3rd International Conference on Public Policy (ICPP3)

June 28-30, 2017 – Singapore

Panel T01P06 Session 2

Designing Policy Mixes for Sustainable Socio-technical Transitions

Title of the paper

Towards a comprehensive policy for electricity from renewable energy: A Structured Design Approach

Author(s)

Kaveri Iychettira, Delft University of Technology, Netherlands,k.k.iychettira@tudelft.nl

Rudi Hakvoort, Delft University of Technology, Netherlands,r.a.hakvoort@tudelft.nl

Pedro Linares, Comillas Pontifical University, Spain, pedro.linares@comillas.edu

<u>Date of presentation</u>

June 28th 2017

This paper has been published in the journal Energy Policy, and can be cited as follows:

Kaveri K. Iychettira, Rudi A. Hakvoort, Pedro Linares, *Towards a comprehensive policy for electricity from renewable energy: An approach for policy design*, **Energy Policy**, Volume 106, July 2017, Pages 169-182, ISSN 0301-4215, https://doi.org/10.1016/j.enpol.2017.03.051.

(http://www.sciencedirect.com/science/article/pii/S0301421517302057)

Keywords: Institutional analysis; IAD framework; Policy design; Renewable energy policy; RES-E support

Towards a comprehensive policy for electricity from renewable energy: An Approach for Policy Design

Kaveri K. Iychettira[a,b,*], Rudi A. Hakvoort[a], Pedro Linares[b]

[a] *Delft University of Technology, The Netherlands*
[b] *Comillas Pontifical University, Spain*

Abstract

Energy policy design in Europe is a complex issue involving multiple levels of governance, and heavily influenced by institutional contexts. However policy design in Europe, and model-based analysis even more so, is arguably shaped by the neo-classical school of thought. There is a need to provide a structured approach that would facilitate the incorporating of institutional contexts into Renewable Energy Sources for Electricity (RES-E) policy design and analysis. This paper presents a formal approach to RES-E policy design based on Design Theory, the Institutional Analysis and Development (IAD) Framework, and Agent Based Modelling and Simulation. Given a certain frame of analysis, we propose that it is theoretically possible to identify the complete policy design space, a set of design elements. Crucially, this aspect potentially opens up to the policy analyst new avenues for intervention, and allows her systematically explore, given a range of uncertainties, which element(s) of intervention is(are) the most vital to achieve the goals of the community. Its empirical applicability is demonstrated by representing and differentiating between six RES-E schemes from Western Europe in terms of the design elements; a model-based illustration demonstrates the value of this approach to quantitatively analyse the impact of design elements.

Keywords: institutional analysis, IAD framework, policy design, renewable energy policy, RES-E support

1. Introduction

1.1. Background: RES-E Policy Analyses So Far and Problem Definition

Energy policy design and analysis, especially in relation to the incentivising of renewable energy, is arguably dominated by the neo-classical school of thought,

*Contact corresponding author at Address: Jaffalaan 5, 2628 BX Delft; email: k.k.iychettira@tudelft.nl; phone: +31685615932

at least in Europe. This is evident in the guidelines for incentivising Renewable Energy Source from Electricity (RES-E) by the European Commission, called the State Aid Guidelines, which primarily urge that all renewable support take the form of competitive bidding, see for instance European Commission (2014). In literature, general equilibrium models and optimization models are the preferred tools. Capros et al. (2014) for instance, offer detailed descriptions of seven EU energy economy models of decarbonisation pathways. Some of the most cited models of RES-E schemes specifically, have been given by Huber et al. (2004), Voogt et al. (2001), Most and Fichtner (2010), and Fais et al. (2014). The outcomes of these models however, depend heavily on underlying assumptions about reality; assumptions of perfect market conditions and perfect information being some of them. A recent controversy regarding the use of equilibrium models for informing policy decisions like EU energy efficiency targets questions their applicability to policy-making; see Riley (2015). The important question to be addressed here, is whether these perspectives and tools are sufficient to help achieve the goals the EU has set for its energy sector - competition, affordability, and sustainability.

The outcomes of a certain policy depend on far more than variables such as price and quantity. They depend on the explicit or implicit institutions, which may be part of the policy, or part of the environment surrounding the policy, that shape the socio-technical system. As Polski and Ostrom (1999) point out, "Institutions delimit the capacity for social change. They are important because they are intentional constructions that structure information and create incentives ...thereby imposing constraints on the range of possible behaviour and feasible reforms." This makes institutional analysis paramount in the study of policy design. In addition, such analyses lend to the policy maker, in a structured fashion, a set of policy design characteristics, with which to operate on the socio-technical system. The challenge then lies in identifying the most essential design characteristics of a policy or set of policies, which are sufficiently informed by their institutional setting, and evaluating their impacts on the socio-technical system.

Some studies have tried to incorporate a more comprehensive approach to RES-E policy design, see for instance work by Bergmann et al. (2008), and Batlle et al. (2012a). Most literature uses a "policy analysis approach" where comparisons, and categorizations are made between and across different *existing policies*; for examples refer to Batlle et al. (2012b), Kitzing et al. (2012), Kitzing (2014), and Fagiani et al. (2013). It is proposed here however, that the basic unit of analysis is not the policy itself, but a set of "design elements". Design elements refer to the detailed components that make up a certain policy, for instance, technology specificity, location specificity, duration of support etc. Two seemingly different RES-E support policies can be designed such that they have an equivalent effect on the market. This idea has been upheld by several authors such as Batlle et al. (2012a), del Rio and Linares (2014), del Rio and Mir-Artigues (2014), and Haas et al. (2011). However, they have been empirical observations, rather than a formal approach to policy design.

1.2. Research Objective

The primary objective of this research is to introduce a formal, structured approach to the design of policies for the stimulation of RES-E in Europe. To achieve this we decompose the objective into the following sub-objectives: (1) to identify a set of necessary and sufficient policy design elements to incentivise RES-E in Europe, and (2) to introduce a modelling framework to analyze the impact of the policy design elements on the socio-technical system.

In order to accomplish the above sub-objectives we introduce a formal method based on design theory and institutional analysis to identify a policy design space, i.e., a set of necessary and sufficient design variables that we term, 'design elements'. These design elements are identified for a certain level of analysis[1], and for a selected set of participants in the socio-technical system. Following this, a modelling framework to facilitate the analysis of the design elements, and identify the impact of each individual design variable on the socio-technical system. The modelling framework is implemented using agent-based modelling and simulation. Such a formal approach would not only help analyse existing policies and their impact on the socio-technical system, but also help explore the full policy design space in a structured fashion, by incorporating the institutional context into the analysis.

This work is part of a two-pronged approach, where the first part aims at identifying the design elements and introducing a structured approach to their modelling, and the second part is dedicated solely to modelling the impacts of design elements. The objective of the current paper is thus to present a delicate, balanced, theoretically-founded, and empirically-supported argument towards the identification of policy design elements and consequently a new approach to analysing and designing renewable policies. The computational model here is only meant as an illustrative example of the modelling framework introduced. In fact, a separate paper by Iychettira et al. (2017), recently published, has been dedicated to describing the computational model in a detailed manner: it comprises the modelling of the design elements, the detailed algorithm, the results, and their interpretation.

[1] In Chapter 2 of Ostrom (2005) 'levels of analysis' are described thus: All rules are nested in another set of rules that define how the first set of rules can be changed It is useful to distinguish levels of rules that cumulatively affect actions taken and outcomes obtained in any setting.

2. Theoretical Foundations and Methodology

The objective of this section is to introduce a methodology to achieve the objectives outlined in Section 1.2. The section consists of a brief description of the different schools of thought on which methodology rests. It comprises three main components: the application of design theory to policy design, the application of the Institutional Analysis and Development (IAD) framework for identification of design elements, and finally, the theoretical foundation to create a modelling framework to analyse policies in terms of their design elements.

2.1. Theoretical Foundations

2.1.1. Design Theory Applied to Policy

"Ubiquitous, necessary, and difficult" is how Bobrow (2006) qualifies the act of policy design. Governments, irrespective of issue type, are interested in effective realization of their goals, by applying knowledge and empirical data to assess appropriateness of alternatives to achieve those goals, and thus engage in 'design,' Howlett (2011). The application of (generic) design theory to policy design and policy analysis is not new. Linder and Peters (1984) are among the earliest, while Howlett and del Rio (2013), Considine (2012), and Taeihagh et al. (2009) are among the more recent authors who have contributed to this topic. Read Howlett (2011) for a comprehensive review of policy design literature.

