYS	14.0
CHP investment allowed	Dmnl	UNIL; PSI-ELC IMP-X; Greenpeace	0
		Others	1

Boundary condition	Unit	Unique boundary condition values	Value
CHP FOM	CHF/kW	VSE; UNIL	25.0
		PSI-ELC	0
		PSI-SYS	12.0
CHP lifetime	Year	VSE; PSI-ELC; UNIL	20.0
		PSI-SYS	25.0
NTC CH to DE-AT	MW	VSE	5100
		PSI-ELC	5600
NTC CH to FR	MW	VSE	1800
		PSI-ELC	2800
NTC CH to IT	MW	VSE	3800
		PSI-ELC	4700
NTC DE-AT to CH	MW	VSE	2800
		PSI-ELC	6800
NTC FR to CH	MW	VSE	3100
		PSI-ELC	3200
NTC IT to CH	MW	VSE	1600
		PSI-ELC	1900

B. Appendix: uncertainty analysis results

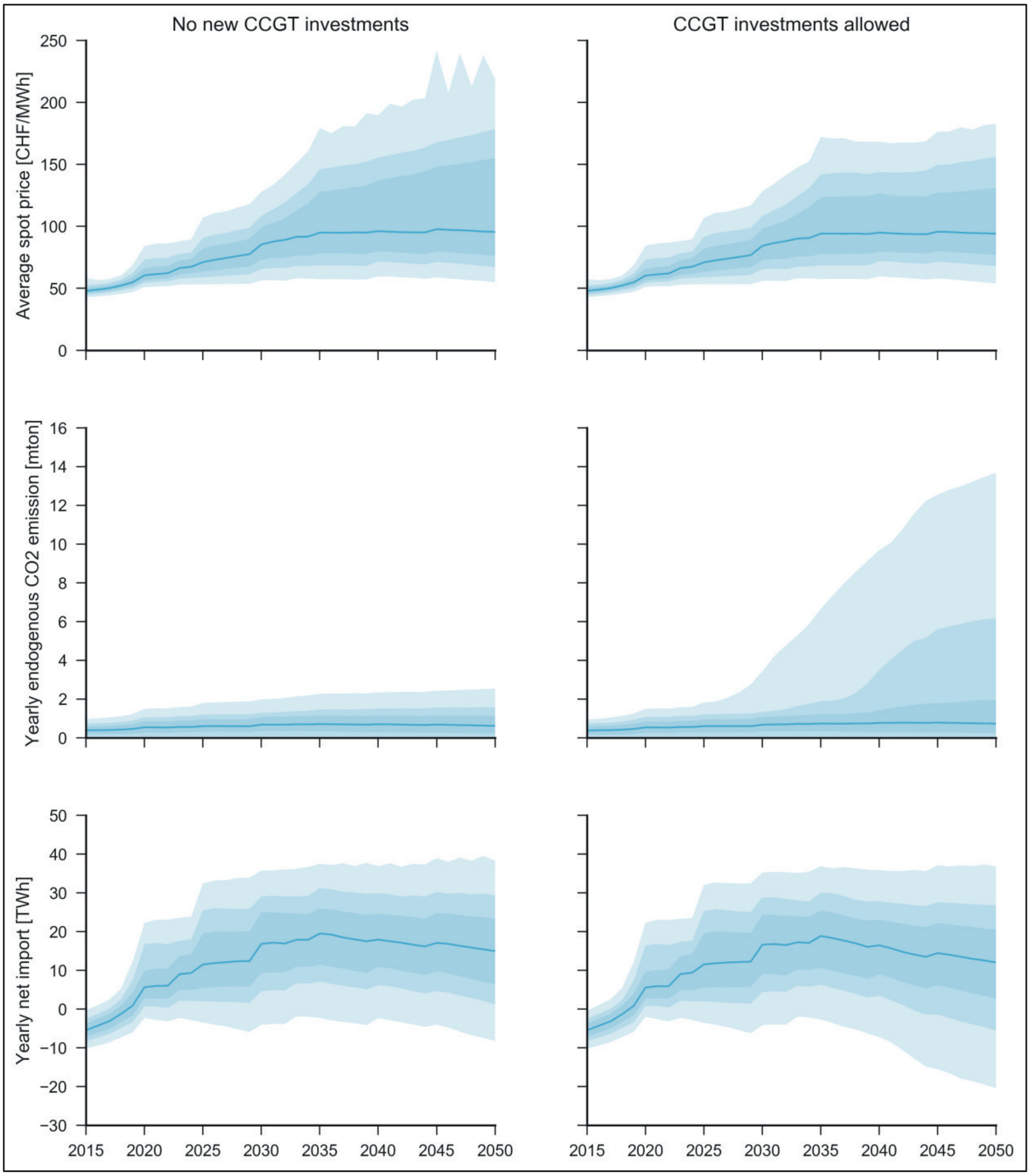

Figure B.1 Uncertainty analysis: CCGT investments boundary condition. The blue line represents the modeled average values. The blue shaded areas respectively represent 50%, 75% and 95% of the EPFL-MIR simulation outputs.

