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System dynamics approaches to energy policy modelling and simulation

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Abstract

Energy systems are complex dynamic systems that are often associated with uncertain system behavior. System behavior is influenced by several dynamic uncertainties, nonlinear relationships between system variables, time lags, and interactive feedback loops that are inherent in the energy system. In turn, these complexities are a result of the underlying structures of energy systems. Under this climate, it is essential to develop systems analysis approaches that can be used for development and evaluation of energy system policies, both at tactical and strategic levels. The purpose of this research is to present a taxonomic analysis of system dynamics approaches to energy policy modelling and simulation. First, we present an outline of dynamic complexities prevalent in energy systems. Second, we make a taxonomic analysis of energy policy formulation problems, learning from the literature. Third, we provide a causal loop analysis of the generic structures of the identified energy formulation problems. The archetypes presented form a valuable platform for system dynamics simulation of energy policy modelling and simulation.

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Keywords: Energy policy; energy mangement; simulation modelling;energy policy modelling; system dynamics

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1. Introduction

Energy systems continue to grow in size and complexity [1] [2]. Several issues and challenges continue to emerge in the energy industry in developed and developing economies. For instance, the energy industry has experienced widespread deregulation in electricity markets and electricity industry, which directly affects energy policy formulation and implementation. Moreover, technological changes and advances have impacted energy policy development and management. Global environmental concerns and issues, coupled with trends in global climate change, have been a major cause for concern in energy industry [3]. As a result, energy policy formulation often involves several stakeholders whose inputs and expectations are to be taken into consideration, if the policies are to be a success. This has exacerbated the dynamic complexities of energy systems. Such dynamic complexities include uncertainties, nonlinear causal relationships among system variables, interacting feedback loops, and time delays [4] [5] [6] [7] [8] [9]. Faced with these challenges and other pertinent issues in the energy industry, energy policy makers have to devise efficient and effective dynamic simulation methodologies which can handle complex energy systems.

Due to the existence of multiple energy demand and supply related factors, the dynamics of energy systems has become a serious challenge to the policy makers. Influenced by emerging changes in the energy market, consideration of uncertain complex dynamic aspects in the policy formulation process is imperative. In retrospect, these complex challenges and issues should be addressed in energy policy formulation and evaluation. To that effect, the purpose of this paper is to present system dynamics approaches to energy policy modelling and simulation. In light of this, this research follows through the following objectives:

1. To identify the dynamic complexities and challenges that are often associated with complex dynamic energy systems;
2. To develop a taxonomic analysis of energy policy formulation problems so as to visualize their generic structures; and,
3. To make a causal loop analysis of the identified energy policy formulation problems based on their generic structures.

The suggested generic causal loop structures provide a platform for system dynamics approaches to energy policy modelling and simulation. The causal loop structures can be useful to analysts and decision makers in the field of energy policy formulation.

The rest of the paper is structured as follows: The next section presents an outline of dynamic complexities prevalent in energy systems. Section 3 presents a taxonomic analysis of energy policy formulation problems, learning from the literature. Section 4 provides a causal loop analysis of the generic structures of energy formulation problems.

2. System dynamics archetypes for copying with dynamic complexities

According to Wolstenholme [7] [9], system dynamics archetypes are generic structures of systems that describe the dynamic system using causality cycles, positive (or reinforcing) and negative (or balancing) feedback loops. In other words, system dynamics archetypes are a useful approach for evaluation of the dynamics of possible scenarios of complex systems [8]. In this respect, system archetypes can assist policy makers to effectively visualize the entire energy system in order to predict unexpected system behavior.

Understanding systems variables and their interactions is very important when analyzing the behavior of complex systems, such as energy systems. In practice, essential system variables are always found in archetypes [7] [9]. Almost always, there exists a generic archetype for each generic problem archetype. Therefore, system archetypes are a useful platform modelling complex dynamic systems.

Table 1. An overview of system dynamics archetypes for copying with dynamic complexities [7] [9]

Generic Problem Archetype		Semi-Generic Archetype	Example
1.	Underachievement	Limits to success	Growth and underachievement
		Tragedy of commons	
2.	Out-of-Control	Fixes that fail	Problem child
		Shifting the burden	Criminal justice
		Accidental adversaries	
3.	Relative Achievement	Success to the successful	VHS vs Betamax
4.	Relative Control	Escalation	Quality improvement
		Drifting goals	Arms race

Table 1 presents a summary of four generic system dynamics archetypes and their semi-specific and specific subclasses, as identified by Wolstenholme [9]. In the next section, we identify the dynamic complexities inherent in energy systems.