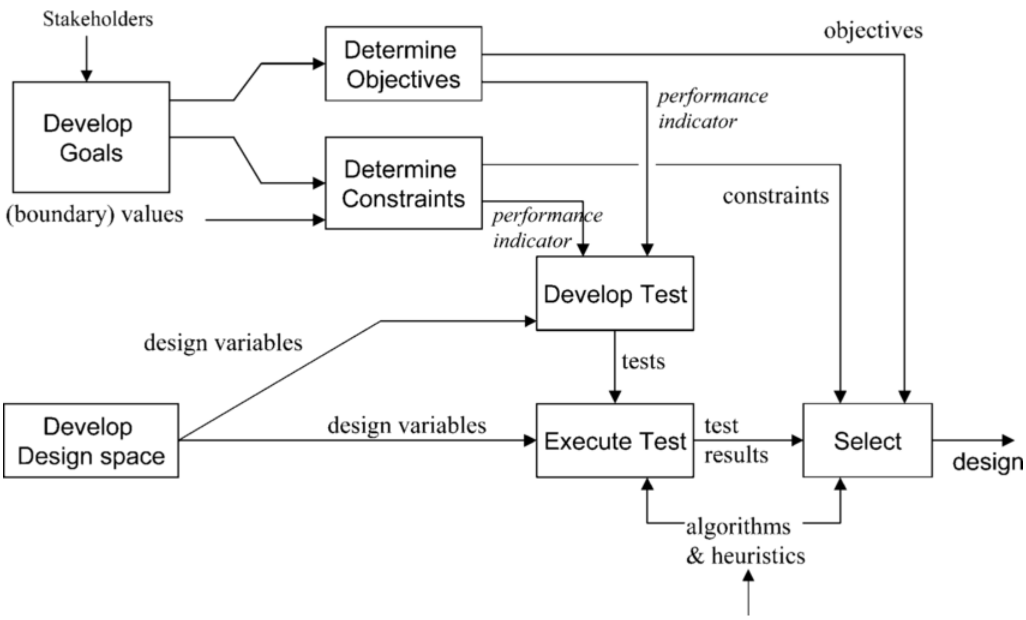

Figure 1: Generic Conceptual Design Framework from Herder and Stikkelman (2004)

In Taeihagh et al. (2009), an analogy has been drawn between process design and policy design, to inform transport policy. Their work is based on the theoretical frameworks of Process System Engineering. The framework used in this work, the Generic Conceptual Design Framework (GCDF), also has its roots in Process System Engineering.

The Generic Conceptual Design Framework has been developed collaboratively at the Carnegie Mellon University and Delft University of Technology. It is illustrated in the Figure 1. This work is based on the design framework (specifically the problem definition and conceptual design aspects) initially developed by Westerberg et al. (1997), which draws heavily from process system engineering, and is described in detail and applied by Herder and Stikkelman (2004) and Subrahmanian et al. (2003). The framework comprises of the following main concepts, which together, structure the content of any level in a design process: 1. design goals; 2. design objectives (selection of goals to be optimized); 3. design constraints (goals that need not be optimised); 4. tests for the goals; and 5. design space.

One may contend, as Rittel and Webber (1973) did, that for most social planning problems or 'wicked problems', the concept of design is a technocratic activity and is not applicable to policy making, as policy-making is a value-laden activity, and therefore its appraisal is highly dependent on each participant's personal value-set. In response, Howlett (2011) writes that there must be a distinction drawn between 'design' as a verb, and that as a noun - instead of treating design as an outcome, he urges the reader to view it as a process of "channelling the energies of disparate actors towards agreement in working towards similar goals in specific contexts." And that is the viewpoint that we wish to subscribe to.

2.1.2. Institutional Analysis to Identify Goals and Policy Design Space

Institutional analysis is a commonly used approach to study socio-technical systems, and especially so in the field of institutional economics; see for instance North (1991), Williamson (1998), and Ostrom (2005). There are several frameworks for institutional studies to describe socio-technical systems. For a concise, informative overview of the different frameworks, refer to Chapter 2 of Ghorbani (2013).

As argued in Section 1, institutional analysis is paramount in the study of policy design. For the purpose of this research, we choose to employ the Institutional Analysis and Development (IAD) framework developed and applied across decades by Ostrom (2005). Conceptually this framework dissects the socio-technical system into composite *holons,* defined as 'a stable sub-whole in an organismic or social hierarchy which displays Gestalt constancy,' Ostrom (2005). This conceptual foundation, of sub-wholes and hierarchies, also corroborates with that

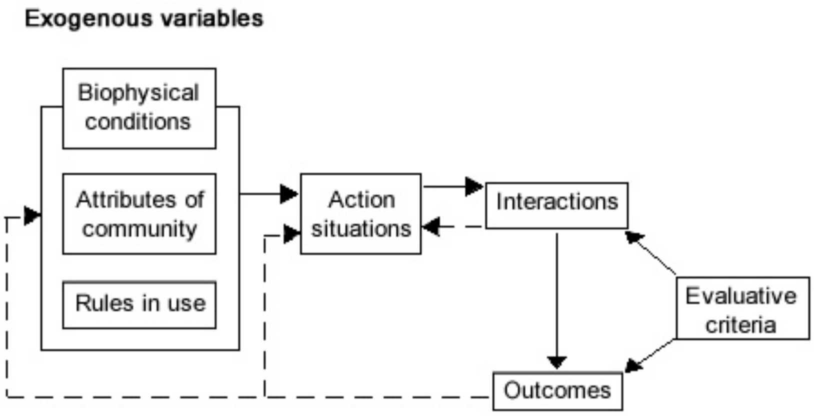

Figure 2: IAD Framework from Ostrom (2005)

of process design theory. Ostrom describes the application of the IAD framework to policy design and analysis, and presents a step-wise process for it in Polski and Ostrom (1999). It also lends itself easily to analysis by computational social sciences such as ABMS, which help construct testable models of socio-technical systems, as Ghorbani et al. (2010) illustrate; this is explained in greater detail in Section 2.1.3.

Ghorbani (2013) describes the IAD thus: "This framework is an institutional driven tool for (1) understanding the underlying structures of a social system, (2) capturing the operational environment, and (3) observing the patterns of interaction and outcomes, given a set of evaluation criteria. The result of this social system analysis is used to give feedback to the system, and as such support institutional change." The framework is depicted in Figure 2.

A note on institutional economic theories: In this work we note that we remain agnostic with regard to the exact theory that should be used; whether it should be institutional economics or neoclassical economics or a combination. We emphasize that we present and apply a *framework*, and not a *theory*, for policy design, based on institutional analysis. All the same, while applying this framework to a model, we make use of a combination of neoclassical economics or the utilitarian perspective, and incorporate strong assumptions of imperfect information and bounded rationality. Imperfect information and bounded rationality are assumptions common in the institutionalist perspectives.

2.1.3. Agent-Based Modelling and Simulation

Agent-based Modelling and Simulation (ABMS) has established itself as being naturally well-suited to represent socio-technical systems, as authors such as

Conte et al. (1998) and Arthur (2006) have argued. ABMS is a form of computational social science, which enables one to model individual entities and their interactions with the environment; see Gilbert (2004). It is then possible to generate emergent patterns at the macro level, simply by specifying properties and interactions at the micro level. They have been successfully used to implement various socio-technical systems, including energy and industrial networks, as shown in Dam et al. (2012). Ghorbani (2013) have shown how agent-based modelling can be used to incorporate institutions into social simulations.

2.2. A Policy Design Framework

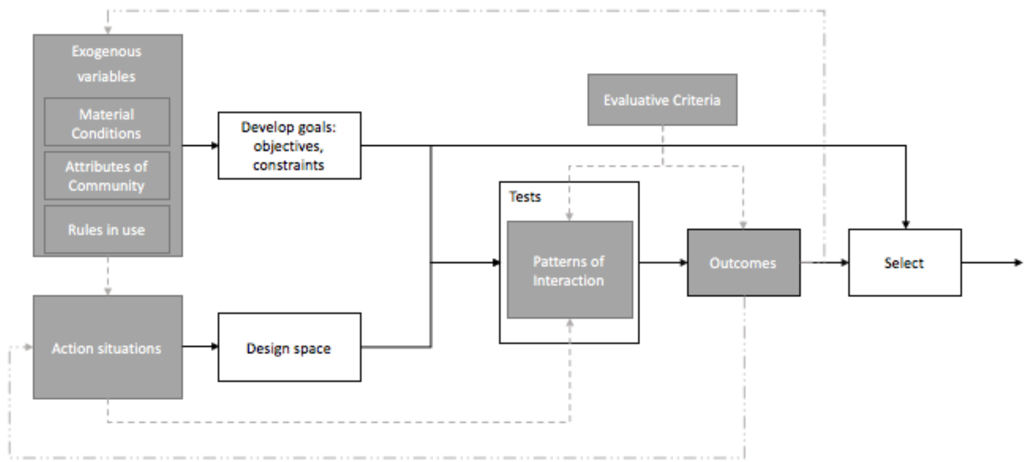

Figure 3: A Generic Policy Design Framework

Drawing from the aforementioned frameworks, a new framework for policy design is introduced in this section. This policy design framework maintains the basic structure of the generic conceptual design framework, while allowing the different components of the IAD framework to inform it. It is depicted in Figure 3. The design framework itself is depicted within dark, bold lines in the figure, while the grey boxes and dashed lines indicate how the IAD framework contributes to the design process.

The design framework facilitates the specification of goals and constraints of the policy maker, the specification of a design space, and provides a framework to evaluate alternatives based on the goals. The IAD framework helps to decompose the socio-technical system, and specifications of interactions between participants, and those between the participants and the physical environment.

The latter therefore plays a paramount role in delineating the design space, understanding and specifying possible behaviours of actors, understanding action-outcome linkages, which can then be tested, while the former provides a structure to the process of formulating the goals, and evaluating potential alternatives.

The policy design framework is described step-wise below:

1. Design goals: The intended goals of the policy to be designed are usually set by the community itself. The concept of 'multiple levels of analysis' described in Chapter 2 of Ostrom (2005), helps identify which participants at what level, frame these goals, and/or constraints. According to her definition, the rules-in-use[2] at the operational level are set one level deeper, at the 'collective' level. This is shown in Figure 4. In reality, the policy maker exists at least in two levels: the member-state level, and at the European level. However, for the sake of illustration in Figure 4, it is assumed that the values and objectives of the two entities are aligned. The policy objectives therefore, are derived from the broad objectives of the European Commission as mentioned in European Commission (2014). The objectives are mentioned below. To improve the ease of associating between policy attributes and overall objectives, we operationalise the objectives into specific ones.