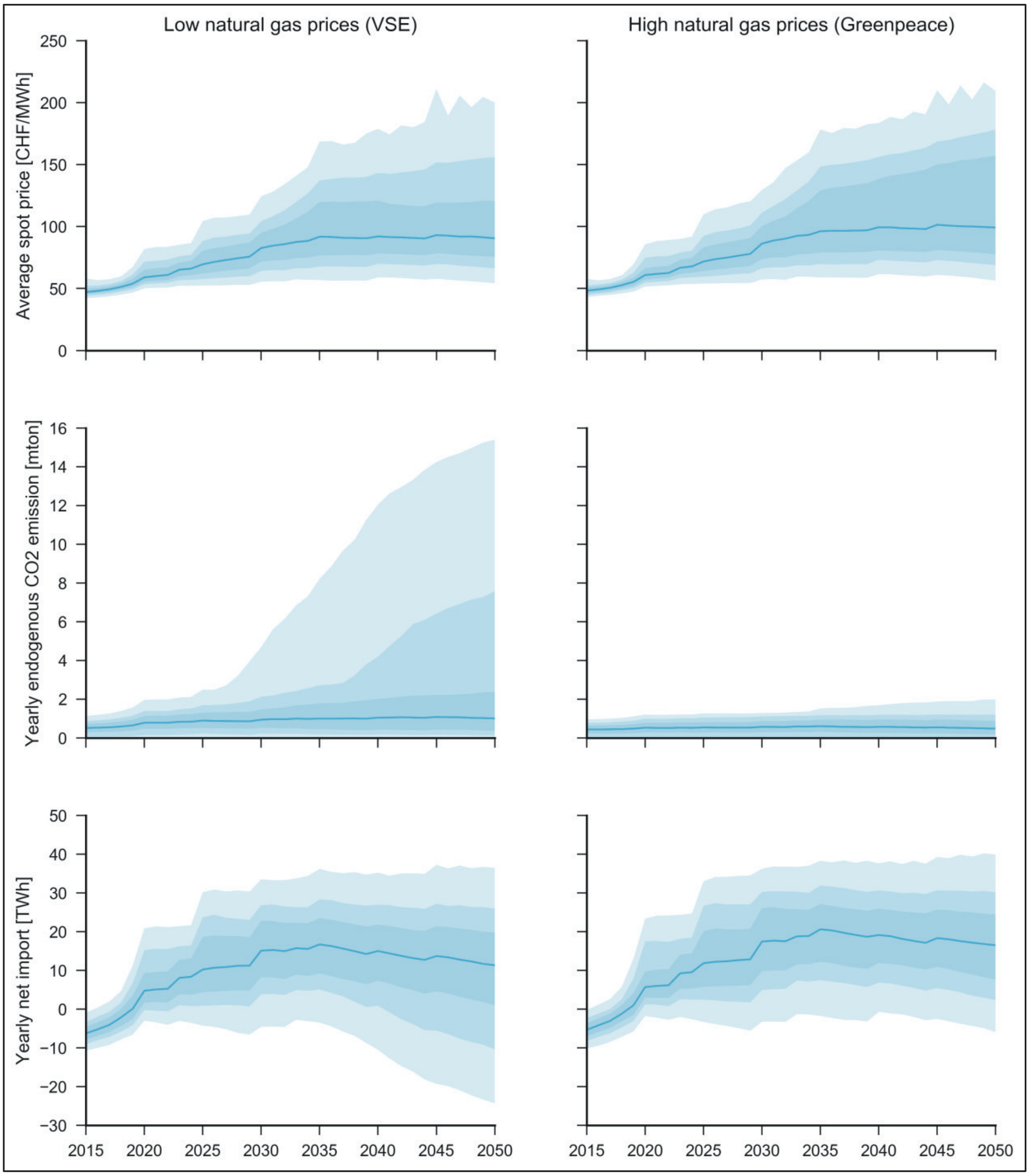

Figure B.2 Uncertainty analysis: natural gas price boundary condition. The blue line represents the modeled average values. The blue shaded areas respectively represent 50%, 75% and 95% of the EPFL-MIR simulation outputs.