3. Dynamic complexities in energy systems

Energy systems are inundated with a wide range of complex dynamic uncertainties, culminating into several challenges to energy policy formulation, both at tactical and strategic levels. We identify and outline four dynamic complexities in this section, namely, system uncertainties, nonlinear relationships between system variables, time lags, and feedback loop structures.

3.1. System uncertainties

Energy sectors are often faced with unprecedented changes [1]. Emerging economies have experienced ever-growing demand for energy, usage of energy, and investments in the energy sectors [2]. This leads to unforeseen dynamic imbalances in the energy system. Some of the major sources of uncertainties common in energy in energy systems are: (i) the influence of government subsidies and incentives may be adjusted from time to time, leading to various dynamic uncertainties; (ii) the influence of technological innovations and developments, such as those related to environmental emissions control, can be difficult to predict; (iii) the effect of price fluctuations are common in the energy sector due to unpredictable demand-supply related factors, leading to complex uncertain complexities; and, (iv) the presence of imprecise human perceptions which in most cases change over time in an unpredictable manner, leading to dynamic complexities. These and other system variables pose serious difficulties in energy policy formulation.

3.2. Nonlinear relationships between system variables

In energy systems, dynamic complexity arises from the fact that the response (or effect) of the system to an action (or cause) is often non-linear [3]. The response of the system to the action depends on its current state. As such, these non-linear relationships between system variables cannot be analyzed using conventional econometric and mathematical programming models. In the electricity markets, for example, a decrease in electricity prices will result in increased industrial usage [4] [5]. However, because the maximum production capacity will limiting the desired energy consumption, the actual industrial usage of electricity will eventually reach a maximum saturation value, even if prices may continue to fall. These non-linear relationships are of common occurrence in energy systems. Consequently, appropriate SD modelling techniques are essential for addressing such complex dynamic non-linear relationships.

3.3. Time delays

Consider an innovation project of a solar powered glass furnace. Such a project would involve several stages, including project approval, funding approval, design, construction and installation. These stages will involve time delays (or time lags), which may come in two forms: (i) material delays, for example, delays in construction, and (ii) information delays, for instance, delays in the notification of project approval [2]. These delays have a significant impact on project investors, shareholders, as well energy policy makers concerned with energy supply at industry level. These inherent time delays are difficult to take into account when developing energy policies [1]. Therefore, energy policy formulation approaches that address the inherent dynamics of time delays are most desirable.

3.4. Feedback structures

Observed dynamic behaviors of energy systems, such as trends in carbon emissions, adoption of renewable energy technologies, energy prices, and energy consumption are a result of underlying feedback structures in the energy systems [5] [6]. For example, increased industrial activities will lead increased demand for fuel, which in turn will lead to capital investment in energy supply in an effort to cover the demand-supply gap. Not surprisingly, delays are often experienced. However, adequate energy supply may influence industrial activities, which may eventually lead to increased demand, until the demand is fully met. This cycle continues until the demand is fully met, where capital investment efforts eventually reduce or stop. In practice, the status of the demand-supply gap will act as a feedback mechanism. The eventual energy system behavior is influenced by feedback structures that contain system variables, typified by the demand, investment and supply variables in our example. To provide appropriate energy policies, system dynamics approaches are crucial for modeling the influence of feedback structures inherent in energy systems.

3.5. Causal relationships between system variables

Energy policy analysts are largely concerned about the causal influence between various energy system variables, in the medium- to long term [4] [6]. It is vital to investigate the influence of regulatory policies, incentives and subsidies on the future energy supply mix and how the mix will eventually affect energy prices in the long run. Moreover, it is essential to know the impact of the energy supply mix on the overall health of the economy, energy resources, and the environment. The dynamics of the intertwined causal linkages between system variables need to be addressed and analyzed adequately using dynamic systems simulation methods. By so doing, cost-effective and sustainable energy policies can be formulated.

4. System dynamics archetypes for energy policy formulation

System archetypes attempt to represent and classify system structures and behaviors, particularly, counter intuitive behaviors [7]. In other words, systems archetypes describe behavioral patterns that are of common occurrence in systems. When used as diagnostic tools, system archetypes provide deeper insight into the underlying structures from which system behavior and events emerge. On the other hand, system archetypes can be used as prospective tools to highlight future unintended consequences [8] [9].