    - Affordability - low cost per unit production or investment
    - Sustainability - effective investment in low carbon technologies and RES-E production
    - Security of Supply - energy adequacy refers to whether sufficient operational capacity exists to meet demand, at any given point in time.
    - Competition - preventing distortions, when multiple countries are considered, in cross border trade and investments.

2. Design space: Discerning the design space requires the policy analyst to make decisions regarding which design variables are relevant. The action situation in the IAD framework is defined thus, "whenever two or more individuals are faced with a set of potential actions that jointly produces outcomes, these individuals can be said to be "in" an action situation" according to Ostrom (2005). Therefore, the action situation outlines potential actions that participants can take, and outcomes an action could lead to, based on their perceived notions of which actions lead to which outcomes, called 'action-outcome linkages'. For instance, the energy producer must

[2]Rules which affect the day-to-day behaviour of the participants, in the context of the issue being analysed.

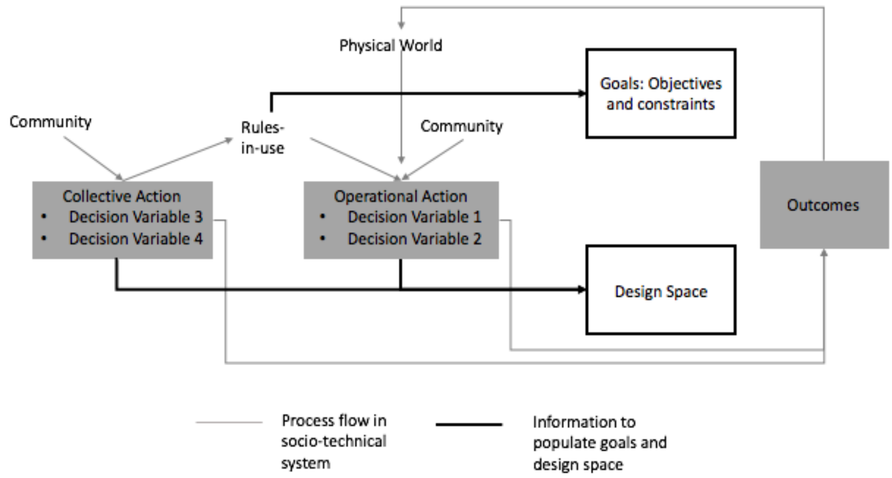

Figure 4: Example Specification of Policy Design Framework

make decisions regarding which technology to invest in, where to place the power plant, and its size. The policy maker would, at the very least have to make decisions regarding the manner in which the remuneration is provided - whether a price or quantity warranty, whether the cost burden is distributed among the tax payers or only the consumers, whether there is a penalty to non-compliance. Combined across different levels of analysis (i.e., the producer at the operational level and the policy maker at the collective level), this would present the complete set of potential actions that a policy may be designed with, i.e., the design space of the policy. This is depicted in Figure 4.

3. Tests: The next step in the design framework calls for developing and executing a test, which would simulate patterns of interactions, based on design objectives, constraints and design variables discerned in the previous steps. In order to simulate patterns of interactions that lead to outcomes, tests must include specifications of action-outcome linkages. This would mean that simulations must specify behaviour, that is theoretically or empirically supported, and that participants are expected to show given certain setting of exogenous variables. The test should help understand and explain, under what conditions of the design space, which outcomes are created. Agent-based modelling is a suitable approach for creating such simulations, as described in Section 2.1.3. A detailed description of the modelling framework created in order to simulate the impact of RES-E design elements is presented in section 3.3.

4. Outcomes and Selection: The outcomes from the simulation help identify which configurations of design variables (design elements) lead to desired outcomes. With the help of the goals identified in step one, it is possible to select a configuration of design elements that meet the objectives and constraints of the policy issue to be resolved.

So far, a rather general overview of the Policy Design Framework has been provided. Central to the objectives of this paper is the identification of a closed set of design elements. Therefore, it is befitting that this aspect of the policy design framework is paid further attention.

2.2.1. Design Space: On Identification of Design Elements

Under step 2 above, the Design Space, i.e., the set of 'design elements' were established as a combination of decision variables across the relevant levels-of-analysis (collective and operational). In order to elucidate the process of arriving at the decision variables, and consequently the design elements, it is necessary to apply the IAD framework to the policy issue; specifically, this would include description of the action arenas relevant to the energy producer and to the policy maker. In Section 3.1 the framework has been applied to RES-E policy making in Europe: the physical and community attributes are outlined, followed by the action arenas themselves.

The *design space* is a set of design elements defined at the community-level, ie., at the level of the policy maker, as a combination of

1. decision variables of the policy-maker at the community level (Decision Variables 3 and 4, in Figure 4), such as type of warranty, cost-burden, scheme duration etc., and

2. variables which indicate whether the purview of one or more of the above decision variables further apply to each decision variable at the operational level (Decision Variables 1 and 2, in Figure 4); for instance whether the warranty could be technology neutral or specific, location neutral or specific, and size neutral or specific.

Depending on the objectives of, and assumptions underlying the analysis, not all design elements may be considered for evaluation. The choice of design elements for evaluation may be strongly influenced by the *frame of analysis*. In an exhaustive work, Bobrow and Dryzek (1987) highlight the different frames of analysis within policy analysis; two such frames are outlined here. A welfare economics perspective would assume a benevolent policy-maker whose only interest is to increase social welfare. A public choice perspective posits that politicians and bureaucrats are more interested in serving their own interests, rather than that of the public. For instance in the particular case of designing RES-E support, the decision regarding whether the subsidy costs are borne by the state budget or only by the electricity consumers, would be much more relevant in the public choice perspective, rather than one of welfare economics. This idea is revisited and clarified in Section 3.1 and critically examined in Section 4.3.2.

3. Applying the policy design framework to RES-E support design

In this section, the Policy Design Framework introduced above is applied to the specific case of RES-E support scheme design. In doing this, three steps are followed: the IAD framework is first applied to the case. This forces the analyst to delineate the problem, the participants, thus creating the boundary conditions, which forms the first, and crucial step towards identifying design elements. This also leads to specification of the policy design framework introduced in Figure 4, to RES-E support. Subsequently, the design-elements of RES-E support schemes are identified from literature in Section 3.2. Finally, a conceptualization of the agent based model for the testing and evaluation of the different designs is presented in Section 3.3.

3.1. Identification of participants, action situations, and exogenous variables

The IAD framework shown in 2 requires the identification of physical attributes, community attributes, and "action situations" related to investment in RES-E. Electricity from renewable energy or otherwise, is an excludable and subtractable commodity. RES-E in particular is produced by installing renewable energy generating capacity, such as for instance, solar PV panels or offshore wind farms.

With the goal of decarbonizing the electricity sector, policy makers have set targets for 80% of all electricity consumption to be from RES-E sources by 2050. In order to realize this target the policy makers design schemes to incentivize investment in RES-E sources. The policy maker implementing a support scheme therefore forms one action-situation. The second action situation involves producers of renewable electricity; they are assumed to be boundedly rational actors attempting to maximize their profits via actions such as investments in electricity producing technologies. Their strategy for investment in RES-E generation capacity is to make a cost benefit analysis, i.e., a net present value calculation for each investment decision, under uncertainty. This is a stylized representation of actors, to make the analysis tractable. It must be noted however that the representation provided here is only one instantiation[3] of the modelling framework presented.

[3]The word instantiation in this context refers to the idea that only one example of the way the current modelling framework can be applied has been provided.

The disadvantage of this abstraction is that it does not consider actors who might have other motives (to be autarkic, to self-consume, to create an energy community, to produce green energy for its own sake). On the other hand, the largest share of current energy production comes from utility companies whose primary motive is profitability, irrespective of differences in ownership or corporate structure. Also, even if other ownership structures were in place, it is hard to imagine a scenario where an actor would not be concerned with the profitability of the project. Therefore, in the current modelling framework, we assume that the Energy Producer agent makes an investment only when the cost-benefit analyses indicate profitability.

Ostrom (2005) defines an action situation in terms of the following elements: participants, positions, actions, outcomes, action-outcome linkages, information about the action situation, and payoffs or the costs and benefits. These elements have been defined, and their corresponding values have been identified for the two action situations presented above.

Table 1: Specification of Action Arenas

Elements of an Action Situation, defined	**Operational Action Arena**	**Collective Action Arena**
Participants: Decision-making entities.	Energy Producers	Government(s)
Positions: Anonymous slots into and out of which participants move.	Energy producers are sellers of electricity and investors in power plants. They are assumed to be boundedly rational, and profit maximizing.	A policy-maker is a participant with the authority to decide on which type of electricity production is preferred, and how the remuneration is organized. She is assumed to be benevolent and is primariliy interested in increasing social welfare.
Action: A selection of a setting or a value on a control variable which a participant hopes will affect the outcome variable.	Act of deciding whether to make an investment in a power plant. This would entail decisions on technology, location, and size	Governments make decisions on how to incentivize RES-E. Based on literature about RES-E support in Europe, and on empirical evidence, the decision variables include price, quantity warranty, contract type (risk allocation), distribution of cost burden, budget limits. These are described in greater detail in section 3.2.

