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Specification of system-of-systems for policymaking in the energy sector

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Abstract

Very detailed models often hinder the ability to develop a broad, high-level understanding of system behavior. A system-of-systems perspective combined with a policy analysis approach offers an alternative approach for policy decision-making. This paper specifies the elements of the energy system-of-systems using this new approach and illustrates its use via an example from the Dutch residential sub-sector. The resulting comprehensive problem representation provides meaningful insights into the interdependencies of relevant factors and values among different levels of the system-of-systems covering both the supply and demand side. The paper also shows that despite the high complexity of the energy sector, an energy system-of-systems can be specified in a manageable way and can be used to formulate tractable decision-making problems on a specific policy issue.

Keywords: System-of-systems perspective, integrated view of policymaking, space heating in residential sector, carbon emission.

1 Introduction

A System-of-Systems (SoS) consists of multiple, heterogeneous, distributed systems embedded in networks at multiple levels that evolve over time. Complexity in an SoS stems primarily from the heterogeneity of its constituent systems, the interaction of these systems, and the presence of deep uncertainty with respect to its future state. The complexity brought by system heterogeneity exists both within a system domain (e.g., power generation) and across domains (e.g., power generation, energy service economics, and governmental

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policy/regulation). This first source of complexity presents challenges to understanding (e.g., different analytical frameworks), modeling (e.g., different dynamical time scales), and assessment (e.g., different stakeholders).

Treatment of the second source of complexity, the interactions among the distributed systems, alone is not necessarily intractable. However, in the presence of the third source, deep uncertainty (Lempert et al., 2003), complications arise since—as the word ‘deep’ implies—important system interactions (and their evolution) are poorly understood. Deep uncertainty results in imprecise models of decision-making. Additionally, uncertainty resident in the environment gives rise to un-modeled feedback dynamics associated with the ultimate decision chosen. Combined with the irreversibility of many decisions, the result is a partially controlled process with path and time dependency.

The foundation for understanding complexity in system-of-systems can be traced back to the work of Herbert Simon and Howard Pattee suggesting that a complex system can be understood by decomposing such a system into subsystems at different levels interacting together both horizontally and vertically (Simon, 1973). Furthermore, relative complexity between two subsystems may differ for each level. One subsystem may have simplistic organizational structure (lower complexity) at an intermediate level but its low level systems are more complex than those of another subsystems. Integration of high fidelity analysis models across multiple layers of abstraction is impractical, and a more refined tack is required which is selective in which information is appropriate. Simon proposed pseudo-decomposable systems as a means to structure and manage complexity, asserting that “resemblance in behavior of systems without identity of the inner systems is particularly feasible if the aspects in which we are interested arise out of the *organization* of the parts, independently of all but a few properties of the individual components” (Simon, 1996).

From this foundation, the system-of-systems perspective is an attempt to further characterize this complexity by taking a broader view than just the physical design (i.e., traditional system engineering view) and operational aspect, to include commercial and financial, economic, social, and policy aspects couched within multiple levels. The goal is improved decision-making, especially for higher level policy problems.

From this introductory description, it is quite evident that the SoS perspective is congruent with the foundations of Integrated Assessment (IA). IA has been described as “a structured process of dealing with complex issues, using knowledge from various scientific disciplines and/or stakeholders, such that integrated insights are made available to decision makers” (Polatidis et al., 2003). The goal of IA, as with SoS, is to supply decision makers with better, actionable information so that they can make better decisions. The objective of this paper is to describe in detail the SoS approach through application to the Dutch-built energy sector, in particular an example problem formulation for making informed policy assessments with uncertainty. The emphasis, therefore, is on problem formulation rather than on simulation and solution synthesis.

Table 1: SoS lexicon

Category	Description
Resources	The entities (systems) that give physical manifestation to the system-of-systems
Stakeholders	The individual/organizational entities that give intent to the SoS through values
Operations	The application of intent to direct the activity of entity networks
Policies	The functions that guide the operation of resource and stakeholder entities
Level	**Description**
Alpha (α)	Base level of entities in each category, further decomposition will not take place
Beta (β)	Collections of β-level systems (across categories), organized in a network
Gamma (γ)	Collections of β-level systems (across categories), organized in a network
Delta (δ)	Collections of γ-level systems (across categories), organized in a network

1.1 System-of-Systems lexicon

The make-up and operation of an SoS has some well-defined characteristics such as hierarchy, independence, interdependency, and emergence. Hierarchy implies that there is a system architecture obtained by decomposing system elements; the other characteristics involve relationships within the hierarchy. An effective lexicon is needed to provide understanding and communication within the hierarchy. The lexicon must ensure that 1) all parties understand the description, and 2) all relevant portions of the problem are covered. The lexicon bridge is critical, since professionals from the various domains are typically trained to solve problems using methods and ideas prevalent to their own domain. This legacy is the source of the often-used term ‘stovepipe’ in reference to the narrow scope thinking in a particular area of specialty knowledge. The real dynamics of the energy sector, for example, can only be fully understood ‘across’ stovepipes, spanning various columns of knowledge, and thus a holistic frame of reference is required for such trans-domain applications. The holistic perspective combined with an effective lexicon is the foundational tool for proper abstraction of an SoS.