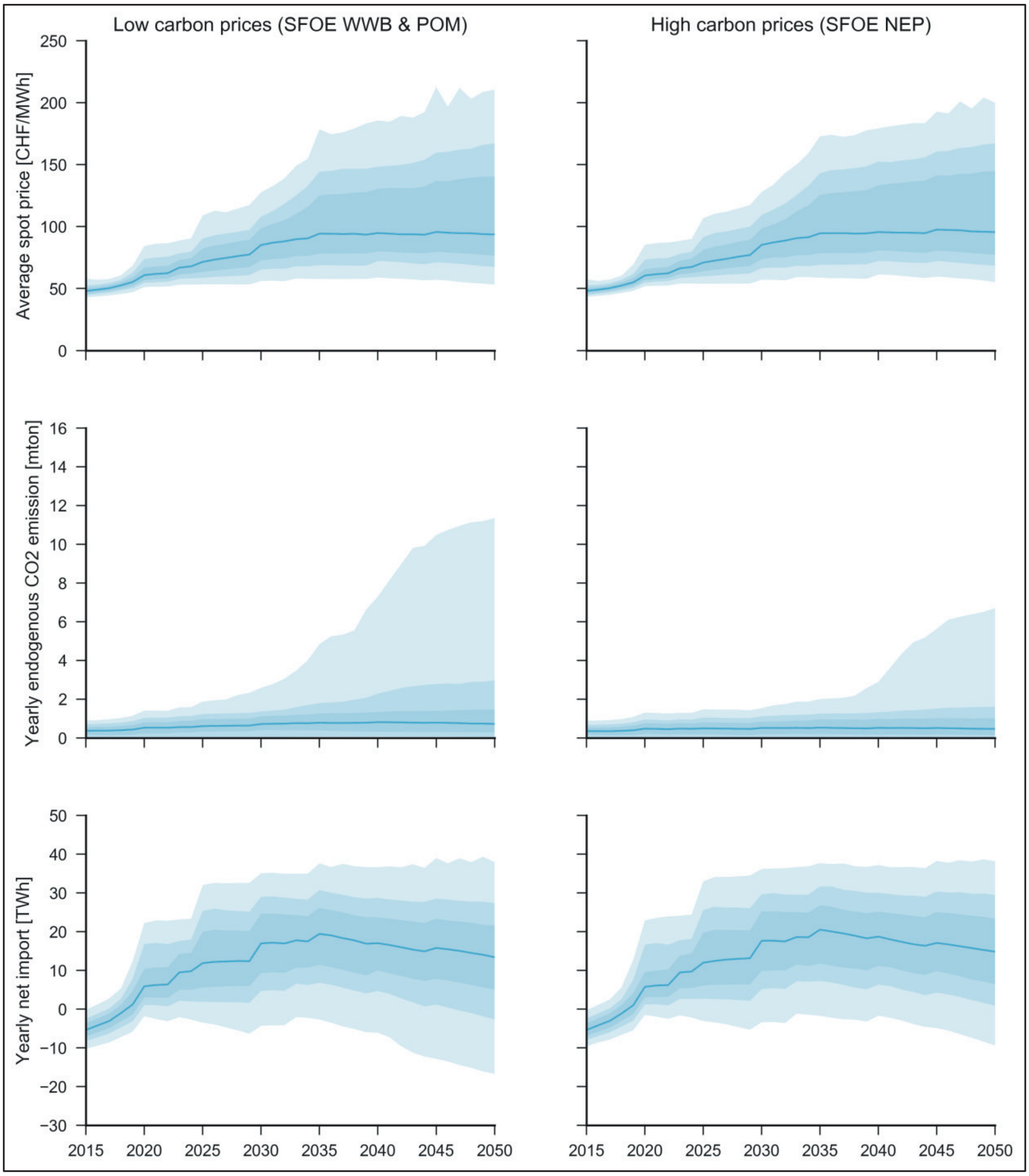

Figure B.3 Uncertainty analysis: carbon price boundary condition. The blue line represents the modeled average values. The blue shaded areas respectively represent 50%, 75% and 95% of the EPFL-MIR simulation outputs.