Action-outcome linkage: A setting on a control variable is considered linked to a state variable when it is possible to use that setting to cause the state variable (1) to come into being, (2) to disappear, or (3) to change in degree.	A decision to invest is taken if the net present value of the investment is positive. An investment occurs, causing a structural change in the physical system, and therefore changing the (expected electricity price) for the next investment.	Each setting of the policy-maker's decision modifies the NPV calculation of the producer in a certain way; different combinations of settings lead to different repeated patterns of interaction, which further lead to different outcomes.
Information: Access to information regarding other participants, their positions, their action sets, and payoffs	Information about how many plants have been invested into is available to each participant at any point in time. However, information about future electricity prices, future fuel prices and future demands, much like in reality, are not available. The producers use forecasting techniques for the same.	It is assumed that the government have the same information as the energy producers.
Costs and benefits	Given by the financial returns of the energy producer equation.	Share in RES-E electricity, at low costs

The IAD framework, thus set-up for impacts of RES-E policies on energy investment, is illustrated in Figure 5. The figure also illustrates how information from the IAD framework feeds into the policy design framework, and populates the design space. In the next section explanations of the design elements are provided.

3.2. Design Space: Design Elements of RES-E Support Schemes

The two action arenas, and potential actions at each arena were outlined in the previous section. The design space is a collection of decision variables or potential actions that participants at two levels can make: the operational (energy producer), and the collective (policy-maker) levels. As mentioned earlier, the assumption is that the actions are of a benevolent policy maker concerned with welfare economics. This is shown in Figure 5.

In this section, the list of design elements is presented. Following this, a brief note on how they relate to prevailing theoretical perpectives is given.

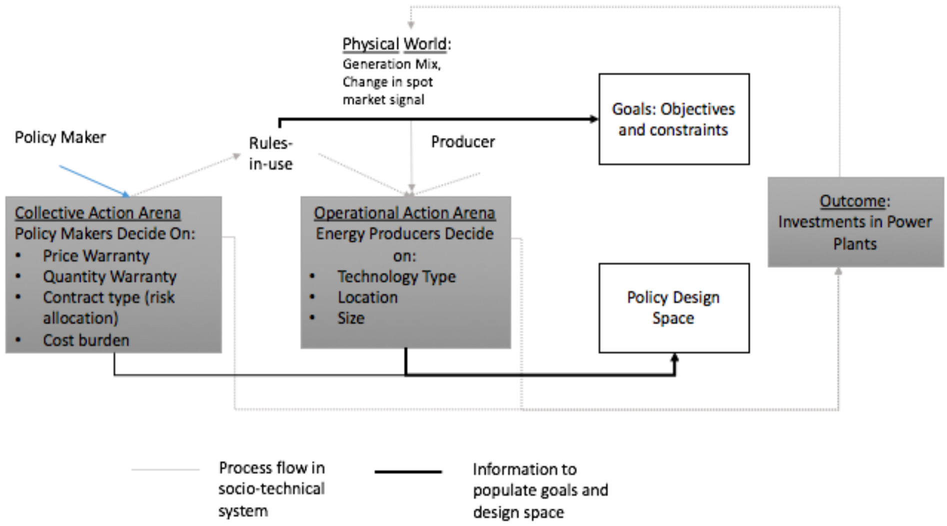

Figure 5: Specification of policy design framework for RES-E support

3.2.1. List of design elements

The design elements are based on insights from literature on renewable support schemes. Looking at the problem from the lens of a welfare economics perpective narrows down the literature to that extent. Another aspect of the way the design elements are chosen is that they are mutually exclusive from another; if two actions are substitutable, then they become alternative states for one design element. For instance, either a price warranty or a quantity warranty must be chosen by the welfare maximizing policy-maker, she does not set both simultaneously. However, she can choose specific technologies in addition to say quantity warranty. The formulation of the design elements is also an iterative process, in which comparisons are made with a set of existing policies. The comparisons with empirical experiences is presented in Section 4.1.

Table 2 below lists the complete set of design elements, and their possible impacts on the socio-technical system, as hypothesised in literature. Their impacts on the socio-technical system is referred to with the term "action-outcome linkages" as per the IAD framework.

Table 2: Design Elements

Design Element	Definition	Action-Outcome Linkages	References

Quantity or Price Warranty	A mandated quantity of electricity supply or consumption from RES technologies, or a mandated price per unit of electricity generated from RES.	Under a quantity warranty with no long-term contract, investors face a substantial price risk. With a price warranty, quantity of investment highly sensitive to the set price.	Batlle et al. (2012b)
Contract w.r.t. electricity market price	Revenue from the electricity market can be accounted for ex ante, or ex post.	When revenue is calculated ex-ante, the uncertainty in future electricity price and consequently the revenue risk lies with agent (either regulator or energy producer) which calculates the subsidy. When calculated ex-post, the electricity market revenue risk lies with the subsidising agent (government).	
Contract Length or Project Duration	The length of time for which the support scheme is valid	Support schemes that last longer are subject to lower regulatory uncertainty, which could mean lower risk for an investor.	Batlle et al. (2012a)
Technology Specificity	The design element which specifies which technologies are eligible for a certain support scheme.	It encourages immature technologies. It may lead to more expensive technologies being incentivized early on, but the overall cost of RES generation could be lower than a technology neutral scenario, due to the lack of windfall profits for the energy producers.	Fais et al. (2014); Huber et al. (2004)
Location Specificity	This element would allow the differentiating of support levels by location.	If higher support is given to locations with less resource endowment, RE power plants would be more evenly distributed in the region, which might lead to a reduced need for grid infrastructure. However, the incentive to use the best locations might be lost.	Batlle et al. (2012a)
Size specificity	This element would allow the differentiating of support levels by size.	Larger installations allow for economies of scale, while incentivizing smaller sized applications lead to more decentralized generation, and could reduce market power. With greater smaller sized technologies, distribution grid would need to be reinforced, and the impact on the transmission grid is unclear.	Batlle et al. (2012a)
Cost burden	The cost of the RES-E support could be borne either by the consumers or by the tax payers (state budget).	When financed by consumers, the scheme is perceived as less risky as compared to when financed by the state budget. This is because taxpayers finance is usually negotiated annually, while laws involving consumers typically last longer. Financing by tax payers set up an implicit cross-subsidy between the tax-payers and electricity consumers. However, since RES-E support is justified by the public good of driving down costs so as to benefit all future users of RES-E, an argument is that the funds should come from general taxation .	Batlle et al. (2012b)

Cost containment mechanisms	Adaptation of support levels to technology costs and state budget related political feasibility concerns. Ex: capacity caps generation caps, cost caps.	They are necessary because controlling the costs of RE support is argued to be absolutely vital for its political feasibility and social acceptability.	del Rio and Mir-Artigues (2014)
Penalty for non compliance	Penalties are a means to deter non compliance of the regulation.	Support schemes are ineffective if developers have the possibility to back-off without consequences. However, penalties may just increase the cost as bidders could include the cost of the penalty into the bid, if the risk of not complying is high enough. Furthermore, penalties may deter participation of small actors.	del Rio and Linares (2014)
Frequency of Change in Warranty	The number of times the price or quantity signal changes over the duration of the support scheme.	If the frequency of change is high, like with the Scandinavian tradable green certificate system, where the signal changes each year, the risk to investment increases. Long term contracts lead to lower prices and they can be used to compensate low support levels.	

3.2.2. Relating above design elements to theorectical perpectives:

While the design elements quantity or price warranty do indeed originate directly from neoclassical economics, many others do not. In a neoclassical firm, the only function of management is to select profit-maximizing quantities of outputs and inputs, which means, determining the quantity and the consequent price that is established; see North (1991).

However other design elements mentioned in the current paper are not typically considered in neoclassical economics, but are more common in institutional perspectives. In order to make analyses with mathematical models tractable, equilibrium models frequently make abstractions regarding perfect knowledge of costs, revenues, and competitive positions; read Himmelweit et al. (2011). Therefore, design elements such as contract duration and frequency of change in warranty do not typically feature as variables in partial or general equilibrium models.

Another important abstraction in neoclassical economics is that firms exist to produce an already fully-defined product. The idea of diversification or specification of products as interchangeable depending on changing institutions (such as policies on asset specificity) is difficult to incorporate into the analysis as the product has already been defined. In transaction cost economics however, asset specificity is an integral part of the basic unit of analysis, a transaction, as Williamson (1998) has explained.

3.3. Testing: Conceptualizing patterns of interactions

In this section, a testing environment designed to evaluate the impacts of design elements that were identified in the previous section, is illustrated. The testing environment simulates an electricity market, producer agents taking investment decisions, and a 'government' agent implementing RES-E support policies in terms of their design elements. A brief description of the conceptualization of the model is presented here, to demontrate one instantiation of the framework presented. The schematic representation of the testing environment for the policy design framework is presented in Figure 6. The model consists of a 'base model' where energy producers' decisions are simulated, and an 'RES-E support scheme model'.

At the outset, it must be noted that three design elements have been modelled, while keeping the others constant. A simplification to three design elements allows for clarity in interpretation, is sufficient for demonstration of the framework, and is a strong first step towards incorporating more design elements. Due to these reasons, and in order to keep within time and other resource constraints, we settled with modelling only three design elements.