For policymaking purposes, DeLaurentis & Callaway (2004) define a lexicon in terms of levels and categories, as shown in Table 1. The categories highlight the presence of a heterogeneous mix of engineered and sentient systems together constituting the dimensions of the problem. For each category, there is a hierarchy of components. To avoid confusion, the lexicon employs the unambiguous use of Greek symbols to establish the hierarchy. Alpha (α), Beta (β), Gamma (γ), and Delta (δ) indicate the relative position within each category. The collection of α entities and their connectivity determines the construct of a β-level network and likewise, a γ-level network is an organized set of β networks. Hence, the δ-level can be described as a network comprised of all of the lower level networks, whose constituents span the category dimensions.

The lexicon highlights the assumed presence of an important element of hierarchical control. A decision made at the higher levels has far reaching effects because it can influence or even determine what takes place in the lower levels. Government regulation in effect can determine how companies operate. So if fundamental change of behavior is desired, such change needs to be made at higher levels.

The desire is that, through use of the lexicon for understanding the multi-level relationships, decisions of one stakeholder may be appropriately tailored in cognizance of the actions of others. In an SoS, the elements at each level maintain a degree of independence, but need to be connected and coordinated with others within and across levels in order to meet specified needs. This, for example, is reflected in the phenomenon in which carrot policies at policy level, such as subsidies, often become a critical push for innovation, which occurs at a lower level of the SoS. New, emergent behaviors sometimes occur as a result of this interconnectivity. For example, liberalization and deregulation in the energy sector, which is based on the assumption that more competition means reliable service, often results in more service disruptions (e.g., the California energy crisis (deVries, 2004)).

1.2 Policy analysis approach: an integrated view of policymaking

Policymaking requires a consideration of the various influencing factors, their possible consequences for system performance, and societal conditions for implementation. The basis for such a view has been provided by Walker (2000). According to this view, policymaking, in essence, concerns making choices regarding a system in order to change the system outcomes in a desired way (see Figure 1). Having its roots in operations research and system analysis, this view assumes that policymakers make their decisions in a rational way (Miser, 1980; Majone, 1985).

The elements from this framework can be assembled in a structure labeled 'XPIROV', where:

- X = External forces: factors that are beyond the influence of policymakers (i.e., exogenous).
- P = Policies: instruments that are used by policymakers to influence the behavior of the system to help achieve their objectives.
- I = Internal factors: factors inside the system (i.e., endogenous) that are influenced by external forces and policies.

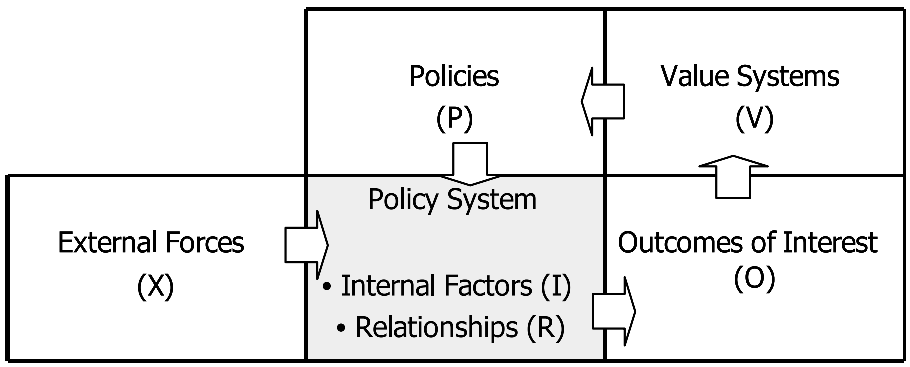

Figure 1: Policy analysis approach with XPIROV structure

- R = Relationships: the functional, behavioral, or causal linkages among the external forces, policies, and internal factors that produce the outcomes of interest.

- O = Outcomes of interest: measurable system outcomes that are related to the objectives of policymakers and stakeholders. Hence,

$$O = R(X, I, P) \tag{1}$$

- V = Value system of policymakers and stakeholders, which reflects their goals, objectives, and preferences. The value system contains the criteria for indicating the desirability of the various policy outcomes based on the resulting outcomes of interest.

For analysts who assist policymakers in choosing policies, the XPIROV structure is useful for assembling and organizing the available information as well as for the process of elicitation and discovery of such information. Since the analysis process is iterative, the structure can serve as “a formal intellectual book-keeping mechanism” (Lempert et al., 2003).

Some of the ideas on this way of problem structuring are not new. The work of Polatidis et al. (2003), for example, proposes an approach for energy policymaking that combines IA with multi criteria decision making under consideration of similar relationships and variables as those outlined in Figure 1. Our work, however, seeks to extend beyond this towards a comprehensive representation scheme that employs these variable sets and exposes the system-of-systems relationships within a conceptual framework that leads naturally to analysis.

This paper presents a conceptual framework to address the complexity and uncertainty of policymaking in the energy sector. The framework is a synthesis between the SoS perspective and the integrated view on policymaking. The paper begins by specifying a SoS for the energy sector. The SoS aggregates energy supply and demand into hierarchical levels. For each level, aspects such as policies, operations, and economics are identified. To illustrate the application of the framework, the Dutch energy policy for the residential sub-sector is used. The interdependencies among relevant factors and values are specified and discussed. The paper then discusses some aspects of the resulting SoS construct and its implications. Concluding remarks summarize the findings.