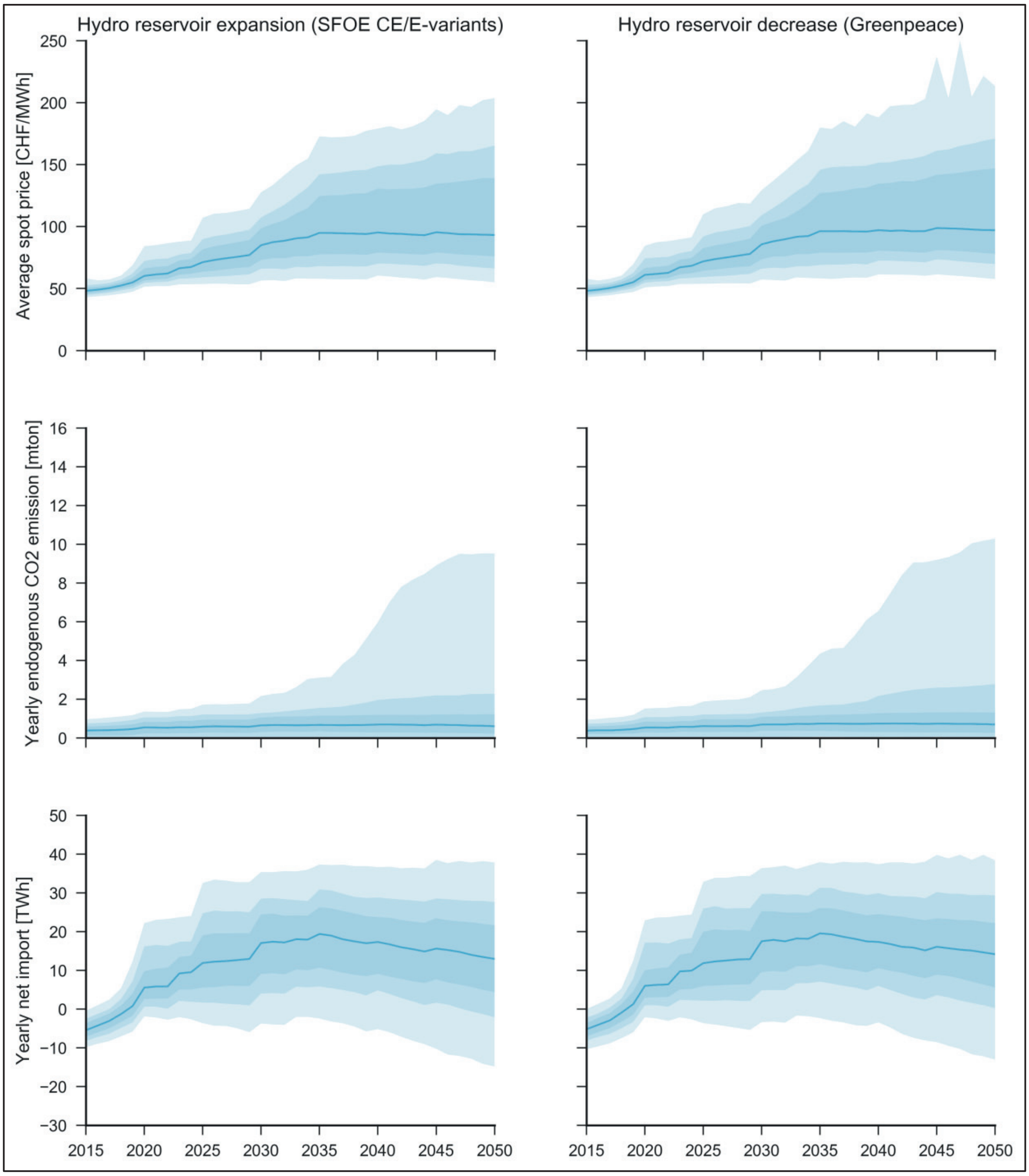

Figure B.4 Uncertainty analysis: hydro reservoir capacity boundary condition. The blue line represents the modeled average values. The blue shaded areas respectively represent 50%, 75% and 95% of the EPFL-MIR simulation outputs.

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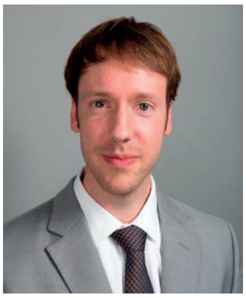

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Education

06/2014 – 03/2018	**PhD in Management of Technology**, ***École Polytechnique Fédérale de Lausanne,*** *Switzerland* ▪ Thesis: “Three methodological contributions towards modelling endogenous policy-emergence in societal transitions”
09/2011 – 09/2013	**MSc. Systems Engineering, Policy Analysis & Management**, ***Delft University of Technology****, the Netherlands* ▪ Thesis: “Exploring biogas stakeholder interaction in the Netherlands: An Agent Based Modelling approach”
09/2008 – 08/2011	**BSc. Systems Engineering**, **Policy Analysis & Management (with distinction)**, ***Delft University of Technology****, the Netherlands*

Research

Peer reviewed journal publications

Verhoog, R., Ghorbani, A., & Dijkema, G. P. J. (2016). Modelling socio-ecological systems with MAIA: A biogas infrastructure simulation. *Environmental Modelling & Software*, *81*, 72-85. (Impact Factor: 4.404)

Verhoog, R., Ghorbani, A., Hardi, E. E., Dijkema, G. P. J., & Weijnen, M. P. (2016). Structuring socio-technical complexity in infrastructure systems: an agent-based model. *International Journal of Complexity in Applied Science and Technology*, *1*(1), 5-21.

Peer reviewed book chapters