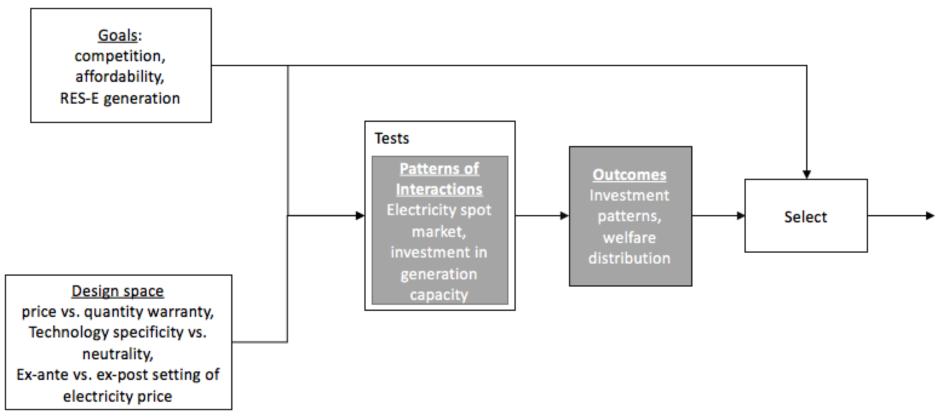

Figure 6: Design space is evaluated by simulating patterns of interactions

3.3.1. The base model

The base model consists of two main algorithms: one simulating an electricity spot market, and another, investment decisions of energy producers. The spot market is implemented as a uniform electricity market clearing; the load duration curve is represented in terms 20 load-segments; each load segment is a demand (in MW) and time (in hours) pair. Each energy producer agent makes investment decisions by computing a net present value for a technology, of a given size, in a certain location. The algorithms are described in detail in Richstein (2015) and

Iychettira et al. (2016). This base model has been previously used to simulate various aspects of the electricity market in several peer-reviewed publications such as Richstein et al. (2015a), Richstein et al. (2015b), and Bhagwat et al. (2016)

3.3.2. Modelling RES-E support as a combination of design elements

The modelling of the three design elements is briefly described here. A separate paper has been published by Iychettira et al. (2016) exclusively to describe the model in detail, the assumptions made, and the resulting outcomes.

- **Price vs quantity warranty:**The *quantity warranty* is implemented as a sealed-bid uniform price auction, for contracts that span the *duration of the project*, similar to a tender. Quantitative targets for renewable energy generation are administratively set in the model by a Government agent. The price warranty is modelled thus: the Government agent computes a price for each eligible technology; the price would be valid for the length of the *contract duration.*
- **Technology specificity or neutrality:** Depending on whether the scheme is *technology specific or neutral*, the warranty is either calculated for each technology individually, or as a single price or quantity warranty for all technologies respectively.
- **Electricity market price setting, ex-ante or ex-post:**As for the contract being designed *ex-post or ex-ante*, while computing the subsidy i.e., the additional remuneration for RES-E technologies, revenue from the electricity market is accounted for either ex-ante (before the actualization of electricity prices) or ex-post (when the electricity price is known).

Since only three design elements are considered, with each element having two possible values, all combinations of designs lead to 2^3 or 8 different support schemes. The naming scheme is presented in Table 3.

3.3.3. Implementation of ABM in Java

It is proposed that an RES-E scheme is represented as an entity with a set of properties, and related methods, much like a 'class' in object-oriented programming[4]. The design elements identified in the previous steps together, make up the properties of the RES-E class. The processes or behaviours related to the different properties are the 'methods' of the class.

[4]In object-oriented programming, a class is a blueprint for objects or entities which share certain properties, and behaviours.

Table 3: Base Case Experiment Set - Naming Convention

RES-E Policy Scenario Name	Design Element 1: Warranty type	Design Element 2: Price Setting	Design Element 3: Tech Neutral vs Specific
P_Ante	Price Warranty	Ex_Ante	Neutrality
P_Post	Price Warranty	Ex_Post	Neutrality
P_AnteTS	Price Warranty	Ex_Ante	Specificity
P_PostTS	Price Warranty	Ex_Post	Specificity
Q_Ante	Quantity Warranty	Ex_Ante	Neutrality
Q_Post	Quantity Warranty	Ex_Post	Neutrality
Q_AnteTS	Quantity Warranty	Ex_Ante	Specificity
Q_PostTS	Quantity Warranty	Ex_Post	Specificity

Along with the RES-E support schemes, the main agents at each level, in this case, the Energy Producer at the operational level, and the policy-maker or government at the community level, are other classes. The properties and behaviours of the agents come from the action set, and the action-outcome linkages outlined earlier. Therefore, for the energy producer, the action set would involve making an investment decision in a certain technology, location, and size, depending on the policy environment that exists. For the policy-maker, the decision set would include specification of design elements to achieve outcomes of affordability, and sufficient share of RES-E in the energy mix. The modelling framework is represented structurally using a UML class diagram, presented in Figure 7. The structure of the model indicates that RES-E Support Scheme is a class, whose attributes are the design elements identified in the previous step.

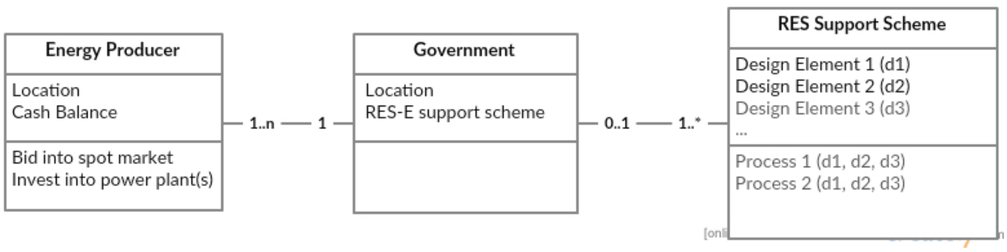

Figure 7: Specification of Class Structure for Generic Design Elements

The model implementation as objects in Java, and a flowchart implementing RES-E policies is presented in Appendix A. The source code is openly accessible [5].

[5] https://github.com/Kaveri3012/emlab-generation/tree/feature/SocialWelfareAnalysis

4. Discussion: Evaluating the approach

In order to evaluate the policy design approach, the following three steps are taken. Firstly we compare how well the design elements formulated above represent RES-E support schemes in reality. Secondly, emergent patterns, interactions, and outcomes of the "testing" using an ABM are presented. The outcomes reveal the impacts design elements have on the socio-technical system. In this way, the outcomes from the model enable us assess the usefulness of the design element approach. Finally, the merits and limitations of the approach are discussed.

4.1. Empirical representativeness of design elements

RES-E support schemes take various forms across Western Europe - tenders, feed-in-tariffs, tradable green certificates, and their variations and combinations. Here, six RES-E support schemes across five countries in Western Europe have been studied and represented in terms of the design elements that were formulated in Section 3.2. Table 4 demonstrates that the design elements can indeed be used to represent, and differentiate, between a variety of policies. This table also shows that this approach lends itself to a broader, and more empirically-founded representation of policies than pure neo-classical economics allows for.

Table 4: Existing RES-E Support Schemes in terms of Design Elements. Source: Commission (2012)

Design element	**DE EEG FiT**	**DE Premium Tariff**	**FR Tender EOLE**	**NL SDE+**	**UK Contract for Differences**	**Sweden Quota System**
Quantity / Price Warranty	Price	Price	Quantity (Auction)	Quantity (Base cost determined based on auction)	Quantity (Strike price determined based on auction)	Quantity (TGC)
Contract w.r.t Electricity Market Price	Ex-post	Ex-ante	Ex-ante	Ex-post, yearly	Ex-post	Remuneration solely depends on certificate market price
Contract Length (project duration in years)	20	20	15	8,12,15 years, based on technology	<15	15
Technology Specificity	technology specific	technology specific	technology neutral	technology neutral	technology neutral	technology neutral

Location Specificity	location neutral	location neutral	location neutral	location neutral	location neutral	location neutral
Size Specificity	<= 10 kW	<= 10 kW	>12MW	differs per technology	none	
Cost Burden	Consumers	Consumers	Consumers	State Budget	Consumers	Consumers
Cost Containment Mechanisms	Quantity cap of 52GW	Max Capacity 400MW	Quantity cap of 52GW	Capped by budget (4 billion in sring 2016)	Capped by quantity	Capped by quantity
Penalty for Non-compliance	None	None	None	None	None	Exists
Frequency of Change in Warranty per Project	remains same during project duration	remains same during project duration	remains same during project duration	remains same during project duration	remains same during project duration	TGC market cleared once a year for all plants; warranty varies annually

4.2. Evaluating outcomes of the ABM

The question remains whether it is indeed possible to relate each design element to specific impacts on the socio technical system. This could potentially let the policy-maker "design" the policy that meets his criteria, simply by picking the right design features. The second question is whether there are specific combinations of design elements which lead to unexpected interactions and consequently, unexpected impacts on the socio-technical system.

As described in Section 3.3, eight policies, originating from all combinations of three design elements were implemented. Each policy led to a different pathway of investment portfolios, electricity prices, costs and revenues of the different participants involved. The complete set of data, assumptions, results, interactions, explanations of the dynamics are described in thorough detail in a separate paper, by Iychettira et al. (2017), dedicated entirely to the model. The main interactions, which relate design features to their outcomes are desribed in this section. In Figure 8 the investment portfolio that came about for each combination of design elements is indicated.