2 Representation of the physical entities (resources) of the energy sector

2.1 Conventional representation of the energy sector

Traditionally, the energy sector has been specified through a large econometric or optimization-oriented system of modules that are used to evaluate the impacts of different policies (Bunn & Larsen, 1997). Incorporating a long time scale and broader economic and environmental impacts requires that a broad system wide perspective be taken. The results have been energy models that comprehensively specify a horizontal chain of energy flow from resource extraction to consumption and cut across several energy demand sub sectors such as residential, transportation, and industrial. (cf. MARKAL (ETSAP, 2008), MESSAGE (IIASA, 2008), and EFOM (deVoort et al., 1985)). These models, however, are relatively unsystematic in their scope. They generally assume that some variables and relationships like demand-price interactions are exogenous to the model (Bunn & Larsen, 1997). The National Energy Modeling System (NEMS) of the US Department of Energy, for example, addresses this limitation by incorporating a macro economic and international energy interactions (Energy Information Administration, 2003).

However, very detailed models, such as those mentioned above, often hinder the ability to have a high-level understanding of system behavior (Davis et al., 2000). These models are often built to be able address multiple purposes in highly detailed fashion. They tend to become large, complex, opaque, and accessible only by specialists in the particular field. This is in fact one of the reasons why many such models have rarely been used as a basis for important policy decisions (see e.g., survey on big models by Meadows & Robinson (1985). There is a limit to human reasoning capacity (i.e., bounded rationality).

These concerns raise the need for a family of models that not only can provide detailed accounts of the system of interest but also a greater abstraction of it so that one can also see the forest rather than only the trees. It is also argued that, at a policy level, critical information for effective modeling is often at a high level of abstraction (Davis & Bigelow, 1998). In climate policy, for example, this high level information addresses issues such as a wide range of conditions in which innovation will drive the cost of non-emitting energy technologies below that of fossil fuels (Lempert & Schlesinger, 2000) rather than low level information such as the exact learning curve (i.e., rate of cost reduction) of a particular technology. To be able to derive such high level information, a relatively low resolution model is required. In this paper, a SoS perspective combined with the integrated view of policymaking is proposed as an alternative way for specifying models in order to enable the extraction of high level information regarding system behavior under conditions of deep uncertainty.

2.2 Representation of the energy sector from an SoS perspective

To conceptualize the energy sector as an SoS, the horizontal chain of energy flow of the energy system must be integrated with the hierarchical view (see Figure 2). As a result, there are six levels (from α to ζ) to represent each portion of the chain from resource extraction to distribution and sale. The rationale behind the levels is as follows. The lowest level (α) comprises the individual equipment and material required to function in each process in the chain. The aggregate of this equipment will make one unit of supply including the process of producing the output (level β). For example, all equipment for an electricity plant is configured and run according to certain processes or procedures so that it can produce the electricity. The next level (γ) is the level at which companies control collections of supply units. The span of control can extend across several chains so that, for example, an oil company owns the resources and conversion facilities, up until the distribution channels, forming its resource supply chain.

On the national level (δ), power generators are linked by a transmission and distribution network to provide a national power grid. When national power grids are interconnected, energy can be transmitted across national boundaries forming a trans-national energy network (level ϵ). This trans-national network usually involves countries in close proximity (e.g., US and Canada) or countries that share common economic and political interests such members of the European Union (EU). Finally, the interconnection of a resource chain and power grid across the globe, in a rather patchy sense, creates a global energy network (ζ level).

The same hierarchical aggregation also applies to the demand side (see Figure 3), where the consuming equipment and appliances (level α) now become the focus. Each will consume different level of energy in its own right (i.e., in the form of efficiency). But more important is the behavior and pattern of use of the users of these apparatuses. The aggregation of these consumption units forms various sectoral energy demands, which constitute the total national energy demand. From level δ and higher, the demand is the aggregate of energy demands from the lower levels. For each level, the energy consumption is decomposed into three major forms of energy: fuel, electricity, and heating.

It is important to note that for example in energy generation, the boundary between supply and demand has become blurred. Enabled by distributed generation technologies and smart metering, end consumers (i.e., the demand side) can become a net producer of energy (e.g., electricity), (see, e.g., Ackermann et al., 2001; Strachan & Dowlatabadi, 2002). A resultant implication on network representation is that what used to be the end node in the distribution network becomes part of the generation grid.

Level	Hierarchical View of Energy Supply	Horizontal Chain of Energy Supply						
		Resource Extraction	*Refining and Conversion*	*Storage and Transport*	*Generation*	*Storage*	*Transmission*	*Distribution and Sale*
α	**Equipment and material**	e.g. mining equipment or biomass material	e.g. catalyst or distillator	e.g. pipelines and fuel tanks	e.g. boilers, turbines or a heat pump	e.g. fuel cells	e.g. cables, transformers	e.g. electricity meters
β	**Supply unit (incl. production process)**	e.g. an oil platform or a biomass farm	e.g. a refinery facility	e.g. a pipeline system or mobile transport	e.g. a power station or a wind mill	e.g. a power storage unit	e.g. transmission line unit	e.g. billing unit and process
γ	**Company**	Company's energy resource supply chain			Aggregate of power generators and storage		Company's transmission network	Company's distribution network
δ	**National**	National energy source and reserve	National energy resource (fuel) supply chain		National power grid			
ε	**Trans-National**	Trans-national energy network						
ζ	**Global**	Global energy network						

Figure 2: Representation of physical entities in the Energy System-of-Systems (supply side)

