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ScienceDirect
Energy Procedia 75 (2015) 2819 – 2825
Energy Procedia

The 7th International Conference on Applied Energy – ICAE2015

Modelling and Simulation in Service of Energy Policy

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Abstract

Modelling and simulation has long and well served the actors and various decision makers in the domain of energy policy. Various modelling approaches and models have been applied to address a variety of energy policy related issues. However, the journey continues. This paper provides an overview of these modelling approaches and models and identifies their key challenges in the face of emerging issues. The identified energy policy modelling related issues include the characterization of energy systems as complex, dynamic system with numerous uncertainties, non-linearities, time lags, and intertwined feedback loops. System dynamics modelling as a viable solution to address these issues is also suggested.

Peer-review under responsibility of Applied Energy Innovation Institute

Keywords: Energy policy; Modelling; Simulation; System dynamics

1. Introduction

In our modern day life, energy policy has always been at the forefront of public debates, legislative fora, and public and corporate decision making. Decision makers have to constantly find ways to balance the two critical aspects of any energy policy: economic welfare and environmental degradation. This is not an easy task. There is a basic dilemma in energy use. Energy use can contribute to economic growth and development activities, and at the same time, it is one of the biggest sources of environmental emissions which pose a serious threat to the sustainability of our planet. Researchers, especially modelling and simulation community, continue to investigate and provide policy insights on dealing with these complex issues. In this paper, we provide a systematic review of energy policy modelling and its challenges.

2. Energy systems modelling and its challenges

Peer-review under responsibility of Applied Energy Innovation Institute
doi:10.1016/j.egypro.2015.07.558

By and large modelling and simulation community has successfully used a variety of methods and techniques to serve energy policy needs. For instance, table 1 lists the major methodologies and themes.

Table 1: Modelling methodologies and major themes

Modelling Methodology	Major Themes	Source
Linear programming and dynamic programing	Capacity expansion and energy-economy analysis	WASP model [1], & MARKAL model [2]
A mixed-integer linear program	Distributed energy resource system	MILP model [3]
Econometric methods	Annual energy outlook and the role of carbon capture and storage	NEMS model [4], & SGM model [5]
Partial equilibrium model	Develop the US Climate Action Plan	IDEAS model [6]
Optimization	Energy-economy interactions and the options for SO_2 control	Meier & Mubayi's model [7] &Islas & Grande' s model [8]
Scenario analysis	Energy policies	Munasinghe and Meier's model [9]
Agent-based	Quantitative support for climate policy formulation and evaluation	ENGAGE model [17]

These models have been applied to address various energy policy related issues, be it in a developing or a developed region or country. Despite the demonstrated applicability and success of these operational methods over the past several decades [10], emerging issues related to energy industry (e.g., wide-spread deregulated electricity markets and industry, climate change and environmental concerns, multiple stakeholders, and technological disruptions) require new capabilities of modelling methods to fully capture the dynamics of energy systems. These challenges* include the existence of uncertainties, times delays, non-linear causal relationships, and interacting feedback looks in the energy systems.

2.1. Uncertainties abound

In general, widespread deregulation and privatization in the energy sector of the economies has created opportunities as well as challenges for the private investors including Independent Power Producers (IPPs). In the case of developing and emerging nations including India, China, and Brazil, growing demand of energy create imbalances proving further impetus for energy sector investments [11]. Hoverer, the dynamics of the much desired stock of "investments" in energy sector are uncertain:

i. *The nature and life of incentives and rules keep changing.* While the learning aspects of these changes are desired, the resulting often costly, lengthy, and uncertain litigations deter potential new investments in the energy sector of the host country (e.g., [12]),
ii. *Technological disruptions can severely impact the investments*. Costly retrofitting or installation of new technologies, say, for monitoring and control of electricity production-related environmental emissions is becoming common and is highly unpredictable,
iii. *The availability and prices of fuels are rarely in smooth order* – creating operational and financial difficulties for the energy projects,
iv. *Deregulation has expanded the nature and dimensions of stakeholders*. Compared with all most monopolized status of regulated regimes, now multiple stakeholders including competitors,

* Basic premise of modelling a system is that we are able to identify the forces (i.e., components or structures of a system) behind the problematic behaviour of this system. By controlling/managing the underlying structures of a system, the problematic behaviour could be improved.

regulators, large institutional investors, shareholders, local communities, end users, and environment lobbyists are involved in energy sector investments. Not only they are "many more" but these stakeholders come with conflicting objectives – making energy policy decisions even more complex,

v. *Perceptions of people change and sometimes in a relatively short order.* For instance, after the Fukushima nuclear accident in Japan in 2011, Germany and Switzerland has decided relatively quickly to close their power plants. Granted that unpredictability of such external events is inherent but the ability of the decision makers to explore such scenarios can better prepare them to deal with such uncertainties.

2.2. Existence of non-linear relationships is a reality

In energy systems, there exist non-linear relationships between the variables of the system that can hardly be analysed with traditional econometric and linear program techniques. For instance, when the price of electricity decreases, its industrial usage can see some growth (as is shown in Fig. 1). However, after a while, when even the price continue to fall, industrial usage of electricity will saturate (e.g., because the production reaches its maximum capacity). Likewise, the relationship between an operator's over time work and her productivity is non-linear – in the beginning, her productivity can increase (e.g., due to learning) but if she continues to over-work for long then her productivity will fall or even a complete collapse, the *burn-out phenomenon*, can occur. Productivity gains by the experienced power plant operators rarely follow a proportional path – more experience leads to the increased productivity but after some time productivity reached a plateau. Such non-linear relationships abound in socio-technical systems such as energy systems. Therefore, the utility of policy-supporting analysis of an energy system without an explicit representation and modelling of its critical non-linear relationships is limited, at best.