Table 5: Impacts of design elements on investment into RES-E and welfare distribution

Design element	Impact on investment in RES-E	Impact on welfare distribution

Quantity vs. price warranty	Quantity-warranty schemes meet their targets more consistently than their price-warranty counterparts. The price warranty schemes incentivize investment up to the potential of the technology, as long as the regulator determines the cost of the technology correctly.	These design elements do not directly impact welfare distribution. The impact however manifests itself through two variables: i. the amount of renewable capacity in the system that a scheme incentivizes, reducing electricity prices, and consequently consumer expenditure and ii. the cost of the subsidy.
Technology specificity vs. neutrality	Technology neutral schemes lead to investment in the cheapest technologies first. Technology specific schemes lead to a more diverse portfolio earlier on.	Technology neutral schemes led to windfall profits being accrued to non-marginal technologies. This increased the cost of subsidy by about 60% in such scenarios, increasing wealth transfer from government to producer in them.
Ex-ante vs ex-post setting of electricity market price	When electricity prices were set ex-ante, the regulator and producer agents were prone to making mistakes while setting the price warranty, leading to severe consequences on the investment levels. Conversely, price setting ex-post removed all price risk from investment decisions.	In the ex-ante schemes, the agents' expectations of revenues from electricity market are higher than actual, over a twenty year period, as they do not fully account for the merit-order effect. The subsidy costs in ex-ante schemes in the model therefore tend to be lower than necessary. Ex-post schemes lead to subsidy costs being higher (by 15%) despite the lack of price risk in them.

Combinations of design elements. One combination of design elements particularly stood out for the authors. When price warranty schemes were combined with technology specificity, and ex-ante price setting, the investments in RES-E capacity remained severely stumped. This is because as mentioned in Table 5, when electricity prices were set ex-ante, the regulator and producer agents were prone to making mistakes while setting the price warranty, leading to severe consequences on the investment levels. This issue was exacerbated due to technology-specificity, as price warranties were set lower than necessary for each technology. This is evident in scenario P_AnteTS in Figure 8.

The results indicate that design elements do impact investment patterns, policy costs, and consequently social welfare. With the help of the modelling framework therefore, it is possible to explore the policy design space systematically,

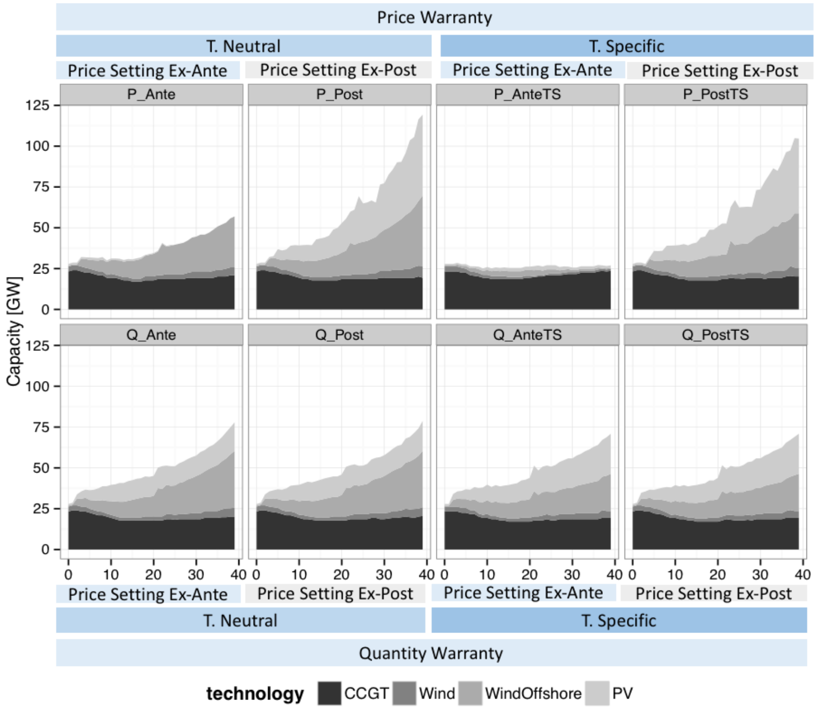

Figure 8: Capacity growth in GW per policy scenario with time (in years) on x-axis

and quantify impacts of the individual design elements on the socio-technical system. The following section explores the implications of the method in greater detail.

4.3. Merits and limitations of the approach

4.3.1. Merits

The approach presented enables us identify what actions can be taken by whom under the current framework of rules and regulations, and therefore identifies the levers and knobs so to say, of energy policy design. Systematically identifying these levers, that we call design elements, at the level of the producers, and then at the level of the national regulations, provides the policy analysts and policy makers at the level of the European Commission, a much, much wider range of variables to use in their policy recommendations.

This is especially important because over the past several decades, the European Commission has been implementing directives towards one common internal electricity market. At the same time, national policies and regulations in related topics (such as renewable support or security of supply policies) sometimes seem to work exactly in the opposite direction; see Glachant and Ruester (2013). The approach presented identifies more levers or variables than just quantity and price, with the help of an institutional analysis approach and empirical evidence and thereby assists us in resolving this dichotomy.

For instance, having technology neutral policies in one country would lead to producers of non-marginal technologies establishing themselves in the first country, even when purely in terms of wind-resources, a different country would be a better choice. In a similar fashion, policies which shield producers from the risk of electricity price volatility in a certain country might make it far more attractive than a country with no such policy, but with far better natural resources. Therefore, a design element such as technology specificity or a method of risk allocation (ex-ante vs ex-post electricity price setting) could severely undermine the idea of efficient resource allocation, which the single internal electricity market promotes. The modelling framework, as demonstrated, thus provides a method to identify which of these design elements impact efficient resource allocation among different member states, and to what extent. The model itself indicates that technology specificity vs neutrality would have a much larger impact (60%) on subsidy costs, than the impact of price setting being ex-ante or ex-post (15%).

A significant advantage of this model is that it is open-source. Models such as PRIMES, GAINS, CAPRI have been traditionally used by the European Commission to evaluate electricity policies; for a brief description of the models, see Capros et al. (2014). They are black-box simulations whose assumptions, models, and data are not open to the public. They cannot be verified, discussed, or challenged. As Pfenninger (2017) has argued, open source models increase transparency, trust among the public and help further scientific debate. In addition, agent-based modelling as a methodology is better suited to incorporating bounded rationality, and true uncertainty in models than optimization models, as has been argued by Iychettira et al. (2016).

4.3.2. Limitations

Important assumptions have been made regarding characteristics of the participants and the action situations that they might find themselves in. For instance, a producer makes decisions mainly regarding economic and physical aspects of the technology. In reality however, there are other action situations through which policy makers could be eventually influenced. For instance, if a severe penalty or taxes were to be introduced, workers could organize a protest. Or if a technology were to be completely banned, as nuclear energy has been in Germany, the producers could file a lawsuit against the government like Vattenfall did. Therefore the analysis is limited in that the design space does not include say, the 'political man' or the 'emotional man', but mainly focusses on the 'rational man', although boundedly so. In that sense, the analysis so far could be characterised as being technocratic. Indeed, if the energy producer agent were to assume multiple identities, such as being politically active and strongly pushing for local autarky, the design elements would be different. Another limitation of the approach as presented is its computationally intensive nature; further attention could be paid to the process of reducing the number of design elements to suit computationally constrained situations.

Despite the limitations, within the action situation and roles outlined in this analysis, and from a welfare economics paradigm, the approach presented provides a methodology for creating, simulating, and testing a complete policy design space.

5. Conclusions and policy implications

Energy policy design in Europe is a complex issue: not least because of the co-existence of a common European policy, along with very disparate policies at the member state levels. The policy maker is faced with the daunting challenge of analysing multiple actors, multiple decision criteria, at multiple levels of operation and/or governance. Using a combination of design theory, institutional analysis, and agent-based modelling (ABM), we provide a method to systematically explore policy design options for RES-E support in Europe. This is done firstly by identification of decision variables, which then lead to the design elements of a policy, and secondly by evaluating the impact of each design element on the socio-technical system using an agent-based model.

Given a certain frame of analysis, we propose that it is theoretically possible to identify the complete policy design space. Crucially, this aspect potentially opens up to the policy analyst new avenues for intervention, and allows her explore, given a range of uncertainties, which element(s) of intervention is(are) the most vital to achieve the goals of the community. The applicability of the approach is demonstrated by representing and differentiating between six renewable electricity support schemes from Western Europe in terms of the design elements. The applicability of the modelling framework using ABM, and consequently of the Design Element Approach, is demonstrated by evaluating the long-term, dynamic impact of three design elements: *price warranty versus quantity warranty, technology neutrality versus specificity,* and accounting for the electricity market price *ex-ante versus ex-post* on the Dutch electricity sector. A vital result is that *technology specificity* leads to making the scheme 60% more cost effective than technology neutrality.

It is important to note here that claims of completeness of the design space come with limitations. For instance, if the energy producer agent were to assume multiple identities, such as being politically active and strongly pushing for local autarky, the design elements would be different. The design framework published here therefore pertains mainly to an analysis which lies within the scope of welfare economics, although founded firmly within an institutational framework and empirical experience. Other limitations of the approach include its computationally intensive nature, and the need to prudently select the most important design elements necessary for the analysis.

Avenues for future work are many. The foremost of these involve demonstrating with modelling, the application of this framework to understand impacts of different renewable electricity policy designs in neighbouring countries sharing one common electricity market, on cross-border welfare effects. Such work would pave the way towards quantitatively understanding whether and how renewable support scheme designs in neighbouring member states should be harmonised, in view of the common electricity market. This analysis is being performed for a forthcoming paper. Other possibilities for future work include designing an endogenous policy maker, who dynamically changes values of design variables based on indicators in the model. The most challenging avenue for further exploration would be to identify a design space involving agents with more than just economical considerations and identities, but are more complex involving perhaps political and cultural considerations as well.