Level	Hierarchical View of Energy Demand	Forms of Energy		
		Fuel	Electricity	Heat
α	**Equipment and appliances**	e.g. a car	e.g. industrial machines	e.g. a heating system
β	**Consumption unit (incl. behavior of consumption)**	e.g. a car with it's owner pattern of use	e.g. a factory with industrial process	e.g. a building with owner's consumption behavior
γ	**Sectoral**	Various consuming sectors (e.g. manufacturing, agriculture, and household)		
δ	**National**	National energy demand structure		
ε	**Trans-national**	Trans-national energy demand structure		
ζ	**Global**	Global energy demand structure		

Figure 3: Representation of physical entities in the Energy System-of-Systems (demand side)

The specifications of physical entities of the energy SoS from both the supply and demand sides are useful in at least two ways. First, one can locate and then address major drivers and bottlenecks. For example, it is becoming quite clear for the EU countries that the major drivers for their energy security lie at the ϵ-level, such as the continuity of gas supply from a major supplier (level γ) like Gazprom of Russia. In another context, the main bottleneck for renewables such as wind energy is the access of windmills (level β) to the national power grid (level δ). Second, the energy SoS may be used as an aid to find innovative solutions, from both the supply and demand side. This use of the SoS specification will be demonstrated in the case discussion in Section 3.

3 Specification of an SoS for policymaking in the Dutch residential sub-sector

The synthesis of the SoS perspective and policy analysis approach will be illustrated using a policy issue for the Dutch residential sub-sector.

Policymakers are facing pressure to reduce emissions of CO_2 in order to mitigate the impact of climate change. The Dutch government has set the target to reduce carbon emissions by 80% in 2050 compared to the emission level of 1990 (Ministry of Economic Affairs, 2005). The residential sub-sector is one of the major contributors of carbon emissions. In the Netherlands, carbon emissions associated with residential housing accounted for about 19% of the national carbon emissions in 2002. Almost half of the 19% emissions share comes from the energy used for space heating. Thus, in the effort to decrease carbon emissions, this particular sector is considered to have a big potential (Treffers et al., 2005). However, there is a great deal of uncertainty surrounding the policy costs and the levels of emission reduction produced by the various policies.

The specification of a SoS for this case involves three steps, each of which will be described and illustrated: (i) formulate policy issue, (ii) specify relevant systems and values, (iii) specify integrated policy system.

3.1 Formulation of a specific policy issue and problem owner

A critical departure point for the SoS specification is how to make the problem 'manageable' considering the many interconnected elements within and across various levels of the SoS. One way to do this is to address one specific policy issue at a time rather than to try to accommodate multiple problems at once. The specification of a problem owner further clarifies who the decision maker(s) regarding the policy is (are) and the levers and instruments under his (their) control.

The policy issue this paper addresses can be formulated as follows: "taking into account the social, economic, technological, political, and value uncertainty, what cost-effective policies should be deployed to reduce the carbon emission to the targeted level for the Dutch residential sub-sector ?" Since the policymaking takes place at the national level (δ), the problem is shared by several governmental agencies: The Ministry of Economic Affairs, The Ministry of Housing, Spatial Planning and Environment, and local municipalities.

3.2 Specification of relevant resources, policy systems, owner of the system, stakeholders and associated values

The specification of the system starts at the level of the policy issue. Relevant systems that share common variables are then specified below and above the defined level. These systems can be either on the demand side, the supply side, or both. The decision makers for the relevant systems and all stakeholders in each system must then be identified so the various criteria that are to be used to value system outcomes can be established.

The identification of the relevant policy systems starts with specifying the physical entities (resources) in the energy SoS (from Figure 2 and Figure 3). The resources are involved in defining the policy issue at hand. The issue of carbon emission due to space heating leads to several resources at various levels of the energy SoS. For instance, at the supply side the resources involve heating generation technologies (α), companies' heat transmission network (γ), and the national power grid (δ). At the demand side, they are the building heating system (α), dwellings and their occupants (β), and companies' dwellings stock (γ).

Table 2 provides the overall view of the relevant systems for Dutch policy on the residential sub-sector together with the values that are at stake in the decision process. For one decision maker at a particular level, the decision makers from other levels will become stakeholders of his decision making. In identifying the relevant systems, there is also a need to cover both the supply and demand side. This is not only because uncertainties emerge from both sides, but, more importantly, innovative policies can be identified by addressing the two sides.

The policy issue in question takes place at the δ level. Going down in the hierarchy leads to the investment system owned (at γ level) by property developers. This system is relevant because it will determine the rate of improvement of building heat efficiency. Other improvements in efficiency, namely building thermal envelopes (demand side) and heat generators (supply side), are the outcome of a system at the α level. At the highest level considered here, the trans-national level, the EU system of renewable energy is relevant because the share of renewables in the energy supply will affect the emission factor contributing to the carbon emissions.

The criteria involved may be subject to changing weights. Property developers, whose main concern is to maximize the return on their investments, may put increasing weight on corporate social responsibility. Tenants of buildings may shift attention from purely economic to environmental considerations.