Verhoog, R., van Baal, P. A. & Finger, M. (forthcoming). System Dynamics Simulation to Explore the Impact of Low European Electricity Prices on Swiss Generation Capacity Investments. In A. Dorsman, V. A. Ediger, & M. B. Karan (Eds.), Energy Economy, Finance and Geostrategy - A Geo-Economic Perspective. Springer.

Verhoog, R. & Finger, M. (2016). Governing Energy Transitions: Transition Goals in the Swiss Energy Sector. In A. Dorsman, Ö. Arslan-Ayaydin, & M. B. Karan (Eds.), Energy and Finance: Sustainability in the Energy Industry (pp. 107–121). Springer.

Book reviews

Verhoog, R. (2015). Book Review: Multi-Level Regulation in the Telecommunications Sector: Adaptive Regulatory Arrangements in Belgium, Ireland, the Netherlands and Switzerland.

Verhoog, R. (2015). Book Review: Roehrkasten, S., Global Governance on Renewable Energy.

Verhoog, R. (2014). Book Review: Renewable Energy Governance. Lecture Notes in Energy.

Working papers

Verhoog, R. *Mixed-methods in sustainability research: a comprehensive literature review and process model*. (Revise and resubmit at the Environmental Innovation and Societal Transitions journal).

Verhoog, R. *Meta-analysis of Swiss energy transition scenarios using System Dynamics simulation*. Target journal: Energy Policy.

Verhoog, R. *Formalizing the multi-level perspective with concepts of power, agency and politics*. Target journal: Environmental Innovation and Societal Transitions.

van Baal, P. A. & Verhoog, R. *Not if, but when? Simulating the impact of timing the nuclear phase-out in Switzerland*. Target journal: Energy Policy.