Energy policy formulation can be broadly classified into three categories, namely, strategic, tactical and operational problems. For enhanced simulation and analysis of energy system policy, we categorize energy policy formulation problems into energy-economy-environment (3E) problem, energy demand-supply management problem, new product innovation problem, capacity management problem, energy pricing problem, and hybrid energy management problem [10] [11].

4.1. Energy demand-supply management models

Researchers and energy policy makers are interested in developing energy systems models that link energy demand and energy supply related factors [10] [11]. A few approaches considered important dynamic factors such as time delays or lags and non-linear relationships between system variables [13] [14]. Variables researchers considered influential demand-supply related factors, such as economic growth, status of energy resources (reserves), industrial activity, propensity for investment, societal development, customer pressure, and technological supply capacity [11] [12]. Two limits to growth can be recognized from these factors, that is, energy resources and supply capacity. This analysis can be represented and analyzed in terms of a reinforcing and a balancing loop [13].

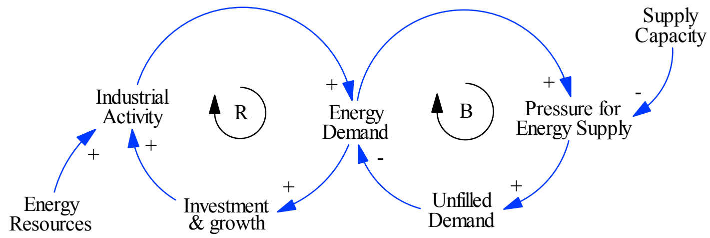

Fig. 1. Energy demand-supply: limits to growth.

Fig. 1 presents a system dynamics causal loop structure for the demand-supply problem based on the limit to growth archetype. Consider the reinforcing loop, identified by *R*. Energy demand leads to increased returns which promote investments and growth in industry. Continued investment will eventually lead increased industrial activity which in turn will increase demand for energy supply. However, this cycle is dependent on the available energy resources. On the other hand, energy demand is also limited by the prevailing supply capacity. Continued pressure for energy supply positively influences perception of unfilled demand which influences future demand in a negative way. As unfilled demand increases, active demand tends to decrease in the future.

4.2. Energy product innovation models

To meet the ever-growing global demand for energy in an economically and environmentally competitive manner, new strategies for energy technology innovation are required [10] [11] [12]. Development of new, clean energy sources is imperative [3]. This calls for strong resource capacity for not only to invent but also to commercialize and turn the innovation into something that will finally be adopted by the customer and provides real world benefits. However, innovation in energy systems is complex. Energy innovation projects tend to take a long time, and have a high failure rate. In today's world, commercialization of new energy technology requires integration of a number of technical and business disciplines, partnerships public and private entities, support from service organizations and most importantly, significant investment capabilities [13].

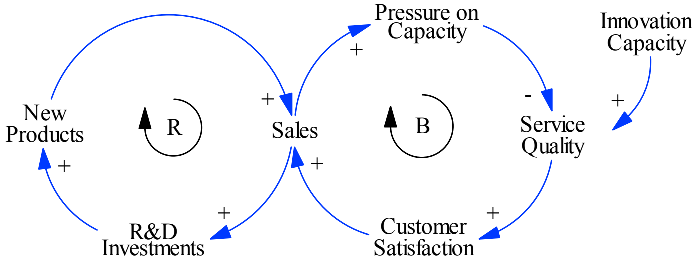

Fig. 2. Energy technology innovation: Limit to growth

Fig. 1 illustrates a system archetype for energy technology innovation with limit to growth. As indicated by the reinforcing loop *R*, significant investments in research and development (R&D) enhance development of new energy innovation products. This will in turn promote sales and profits. The growth cycle continues, subject to the balancing loop B. Growth is limited by the available innovation capacity of the system. As the capacity increases, service quality is enhanced, leading to customer satisfaction. With customer satisfaction, sales continue to increase, putting more pressure on the current innovation capacity. This negatively affects service quality, unless innovation capacity is adjusted accordingly.

4.3. Energy capacity management models

Energy capacity models are centered on managing capacity adjustment decisions in light of energy demand-supply factors [11], subject to capacity bounds such as availability of energy resources. Energy policy makers desire to make informed changes to capacity, at the right time, while anticipating the likely effects of their decisions when implemented. This problem lends itself to growth and underinvestment archetype [7] [8] [9].