Table 2: Definition of relevant systems and values. S = Supply side, D = Demand side

Level	Physical entities (resources)	Policy System	Problem owner/ decision makers	Decision Makers' Criteria
α	Heating generation technologies (e.g. boilers, micro CHP, Solar PV) (S)	Heating Technology Innovation System (S)	Equipment manufacturers, research institutions	Commercial success and personal motives
	Buildings heating system (including insulation states) (D)	Dwelling Thermal Envelope System (D)	n.a	n.a
β	Dwellings and consumption behavior of their occupants (D)	Heat Consumption System (D)	Building owners and tenants	Cost minimization and environmental awareness
γ	Companies' heat transmission network (S)	Dwelling Investment System (D)	Housing cooperatives and properties investors	Capitalistic measures (profit maximization) and corporate social responsibility (public task)
	Companies' dwellings stock (D)	Dutch Heating Infrastructure System (S)	Utility companies	
δ	National power grid for heating and electricity (S)	Dutch Residential Emission system (D)	Dutch Ministry of Housing and Environment, Economic Affairs, and local Municipalities	Economic growth, security of energy supply, and environmental protection (national interest)
		Dutch Renewable Energy System (S)		
ϵ		European Union (EU) Energy Policy System (S+D)	European Union commission for energy	Equity, economic growth, security of energy supply, and environmental protection (common interest)

3.3 Specification of the system models for the policy issues in the XPIROV structure

At this stage, we now have a specific policy issue of interest and the relevant systems and values in the SoS. The next step is to construct relevant policy systems at each level of the SoS and from both the supply and demand side. In the construction of the system domain, the XPIROV structure is operationalized. In the following sub-sections, each policy system is described, highlighting some issues at each level and the interconnections among them. The elaboration is also meant to shed light on uncertainties about the structure. The overall structure is presented after these descriptions in Figure 4.

3.3.1 Alpha level demand side: Dwelling thermal envelope system

The demand side policy system, at alpha level concerns itself mostly about the states of heating installation and insulations of the dwelling stocks (the I at this level), which affect the thermal efficiency of the dwellings (O). The existing Dutch dwelling stocks, which numbered around 6.5 million in 2000, for instance, can be disaggregated into 16 types. The classification is based on the form of the dwellings (e.g., flat, detached, or terraced) and the year of construction. Each dwelling type has distinctive thermal envelope characteristics as a result of the thermal efficiency of its floor, wall, windows, and roof elements. Insight on dwelling thermal efficiency can be obtained from some existing models such as NEMS (especially the residential module) (Energy Information Administration, 2003), SAWEC (Jeeninga & Volkers, 2003), and BREDEM based models (Johnston, 2003). These models are highly disaggregated and require detailed physical information on dwelling stocks and state of thermal insulation.

The state of heating installation and insulation will be determined by the rate of dwelling refurbishment and demolition (X) carried out by both private owners (β level) and housing cooperatives (γ level). Demolition rate of building, for instance, has been identified as one key factor that influences future carbon emissions in the residential sub-sector (Treffers et al., 2005). Different mechanisms for such forms of refurbishment for improving the insulation performance of existing dwellings (R) can be found in Lowe (2004).

3.3.2 Alpha level supply side: Heating technology innovation system

A primary issue in the supply side system at alpha level is the aggregate efficiency of heating technologies (O) and how Research, Development and Demonstration (RD&D) efforts and activities (i.e., P at this level) may affect efficiency improvements by increasing the rate of diffusion and thus the market share of a variety of new (and improved) heating technologies. For the owner of this policy system, which includes equipment manufactures and research institutions, the major driver (V) for their efforts can be a mix of commercial incentives (e.g., profitability) and personal rewards (e.g., fame).

The Relationships (R) that explain the underlying mechanism and theories about innovation dynamics are well recorded. Grubler et al. (1999), for instance, argue about three driving forces (I): (i) the learning effects that cause improved cost and performance, (ii) competition among technologies that determine barriers for entry and exit, and (iii) network effects that shape the pattern of technology co-evolution. However, in addition to this widely used construct, there are also alternative explanations for technology innovations, such as the application of ecological theory to suggest how we might better anticipate the locus of innovation in socio-technical systems (Hubbell, 2001), and a combination between evolutionary economics and technology studies (Geels, 2002).

Policymakers can influence the course of the innovation process by several instruments. Although the results so far have been mixed, incentives such as subsidies and grants can be used to bring innovation technology into early demonstration on commercial niche markets (Sanden & Azar, 2005). More effective, however, are policies that promote technology diversity to prevent the lock-in effect and policies that lower barriers of entry for new infrastructure to produce the network effects (Grubler et al., 1999). For the owner of the system, these instruments will become uncertain external forces (X) that are beyond their control. And, as will be motivated later, the policy may come from decision makers at the national and even trans-national level (i.e., P at δ and ϵ level).

3.3.3 Beta level demand side: Heat and electricity consumption pattern system

At the β level, an important piece of information obtained from the policy system is how much energy and at what cost it is consumed over time for space heating (O) by dwelling occupants (i.e., the problem owners of the β level policy system). This pattern of consumption will be the result of the physical insulation states of dwellings (the I at α level), as well as occupants' changes in life style and investment decisions in energy saving measures (P). For the first, for example, decisions such as to have fewer children and to postpone marriage have contributed to a steadily decreased size of household (e.g., in Lowe, 2000; Johnston et al., 2005). These decisions may be the result of changing values to a more individualistic one (V). A specific demographic trend for The Netherlands has also been investigated under four economic scenarios (Bollen et al., 2004; Hilderink et al., 2005).

Second is the kind of investments the house owner make regarding the heating technology and the state of thermal insulation of their dwellings, which is linked to the policy system at the alpha level-demand side. These decisions may be the result of tension between capitalistic value (e.g., cost-performance preference) and social value (i.e., to protect the environment) (V). Indeed, in the debate about climate change, the need to address the capitalistic value is often overlooked (Birge & Rosa, 1996). The willingness to invest in turn may be a function of personal disposable income (X). In theory, when people have a lot to spend they are willing to sacrifice near term consumption for future benefits, such as improved climate conditions.