Peer reviewed conference proceedings

Verhoog, R., Ghorbani, A., Dijkema, G. P. J. & Lukszo, Z. (2015). Transmission Capacity as a Common-Pool Resource: The Case of Gas Interconnector Capacity. In: Dolan, T. & Collins, B., (eds.) *International Symposium for Next Generation Infrastructure Conference Proceedings*, 30 September - 1 October 2014, International Institute of Applied Systems Analysis (IIASA), Schloss Laxenburg, Vienna, Austria.

Verhoog, R., Ghorbani, A., Dijkema, G. P. J. & Weijnen, M. P. C. (2014). Structuring Socio-Technical Complexity in Infrastructure Systems: The Biogas System. In: Campbell P. & Perez P. (Eds), *Proceedings of the International Symposium of Next Generation Infrastructure*, 1-4 October 2013, SMART Infrastructure Facility, University of Wollongong, Australia.

White papers

van Bloemendaal, K., Dijkema, G. P. J., Özdemir, Ö., Woerdman, E., Lukszo, Z., Bas, G., Chappin, E. J. L., Davis, C. B., van Hout, M., Jong, T., de Joode, J., Kiewiet, B., Kooshknow, A. & Verhoog, R. (2015). *White Paper on Modelling*. Groningen: EDGaR (Energy Delta Gas Research).

Teaching experience

02/2017 – ongoing

Lecturer Certificate of Advanced Studies in Governing Energy Transitions, ***École Polytechnique Fédérale de Lausanne****, Switzerland*

- Topics: Simulating energy transitions; Complex Adaptive Systems.
- **2017 teaching evaluation: 4.4/5.0**

03/2015 – ongoing

Program Manager Governing Energy Transitions, ***École Polytechnique Fédérale de Lausanne***, *Switzerland*

- Curriculum development Executive Education program for Swiss energy managers.
- Website: www.energy-transition.ch

10/2017

Teaching Toolkit workshop, ***École Polytechnique Fédérale de Lausanne***, *Switzerland*

01/2015 – 08/2016

Teaching assistant, ***École Polytechnique Fédérale de Lausanne***, *Switzerland*

- MSc. course: Leadership and Human Resource Management in a Global Context.

07/2009 – 02/2013

Teaching assistant, ***Delft University of Technology***, *the Netherlands*

- MSc. course: Engineering & Policy Analysis (workshops & project supervision).
- BSc. course: Introduction to policy analysis (course & exam).
- BSc. course: Mini-projects related to policy analysis (project supervision).
- Mentoring of first-year BSc. and MSc. students.

Supervision activities

2016

MSc. Thesis supervision, ***École Polytechnique Fédérale de Lausanne***, *Switzerland*

- van Baal, P. A. (2016). *Business implications of the energy transition in Switzerland*. In collaboration with BKW.

- Jiménez, A. N. (2016). *The influence of bottlenecks on firms' collaboration patters in innovation ecosystems*. In collaboration with ETHZ SusTec.

2014 – 2016	**MSc. Project supervision**, ***École Polytechnique Fédérale de Lausanne***, *Switzerland* - Topics: energy transition, politics and system dynamics modelling. - A total of 9 MSc. Semester projects of 10 ECTS each.

Professional grants and awards

2017	**Coordinated the successful EPFL-CDM (450,000 CHF) grant application**, *SCCER-CREST*
2017	**Award for exceptional professional performance (2,000 CHF)**, *École Polytechnique Fédérale de Lausanne*, *College of Management*
2015	**Main grant applicant (CHF 200,000)**, *Swiss Federal Office of Energy* - Executive Education to support the Swiss Energy Strategy 2050.
2014	**2nd place Dutch Gas Industry Prize**, *Royal Holland Society of Sciences and Humanities* - Bi-annual MSc. Thesis award in the Netherlands.