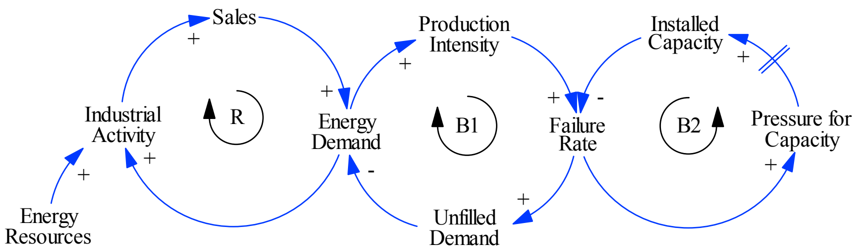

Fig. 3. Causal loop analysis: Growth and underinvestment

Fig. 3 presents the causal loop analysis for archetype 2 with growth and underinvestment. Subject to availability of energy resources, industrial activity enhances sales and energy demand, which in turn influences industrial activity. This is illustrated by the reinforcing loop *R*. On the other hand, energy demand activates more production intensity which often leads to high failure and unfilled demand, if capacity is not adjusted on time. With increased unfilled demand, the effective energy demand will eventually fall, as depicted by the balancing loop *B1*.

4.4. Energy pricing models

Energy pricing models are concerned with the dynamic non-linear interactions between energy prices, energy supply, and energy demand in the market [4]. As market prices dynamically adjust to changes in supply and demand, energy systems continually transition towards the point of equilibrium [13]. Nonlinearities, multiple feedback loops and time delays lead to unexpected system behaviors. Therefore, system dynamics archetypes are a more viable approach for evaluating the interactions among dynamic variables when formulating energy policies.

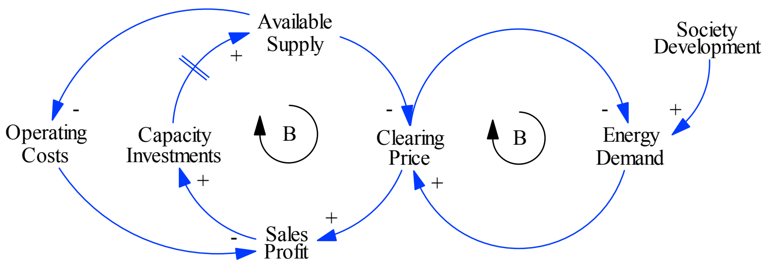

Fig. 4. Energy pricing: Limits to growth

Fig. 4 presents a generic structure of an energy pricing problem with limits to growth, consisting of a balancing loop *B* and a reinforcing loop *R*. The causal loop analysis shows that sales profit positively influences capacity investments, which in turn leads to more available energy supply. With more supply, the clearing price will be pushed down. On the other hand, the price is positively influenced by energy demand. While energy demand is negatively impacted by the price, it is positively affected by the level of society development which limits the resulting energy demand.

4.5. Energy-economy-environment models

Decision makers in energy policy have always desired to incorporate the 3Es concept in policy [6] [10]. Models in this category focus on fulfilling not only economic profit focused objectives, but also on the sustainability of energy resources, and environmental health [12]. The emissions tax policy promotes the polluter pays principle [Shafiei et al.]. Fig. 5 presents a causal loop diagram for a 3Es policy formulation model. The company that causes pollution pays for the cost of removing it and compensates those affected by it. This adds to the company's operating costs, which then reduces its profits, according to loop *B4*. In this case, capacity investments, and, eventually industrial activity, will be affected negatively. This cycle is defined by loop *B1*. However, industrial activity is controlled by the balancing loop *B2* with a limit of availability of energy resources.

Loop *B3* represents capacity growth cycle. Because of the inherent influence of price elasticity of demand, the price of energy finally affects the demand of users. However, the demand is also limited by society development, as illustrated by loop *B5*.