The willingness to invest may also be influenced by energy prices (X). High energy prices increase the attractiveness of investment in high efficiency heating technology (R). It is confirmed, for example, that high energy prices stimulate investments by shortening the payback period (Boon & Sunikka, 2004).

How the energy price, especially that of gas and electricity, will evolve in the future is uncertain. According to the logic of limited resources, the prices will tend to rise as the resources become scarcer. Lowe (2000), however, suggests a tendency of falling natural gas price for the household market, partly as a result of successful liberalization of the gas market. There have been numerous attempts to forecast energy prices by extrapolating past trends (Energy Information Administration, 2004; International Energy Agency, 2004). Others stress the importance of the dynamics, rather than equilibrium assumptions, with behavioral decision rules that lead to several patterns of price evolution, such as exponential growth, oscillatory decline, etc. (e.g., Fiddaman, 2002; Barlas & Kanar, 1999). Alternatively, in the real options literature (e.g., Trigeorgis, 1999; Amram & Kulatilaka, 1999), the evolution of an uncertain variable such as energy price can be modeled as a random walk. These variety of views may indicate plausible paths of price evolution.

It is worth noting, however, that the application of option theory is not limited to the evolution of energy prices. The option theory can be applied to other variables whose volatility can be correlated with portfolio of stocks or commodities in the financial market.

In the government's policy, both 'sticks' and 'carrots' are effective in influencing technology adoption decisions (Robalino & Lempert, 2000). Lessons from Dutch incentive schemes on the adoption of technology such as heat pumps, combined heat and power (CHP), and condensing boilers can be found in Dieperink et al. (2004). Another external force (X) that determines the energy demand for space heating is the so-called heating degree days. This factor indicates the severity and duration of cold weather. As the average temperature increases, for example, people will need more energy for cooling rather than heating (Lowe, 2004; Johnston, 2003).

3.3.4 Gamma level—demand side: Housing investment system

At γ level, the policy system on the demand side addresses the investment rationale used by commercial players. Controlling almost half of the total existing dwelling stock (I), housing cooperatives are major players in the Dutch market. They decide on the rate of dwelling refurbishment and demolition and on house stock (P), in order to make sure of its financial survivability (V). This value is translated into measures of return on investment such as NPV and payback period (O). A relevant logic for investment that considers the future uncertainty of the value of building stock has been investigated by Gruis (2000).

Government interventions are part of the uncertain external forces (X) for these housing cooperatives. Financial incentives, such as tax exemptions for building refurbishment costs, as well as regulatory measures, such as EU building energy performance and regulation on cap of house rents can affect investment decisions. In addition, market forces, such as the level of housing demand, may also drive or constrain such investments.

3.3.5 Gamma Level—supply side: Heating infrastructure investment system

At γ level supply side, the policy system addresses similar investment issues, but now on heating infrastructure. Similar values and outcomes of interest also apply.

It is known, for example, that the natural gas grid has been instrumental in enabling the application of small and large scale CHP and heat pumps to serve the urban heat market. However, the other type of infrastructure, namely district heating, is in competition with the natural gas grid. Using industrial heat byproducts and geothermal heat, the district heating network has high potential of reducing carbon emissions. So, to encourage investment in district heating, infrastructure regulatory schemes can be used, for example, to limit consumer's choice on particular heating systems (Grohnheit & Mortensen, 2003). Whether this scheme is adopted by a regulatory institution such as the European Union (EU) has become a major uncertainty for the players in the industry (X).

3.3.6 Delta Level—demand side: Dutch residential sub-sector emission system

At δ level-demand side, the major issue for policymakers is the cost-effectiveness of measures to reduce carbon emissions (O). In order to ensure the emission reduction goal, policymakers have financial incentives and disincentives to decision makers at level α, β, and γ.

A key determinant of emission reduction is the emission factor (I). This factor accounts for the quantity of emissions that are generated for each unit of energy produced. The emission factor is influenced by: (i) the efficiency of heat generation (O at α level), (ii) building thermal efficiency (O at α level), and (iii) the share of renewables in the energy supply for heating (O at δ level). The fuel mix for electricity generation will then be an aggregated emission factor that can be calculated from the contribution of each source of generation (e.g., Hondo, 2005; van de Vate, 1997). In addition, demographics developments in terms of the size of the population have a direct impact on the demand for housing and, therefore, energy for space heating.

As far as value judgments (V) are concerned, it has been made clear that the governments will not take environmental protection measures that will jeopardize the economic growth and competitiveness (Ministry of Economic Affairs, 2005). This tension might imply that one might be sacrificed for the sake of the other.

3.3.7 Delta Level—supply side: Dutch renewable energy system

At δ level-supply side, the effort to reduce carbon emissions in the residential sub-sector cannot be separated from the emissions resulting from electricity generation. In 2003, the fuel mix in the residential use of energy (including the fuel for heating) was 60% natural gas, 36% electricity, and 4% others. In the near future, the electricity share is expected to match that of natural gas

(International Energy Agency, 2004). Given this context, the Dutch government has set a target of 17% share of renewable electricity in the domestic demand in 2020 (Junginger et al., 2004).