The implications of this work are from the perspective of the authors, most useful for policy makers of RES-E support schemes, at both the member-state and at European levels. Given that governance of renewable energy support beyond 2020 at the European level is still undefined, while a European target for renewables has been set, this work paves the way for a more comprehensive, formal, empirically founded analysis of RES-E policy design than what currently prevails.

6. Acknowledgements

This research was supported by a fellowship from the Erasmus Mundus Joint Doctorate in Sustainable Energy Technologies and Strategies, and the authors gratefully acknowledge the same. I also wish to thank Amineh Ghorbani for her insightful comments on the initial drafts of this work. Yeshambel Girma and Vikram Srinivas have also helped me clarify and articulate my ideas better at different stages of the work.

7. References

Anderson, R., Taylor, L., Jul. 1986. The social cost of unsupplied electricity: A critical review. Energy Economics 8 (3), 139–146.
URL http://www.sciencedirect.com/science/article/pii/0140988386900125

Arthur, W. B., 2006. Chapter 32 Out-of-Equilibrium Economics and Agent-Based Modeling. Vol. 2 of Handbook of Computational Economics. Elsevier, pp. 1551 – 1564.
URL http://www.sciencedirect.com/science/article/pii/S1574002105020320

Batlle, C., Linares, P., Klobasa, M., Winkler, J., Isi, F., Ortner, A., Eeg, T. U. W., 2012a. Interactions between RES-E support instruments and electricity markets. Tech. Rep. October, Beyond 2020.
URL http://www.res-policy-beyond2020.eu/pdffinal/InteractionsbetweenRES-Esupportandelectricitymarkets(beyond2020-D5-1).pdf

Batlle, C., Prez-Arriaga, I. J., Zambrano-Barragn, P., Feb. 2012b. Regulatory design for RES-E support mechanisms: Learning curves, market structure, and burden-sharing. Energy Policy 41, 212–220.
URL http://www.sciencedirect.com/science/article/pii/S0301421511008238

Bergmann, J., Bitsch, C., Behlau, V., Jensen, S., 2008. A European harmonised policy to promote RES-electricity - sharing costs and benefits. Tech. Rep. D17, Vienna University of Technology.
URL http://www.futures-e.org/

Bhagwat, P. C., Richstein, J. C., Chappin, E. J. L., Vries, L. J. d., 2016. The effectiveness of a strategic reserve in the presence of a high portfolio share of renewable energy sources. Utilities Policy 39, 13 – 28.
URL http://www.sciencedirect.com/science/article/pii/S0957178716300169

Bobrow, D. B., 2006. Chapter 5: Policy Design: Ubiquitous, Necessary and Difficult. In: Handbook of Public Policy. SAGE Publications.
URL http://dx.doi.org/10.4135/9781848608054.n5

Bobrow, D. B., Dryzek, J. S., 1987. Policy Analysis by Design. Pittsburgh University Press.

Capros, P., Paroussos, L., Fragkos, P., Tsani, S., Boitier, B., Wagner, F., Busch, S., Resch, G., Blesl, M., Bollen, J., Feb. 2014. Description of models and scenarios used to assess European decarbonisation pathways. Sustainable Energy System Changes 2 (34), 220–230.
URL http://www.sciencedirect.com/science/article/pii/S2211467X13001065

Commission, E., Oct. 2012. RES Legal Europe Database for Regulation on Renewable Energy Generation. RES LEGAL Europe is the website on regulations on renewable energy generation. In the database you will find information on the important legislation on the support schemes, grid issues and policies for energy from renewable sources covering all three energy sectors: electricity, heating & cooling and transport. The scope of this database covers all the EU 27 Member States, the EFTA Countries and some EU Accession Countries. The website offers links to all relevant original legislation, is free of charge and is updated on a regular basis.
URL http://www.res-legal.eu/search-by-country/

Considine, M., 2012. Thinking Outside the Box? Applying Design Theory to Public Policy. Politics and Policy 40, 704–724.
URL http://onlinelibrary.wiley.com/doi/10.1111/j.1747-1346.2012.00372.x/abstract

Conte, R., Gilbert, N., Sichman, J. S., 1998. Multi-Agent Systems and Agent-Based Simulation: First International Workshop, MABS '98, Paris, France, July 4-6, 1998. Proceedings. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 1–9.
URL http://dx.doi.org/10.1007/10692956_1

Dam, K. H. V., Nikolic, I., Lukszo, Z., 2012. Agent-based modelling of socio-technical systems. No. May. Springer.

del Rio, P., Linares, P., Jul. 2014. Back to the future? Rethinking auctions for renewable electricity support. Renewable and Sustainable Energy Reviews 35, 42–56.
URL http://www.sciencedirect.com/science/article/pii/S1364032114002007

del Rio, P., Mir-Artigues, P., Dec. 2014. Combinations of support instruments for renewable electricity in Europe: A review. Renewable and Sustainable Energy Reviews 40, 287–295.
URL http://www.sciencedirect.com/science/article/pii/S1364032114004912

European Commission, 2014. A policy framework for climate and energy in the period from 2020 to 2030.

URL http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52014DC0015
Fagiani, R., Barqun, J., Hakvoort, R., Apr. 2013. Risk-based assessment of the cost-efficiency and the effectivity of renewable energy support schemes: Certificate markets versus feed-in tariffs. Energy Policy 55, 648–661.
URL http://www.sciencedirect.com/science/article/pii/S0301421512011330
Fais, B., Blesl, M., Fahl, U., Vo, A., 2014. Comparing different support schemes for renewable electricity in the scope of an energy systems analysis. Applied Energy 131, 479 – 489.
URL http://www.sciencedirect.com/science/article/pii/S030626191400628X
Ghorbani, A., 2013. Structuring Socio- technical Complexity. Ph.D. thesis, Delft University of Technology.
Ghorbani, A., Ligtvoet, A., Nikolic, I., Dijkema, G., 2010. Using institutional frameworks to conceptualize agent-based models of socio-technical systems. Proceeding of the 2010 workshop on complex system modeling and simulation 3, 33–41.
Gilbert, N., 2004. Agent-based social simulation: dealing with complexity. The Complex Systems Network of Excellence 9 (25), 1–14.
Glachant, J.-M., Ruester, S., 2013. The EU internal electricity market : done forever? Working Paper.
URL http://cadmus.eui.eu/handle/1814/28123
Haas, R., Panzer, C., Resch, G., Ragwitz, M., Reece, G., Held, A., Feb. 2011. A historical review of promotion strategies for electricity from renewable energy sources in EU countries. Renewable and Sustainable Energy Reviews 15 (2), 1003–1034.
URL http://www.sciencedirect.com/science/article/pii/S1364032110003849
Herder, P., Stikkelman, R. M., 2004. Methanol-Based Industrial Cluster Design: A Study of Design Options and the Design Process. Industrial & Engineering Chemistry Research 43 (14), 3879–3885.
URL http://dx.doi.org/10.1021/ie030655j
Himmelweit, S., Simonetti, R., Trigg, A., 2011. Microeconomics: Neoclassical and Institutionalist Perspectives on Economic Behaviour, 1st Edition. Cengage Learning.
Howlett, M., Nov. 2011. Revisiting Policy Design: The Rise and Fall (and Rebirth?) of Policy Design Studies. Reykjavik, Iceland.
Howlett, M., del Rio, P., 2013. Policy Portfolios and their Design: A Meta Analysis. Grenoble, France.
URL http://www.icpublicpolicy.org/IMG/pdf/panel11.s3.howlett.pdf
Huber, C., Faber, T., Haas, R., Resch, G., Green, J., Olz, S., White, S., 2004. Deriving optimal promotion strategied for increasing hte share of RES-E in a dynamic European electricity market. Tech. rep.
URL http://www.eeg.tuwien.ac.at/eeg.tuwien.ac.at_pages/research/downloads/PR_25_Green-X_final.pdf
Iychettira, K., Hakvoort, R., Linares, P., 2016. Towards a comprehensive policy for electricity from renewable energy I: A Structured Design Approach. Energy Policy Submitted.
Iychettira, K. K., Hakvoort, R. A., Linares, P., Jeu, R. d., 2017. Towards a comprehensive policy for electricity from renewable energy: Designing for social welfare. Applied Energy 187, 228 – 242.
URL http://www.sciencedirect.com/science/article/pii/S0306261916316208
Kitzing, L., Jan. 2014. Risk implications of renewable support instruments: Comparative analysis of feed-in tariffs and premiums using a meanvariance approach. Energy 64, 495–505.
URL http://www.sciencedirect.com/science/article/pii/S0360544213008414
Kitzing, L., Mitchell, C., Morthorst, P. E., Dec. 2012. Renewable energy policies in Europe: Converging or diverging? Energy Policy 51, 192–201.
URL http://linkinghub.elsevier.com/retrieve/pii/S030142151200746X
Lako, P., May 2010. Technical and economic features of renewable electricity technologies. Tech.

Rep. ECN-E–10-034, ECN.
URL https://www.ecn.nl/docs/library/report/2010/e10034.pdf

Linares, P., Rey, L., 2013. The costs of electricity interruptions in Spain. Are we sending the right signals? Energy Policy 39.

Linder, S. H., Peters, B. G., 1984. From Social Theory to Policy Design. Journal of Public Policy 4 (03), 237–259.

Most, D., Fichtner, W., Jun. 2010. Renewable energy sources in European energy supply and interactions with emission trading. The Role of Trust in Managing Uncertainties in the Transition to a Sustainable Energy Economy, Special Section with Regular Papers 38 (6), 2898–2910.
URL http://www.sciencedirect.com/science/article/pii/S0301421510000297

North, D. C., 1991. Institutions, Institutional Change and Economic Performance.