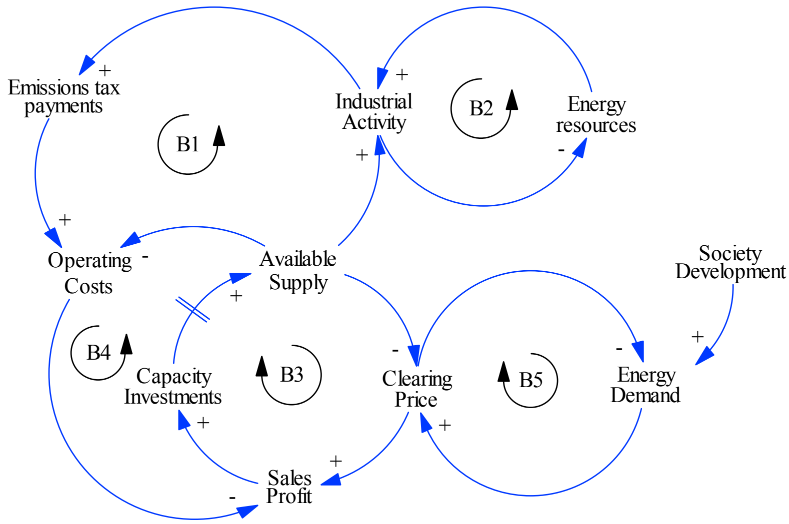

Fig. 5. Energy, economy and environment policy simulation

The 3Es policy simulation approach provides a more holistic perspective than other models, howbeit, it is more complex. The next section presents conclusions and further research prospects.

5. Conclusions and further research

Energy systems are associated with complex uncertain system behavior, which is influenced by several dynamic uncertainties, nonlinear linear relationships between system variables, time lags, and interactive feedback loops that are inherent in the energy system. This study presented a taxonomic analysis of energy policy formulation problems and classified them into five broad categories. Suitable archetypal structures were proposed for each of the categories. These archetypes are helpful to energy policy makers in three ways:

- The archetypes can be used for describing the behavioral patterns that are of common occurrence common in energy systems;
- The archetypes can be used as diagnostic tools to provide deeper insights into the underlying structures from which energy system behavior and events emerge; and,
- The archetypes can be used as prospective tools to highlight and inform energy planners in regards to the likely future unintended consequences.

In view of the above, system dynamics archetypes are useful in energy policy modelling and simulation in uncertain environments. Further research is expected to focus on applications of system dynamics archetypes to specific energy systems. The 3Es policy formulation approach is a promising area for further research.

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References

[1] Qudrat-Ullah H. Modeling and Simulation in Service of Energy Policy: The Challenges. The Physics of Stocks and Flows of Energy Systems, Springer Briefs in Complexity, Springer 2016: 7-12

[2] Qudrat-Ullah H. Modelling and Simulation in Service of Energy Policy. Energy Procedia 2015, 75: 2819 – 2825

[3] Shafiei E , Davidsdottir B, Leaver J, Stefansson H, Asgeirsson EI. Simulation of alternative fuel markets using integrated system dynamics model of energy system. Procedia Computer Science 2015; 51: 513–521

[4] Liuguo S, Shijing Z, Jianbai H. Pricing Simulation Platform Based on System Dynamics. Systems Engineering Procedia 2012; 5: 445 – 453

[5] Panda D. Impact of renewable energy sources in power supply of India – a system dynamics approach, (3), 5-9. International Journal of Power System Operation and Energy Management 2011; 2(3,4): 2231-4407.

[6] Qudrat-Ullah H. Understanding the dynamics of electricity generation capacity in Canada: a system dynamics approach. Energy 2013; 59: 285-294.

[7] Wolstenholme EF. Using generic system archetypes to support thinking and modelling. System Dynamics Review 2004; 20 (4): 341–356

[8] Braun, W. The system archetypes. System 2002 (2002): 27.

[9] Wolstenholme EF. Towards the definition and use of a core set of archetypal structures in system dynamics. System Dynamics Review 2003; 19 (1): 7–26

[10] Mutingi M, Mbohwa C. Fuzzy System Dynamics: A Framework for Modelling Renewable Energy Policies. In Energy Policy Modelling in the 21st Century (Ed. Quadrat Ullah H.), Springer, London, pp. 31-47.

[11] Jebaraj S, Iniyan A S. A review of energy models. Renewable and Sustainable Energy Reviews 2006; 10: 281–311

[12] Gimenez C, Sierra V, Rodon J. Sustainable operations: Their impact on the triple bottom line. International Journal of Production Economics, 2012; 140: 149–159.

[13] Shafiei E, Davidsdottir B, Leaver J, Stefansson H, Asgeirsson E.I. Simulation of alternative fuel markets using integrated system dynamics model of energy system. Procedia Computer Science 2015; 51: 513–521

[14] Sisodia GS, Sahay M, Singh P. System dynamics methodology for the energy demand fulfillment in India: A preliminary study. Energy Procedia 2016; 95: 429-434