There are, however, several uncertainties. First is the issue of access of renewable electricity production into the main electricity grid. For instance, due to the intermittent nature of wind, a stable electricity production from this source cannot be guaranteed. To deal with this issue, several strategies to integrate wind power, for instance, are discussed by Lund (2005). Second is the pace of technological progress that influences the cost of producing electricity by conventional fuels such as coal, oil, and gas. As long as the difference cannot be mitigated by outside interventions (e.g., government policies), there is little chance that renewables will thrive. Various on-going and discontinued Dutch government financial measures (P) to promote renewables are summarized in Junginger et al. (2004). Finally, the often overlooked factors are social preferences (V at β level) that, for example, may hinder the installment and placement of wind mills (e.g., Wolsink, 2000).

3.3.8 Epsilon Level—supply and demand side: European union energy policy system

At this ϵ level, the highest level considered, the emphasis is on the coordination and balancing the diverse and often conflicting interests of EU member states' energy policies (V). The expected result is a coordinated and synergistic implementation of EU energy policies among member states. The EU role in this case is more to provide guidelines that will then be translated and suited to the needs and conditions of each member state. EU directives on building performance are one example. The EU also sets the agenda for the energy policy debate among its members to make sure that policymakers at the national level coordinate their policies to achieve common EU goals, such as security of energy supply, competitiveness, and sustainability (see, e.g., European Commission, 2006). The bigger role of the EU, however, is in allocating its budget. All these dynamics will be dependent on political will for cooperation of the member states (X). For this, the EU can, in theory impose financial penalties on members who violate EU legislation.

Figure 4 illustrates how the specifications of policy systems from an SoS perspective can be made manageable despite the highly complex nature of the energy sector. This is achieved by formulating a specific policy issue, on which the definition of relevant system domains is based. The extent to which the relevant system is examined depends on the needs of insights. When the insight on a particular relevant system is crucial for the understanding of a policy issue, the system has to be defined explicitly in terms of XPIROV. For instance, in our illustration we take different manifestations of energy prices as one input for the heat and electricity consumption system. In reality, these manifestations are the result of a distinct dynamic in which unique XPIROV elements interact. So, whenever insight into this dynamic is required for the policy issue at hand, a complete XIPROV set will be specified.

To summarize, this section has have demonstrated conceptually how, within a specific policy issue, relevant policy systems can be identified and specified within the context of a energy SoS. Interdependencies between relevant variables across the various levels have been motivated. In addition, we have also highlighted the multi-actor nature of policymaking, in which each player has to take the other players' value systems into consideration.

4 Observations and Implications

From the construct in Figure 4, we can make some observations regarding (1) horizontal interactions, (2) non-linear behavior and (3) dealing with uncertainty. We discuss also some implications for policymaking.

The specification of SoS for the Dutch residential sector described in Figure 4 highlights not only the interactions among actors across the vertical hierarchy but also among the actors at the same hierarchic level (i.e., the horizontal interaction). For instance, at the national level, there is horizontal interaction between the policy system on the supply side and on the demand side. The share of renewables (i.e., the O of the Dutch renewable energy system) influences the emission factor (i.e., the internal factors, I) for the Dutch residential emission system. This dependency entails communication and coordination among decisionmakers that control the supply side (e.g., the ministry of economic affairs) and the demand side (e.g., the ministry of housing and environment). So within an SoS, both vertical and horizontal interactions among policy systems are major determinants of the aggregate behavior.

The construct in Figure 4 does not explicitly show that non-linearity in interactions among the policy systems may exist and further may be time-variant. While some non-linear effects may be anticipated, particular behavior may become visible only after the SoS construct is simulated. One example is on the so-called "locked-in effect". As the share of renewables is partly influenced by the cost of conventional fuel (δ level—supply side), obviously there is a threshold value of conventional fuel cost above which renewables would become competitive. When this threshold is passed, the share of renewables may increase at an accelerated (non-linear) rate. Another example is the diminishing return effect of subsidy effectiveness (δ level—demand side). Thus, for instance, increasing the subsidy level to encourage investment in more efficient heating technologies does not necessarily (and proportionately) increase such investments since some would be carried out (e.g., due to end of equipment service life) regardless of the subsidy. In conclusion, the non-linearity of the construct is embedded in the non-linearity of "if-then" logic that is applied to the construct.

On dealing with uncertainty, the construct in Figure 4 implies that one needs to specify the realizations of all the relevant XPIROV elements over time. We strongly argue that under conditions of deep uncertainty, broader, rather than the best estimate assumptions about these realizations are appropriate to base the representation of the system (see for example the idea of exploratory modeling in (Bankes, 1993)). As we argue in Subsection 3.3, alternative scenarios,