Administrative positions

06/2017 – ongoing	**Search committee member**, ***École Polytechnique Fédérale de Lausanne***, *College of Management of Technology*
09/2014 – ongoing	**Advisory Editor**, ***Competition and Regulation in Network Industries journal***
02/2016 – 10/2017	**PhD representative**, ***École Polytechnique Fédérale de Lausanne***, *College of Management of Technology*
06/2016 – 04/2017	**Organizing Committee member**, ***2nd PhDs in transition conference*** - 27-28 April 2017, *École Polytechnique Fédérale de Lausanne*, Switzerland

Academic presentations

Verhoog, R. (2017). *Meta-analysis of Swiss energy transition scenarios: A System Dynamics simulation approach.* 4th Annual SCCER-CREST Conference, September 12, 2017, St. Gallen, Switzerland.

Verhoog, R. (2017). *Formalizing the multi-level perspective with concepts of power, agency and politics*. 8th International Sustainability Transitions Conference, June 18-21, 2017, Gothenburg, Sweden.

Verhoog, R., van Baal, P. A. & Finger, M. (2017) *System Dynamics Simulation to Explore Impact of Low European Electricity Prices on Swiss Generation Capacity Investments*. 6th Multinational Energy and Value Conference, May 18-20, 2017, Guzelyurt, Northern Cyprus.

Verhoog, R. & Paramonova, E. (2016). *Influence of political power on the outcomes of the Swiss energy transition*. 3rd Energy and Society Conference, September 12-14, 2016, Leipzig, Germany.

Verhoog, R. (2016). *A mixed-methods framework for studying transitions in infrastructure systems*. 1st PhDs in transition conference, April 28-29, University of Greenwich, London, United Kingdom.

Verhoog, R. (2016). *A mixed-methods framework for studying transitions in infrastructure systems*. SAEE-SCCER CREST conference, February 26, 2016, Lausanne, Switzerland.

Verhoog, R., Armada, K., van Baal, P. A., El Dabbak, G. & Jiménez, A. N. (2015). *Modelling and simulation of renewable energy transitions: nuclear phase-out in Switzerland*. International Symposium of Next Generation Infrastructure, 14 – 15 September 2015, Virginia Tech, Washington D.C., USA.

Verhoog, R. & Finger, M. (2015). *Energy systems in transition: changing roles, power and agency of key stakeholders in the Swiss electricity market*, The International Conference on Public Policy, July 1-4, 2015, Milan, Italy.

Verhoog, R. & Finger, M. (2015). *Energy systems in transition: changing roles, power and agency of key stakeholders in the Swiss electricity market*, 5th Multinational Energy and Value Conference, May 7-9, 2016, Istanbul, Turkey.

Verhoog, R., Ghorbani, A., Dijkema, G. P. J. & Lukszo, Z. (2014). *Transmission capacity as a Common-Pool Resource: the case of gas interconnector capacity*. International Symposium of Next Generation Infrastructure, 30 September – 1 October 2014, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

Professional memberships

Sustainability Transitions Research Network (STRN)

Network of Early Career Researchers in Sustainability Transitions (NEST)

Work experience

12/2013 – 05/2014 **Junior Researcher**, ***Delft University of Technology***, *Delft, the Netherlands*

- Created an evolutionary agent-based model to study intra- and inter-market capacity booking and trading interactions in the European gas sector.

12/2011 – 12/2012 **Project leader**, ***Alliander***, *Arnhem, the Netherlands, part-time*

- Developed an online social energy game with a project budget of €50.000.

Extracurricular activities

11/2011 – 03/2012 **President at Ocean Thermal Energy Conversion Foundation,** *Delft, the Netherlands*

06/2011 – 11/2011 **President**, ***TEDxDelft Award***, *Delft, the Netherlands*

- Organized the first edition with great success, resulting in a repeat event and additional side-event for TEDxDelft.

Skills

Simulation software	Arena, Netlogo, Powersim, Vensim
Statistical software	SPSS, R
Programming	Python

Languages

	Speaking	Reading	Writing
Dutch	Native	Native	Native
English	Fluent (C2)	Fluent (C2)	Fluent (C2)
German	Intermediate (B1)	Proficient (C1)	Intermediate (B2)
French	Basic (A2)	Intermediate (B1)	Basic (A2)