Ostrom, E., 2005. Understanding Institutional Diversity. Princeton University Press, Princeton, New Jersey.

Pfenninger, S., Feb. 2017. Energy scientists must show their workings. Nature 542 (7642), 393–393.
URL http://www.nature.com/doifinder/10.1038/542393a

Pfenninger, S., Staffell, I., 2016. Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. Energy (in review).
URL https://www.renewables.ninja

Polski, M. M., Ostrom, E., 1999. An Institutional Framework for Policy Analysis and Design. Indiana University, Bloomington, IN.

Ragwitz, M., Resch, G., Huber, C., White, S., Aug. 2003. Dynamic Cost Resource Curves. Tech. Rep. ENG2-CT-2002-00607, Energy Economics Group, Vienna University of Technology.
URL http://www.green-x.at/downloads/WP1%20-%20Dynamic%20cost-resource%20curves%20(Green-X)(final%20draft%2009-2003).pdf

Richstein, J., 2015. Interactions between carbon and power markets in transition. Delft University of Technology, Netherlands.
URL http://repository.tudelft.nl/view/ir/uuid%3A0e1dcc59-40f0-4ff9-a330-c185fdfca119/

Richstein, J. C., Chappin, . J. L., Vries, L. J. d., 2015a. Adjusting the {CO2} cap to subsidised {RES} generation: Can {CO2} prices be decoupled from renewable policy? Applied Energy 156, 693 – 702.
URL http://www.sciencedirect.com/science/article/pii/S0306261915008533

Richstein, J. C., Chappin, . J. L., Vries, L. J. d., 2015b. The market (in-)stability reserve for {EU} carbon emission trading: Why it might fail and how to improve it. Utilities Policy 35, 1 – 18.
URL http://www.sciencedirect.com/science/article/pii/S0957178715300059

Riley, B., Oct. 2015. What VW and the EU's climate models have in common.
URL http://www.energypost.eu/volkswagen-eus-climate-models-common/

Rittel, H. W. J., Webber, M. M., 1973. Dilemmas in a general theory of planning. Policy Sciences 4 (2), 155–169.
URL http://dx.doi.org/10.1007/BF01405730

Subrahmanian, E., Westerberg, A. W., Talukdar, S., Garett, J., Jacobson, A., Paredis, C., Christina, A., Herder, P., Adam, T., 2003. Integrating Social Aspects and Group Work Aspects in Engineering Design Education. International Journal of Engineering Education 19 (1).
URL http://hdl.handle.net/1853/34074

Taeihagh, A., Banaras-Alcantara, R., Claire, M., Oct. 2009. Development of a novel framework for the design of transport policies to achieve environmental targets. Computers & Chemical Engineering 33 (10).

URL http://www.sciencedirect.com/science/article/pii/S0098135409000416
Voogt, M. H., Uyterlinde, M. A., Skytte, K., Leonardi, M., Whiteley, M. H., 2001. Renewable energy burden sharing. REBUS. Requirements and expectations of utilities and consumer organisations in the European energy sector. Tech. rep., Energy research Centre of the Netherlands ECN, Petten (Netherlands).
URL http://inis.iaea.org/search/search.aspx?orig_q=RN:32037197
Westerberg, A. W., Subrahmainan, E., Reich, Y., Konda, S., 1997. Designing the process design process. Computers & Chemical Engineering 21, Supplement, S1 – S9, supplement to Computers and Chemical Engineering6th International Symposium on Process Systems Engineering and 30th European Symposium on Computer Aided Process Engineering.
URL http://www.sciencedirect.com/science/article/pii/S0098135497874704
Williamson, O. E., Apr. 1998. Transaction Cost Economics: How It Works; Where It is Headed. De Economist 146 (1), 23–58.
URL http://link.springer.com/article/10.1023/A%3A1003263908567

Appendix A. Implementation of design elements in Java

Figure A.9 shows four of the eight possible inherited RES-E Schemes for three design elements. The quantity-based schemes include a function or a method to organize auctions based on the other design elements of the scheme, such as technology specificity, location specificity, contract (ex-post or ex-ante). The price based schemes includes a function to compute the remuneration, depending on specified design elements. A high-level flow chart of the process flow in the model is presented in Figure A.10.

Different representations of the RES-E Support Schemes are be inherited[6], and contain processes that are functions of design elements. Other classes in the model represent the agents Energy Producer and Government, and their decision-making processes.

[6]Inheritance is the defining of new classes as extensions of existing classes: the existing class is the parent class and the new class is the child class.

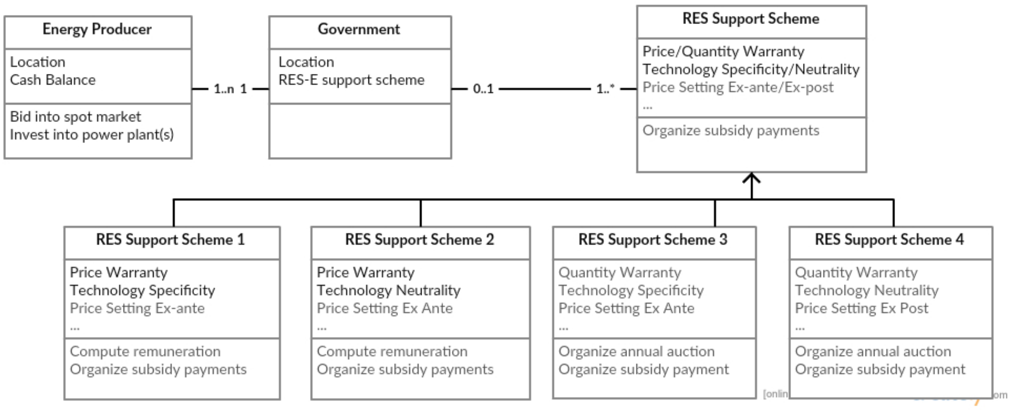

Figure A.9: Specification of Class Structure

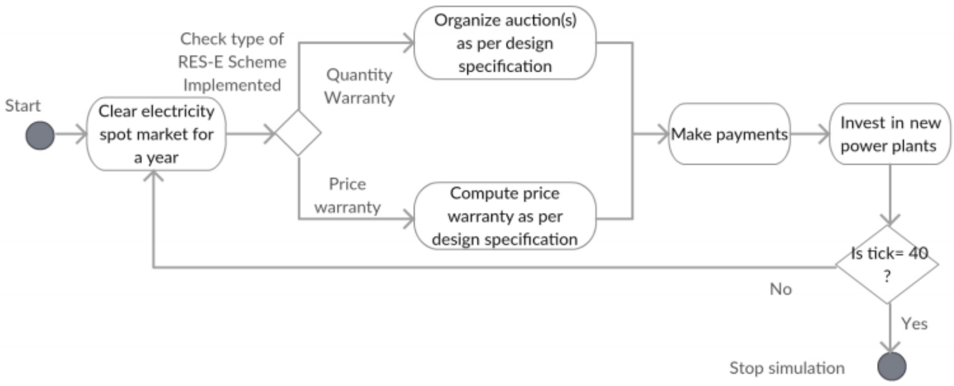

Figure A.10: Flowchart - Implementation of RES-E Policies

Appendix B. Data for Test Model

A single (isolated, uncongested) electricity market is considered, with four energy producer companies, whose initial portfolio is based approximately on the existing generation mix in the Netherlands. However, to ensure focus on assessing RES-E design elements, the model is simplified such that all conventional capacity in the Netherlands is represented by the Combined Cycle Gas Turbine (CCGT) technology. Along with CCGT, three renewable technologies are considered, and assumptions regarding their characteristics are described in Table B.7. The intermittent nature of renewable generation sources is represented by hourly availability factors, which are then aggregated to segment-based[7] availability factors. The data for hourly availability for the renewable technologies is obtained from Pfenninger and Staffell (2016). The model runs for 40 ticks, with each tick representing a year starting from 2014.

The targets and realistic potentials for renewable technologies have been set based on data from Lako (2010) andRagwitz et al. (2003). Fuel prices of natural gas and electricity demand, have been represented in terms of stochastic trends, where the annual rate of growth is determined using a triangular distribution. The assumptions for modal growth rate, and its upper and lower bounds are summarized in Table B.6. The initial load duration function is based on 2014 ENTSO-E data for Netherlands. A value of lost load of 2000 Eur/MWh has been used for this work, based on Anderson and Taylor (1986); Linares and Rey (2013).

Table B.6: Demand and Fuel Price Trends

		Growth Rate		
	Start value (Eur per Million Btu)	Mode	Min	Max
Electricity demand growth rate	1	1.1	0.99	1.03
Gas price - Basecase	4	1	1	1
Gas price - high	4	1.02	1.04	1
Gas price - low	4	0.98	0.96	1

Table B.7: Assumptions regarding Technologies

Technology	CCGT	Wind Offshore	PV	Wind Onshore
Capacity [MW]	776	600	500	600
Construction time [Years]	2	1	1	1
Permit time [Years]	1	0	0	0
Technical lifetime [Years]	40	20	20	20
Depreciation time [Years]	15	20	20	20
Minimum Running hours	0	0	0	0
Fuels	Natural Gas	-	-	-

[7] In order to represent variability of load across the year, the load duration curve is divided into segments; each segment being a (load, time) pair value, and each segment is cleared separately.