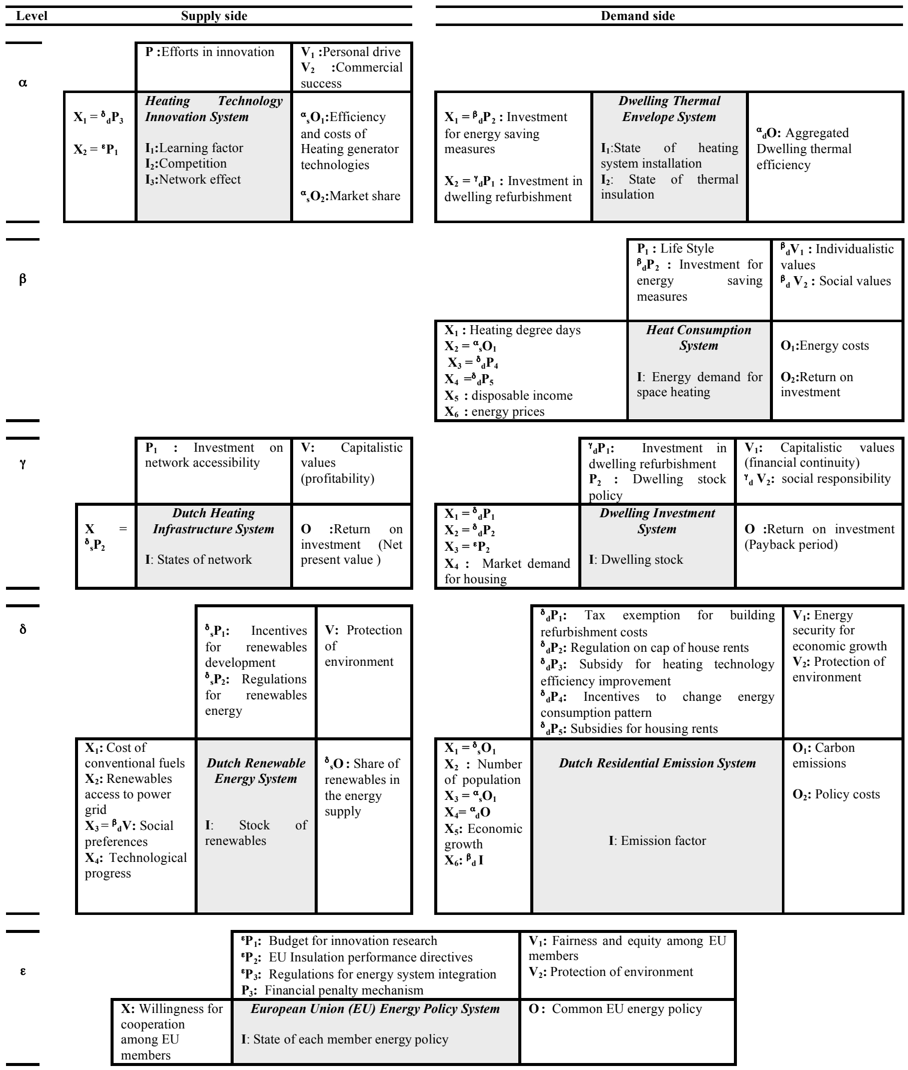

Figure 4: Specification of policy system across SoS levels and XPIROV structure Note: the elements with sub and superscripts indicate the interdependencies among SoS levels (s: supply side, d: demand side)

relationships, system structure, and decision/behavioral rules need to be explored in order to represent the policy system. In this way, the behavior of the system is examined using multiple "mirrors", which provide a more reliable picture than a single mirror does.

One major implication for policymaking illuminated by our formulation is that choice of a policy set should be based largely on the feasibility to influence the system variables. Obviously, there is a tradeoff to be made, especially among options that reside at differing levels. It might be the case that influencing the price of gas (β level) by tax for instance is more feasible than influencing demolition rate (γ level) by regulation or influencing the building code (δ level). Another example is policy alternatives to reduce carbon emissions. They might include a fiscal policy to influence the investment behavior represented by the discount rate (γ level) or awareness campaign to relax the hurdle for investment on energy efficiency technology represented by higher payback threshold (γ level). Controversially, policymakers might envision demographic policies to avert the decreasing trend of the household size (δ level), which has a large impact on the emission level. While determination of best choice of policy set requires careful analysis that is beyond the scope of this paper, we believe that the SoS perspective can provide a conceptual framework to structure the complexity of policymaking.

Another implication involves the trade-offs especially among options that are related in effect (on policy goal) but independent in control/implementation. The insights on such trade-offs can be used to facilitate informed debate and negotiation among multiple parties and stakeholders involved in the policymaking. Since different actors have direct influence on each policy system at each level of SoS, such insight informs them about different propositions one party can make to the other to achieve emission reduction target. For instance, house developers who are in control of demolition rates of old, inefficient buildings might be prepared to pursue a faster demolition rate to hedge against higher than expected population growth. They may make such propositions provided that the government increases the cap on house rents and does not impose a strict building code. This potential use should be further investigated in a real policymaking setting (see e.g., (Gregory et al., 2003)).

5 Concluding remarks

We started the paper by arguing that highly detailed models often hinder the ability to have a broad, high level understanding of long-term system behavior. We furthered argued that by taking broader assumptions about the XPIROV structure of the policy systems (rather than the best estimate of them), we can gain insight on robustness of policies under a wide range of system assumptions resolve the boundaries of regions that defined failed or successful policies. This broader view was enabled in a structured way through the system-of-systems perspective and integration of the associated lexicon. The relatively low resolutions of the model potentially enable the exploration and uncovering of knowledge and patterns of system behavior.

Using the specific policy issue involving the Dutch energy sector, we have illustrated how relevant policy systems are defined across SoS levels. We believe that the SoS perspective enables development of a problem model for a specific policy issue that is tractable, transparent, accessible, and communicable, thereby avoiding the problems faced by complex, fine-grain models. While determination of the best choice of policy set for the problem posed requires careful analysis that is beyond the scope of this paper, we believe that the SoS perspective applied with the XPIROV provides a conceptual framework to structure the complexity of policymaking.

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