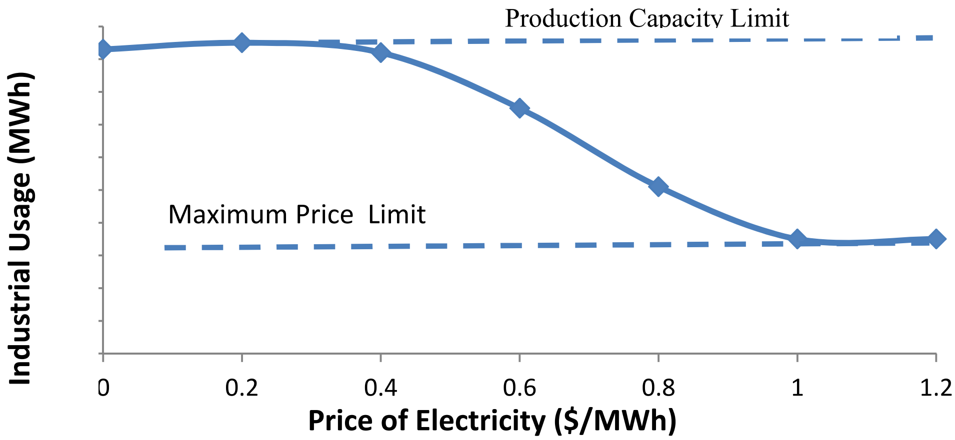

Figure 1: Non-linear Relationship between Industrial Usage and Price of Electricity

2.3. Time lags can't be ignored

Delays are inherent in energy systems. Consider the case of a new investor in, say gas-fired power plant. The major milestones of this new project, including approval of the application, securing of project funding, construction, testing and commissioning of the power plant, not only take time but often are characterized by delays. In general, these delays are of two kinds: (i) material delays (e.g., delay in the construction power plants (e.g., on average it takes 3-4 years to build thermal power plants and 6-10 years for nuclear and hydro (reservoir-based) power plants [13])) and (ii) information delays (e.g., delay

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in the notice of approval of the application and commissioning permit etc.). These delays have severe implications not only for the power plant investors themselves (e.g., delayed operations mean much delayed earnings leading to say, shareholders' discomfort) but also for the relevant energy planners and decision makers (e.g., the concerns of off-the-grid industry and population). Therefore, the modelling method for energy policy should have the capability to account for the potential dynamics of these inherent time lags of the energy systems.

2.4. Causation not correlation informs strategic decisions

Indeed energy policy decisions are strategic decisions – these decisions dictate the nature of future energy supply mix and influence the associated economics for the region. It is the information about the causal nature of the relationships between the variables of energy system that is useful for enacting an integrated energy policy. For instance, energy policy makers are interested in knowing the influence (s) of the various stocks of the energy system e.g., how does the stock of "electricity capital" (i. e., various power plants) impact electricity prices, over time? or which electricity supply-mix can provide affordable and cleaner electricity? or what would be the long-term impact of certain policy regulations and incentives? Therefore, the candidate modelling method for energy policy should be able not only to represent such relationships but also should provide information on the dynamics of these influences.

2.5. Energy systems are essentially feedback systems

Increased economic activities lead to higher electricity demand. Higher electricity demand requires new investments. New investments, after some delays, provide more electricity to close the loop (i.e., either the demand is fulfilled or the cycle, demand --- > investments --- > supply ---> demand, continues until the demand is fully met). Such a cycle is essentially a feedback loop where three variables of an energy system, demand, investments, and supply, are responsible for the resulting dynamic behaviour of this feedback loop (as is shown in Fig. 2).

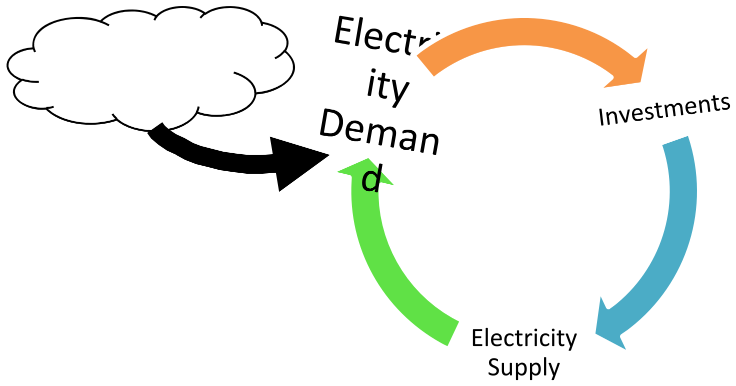

Figure 2: A Demand-Supply Balancing Feedback Loop

There exist several such feedback loops in an energy system and they are interacting among each other to produce the dynamic behaviour of the energy system (.e.g., a particular trajectory of electricity prices, environmental emissions, the stock of renewable technologies (e.g., windmills), sector related employment etc.) – much needed information for the decision makers to enact a systematic and integrated energy policy. Traditional modelling approaches are hardly adequate for providing such a feedback-oriented analysis of the energy systems to the energy policy decision makers.

3. The solution: System dynamics modelling approach

System dynamics approach [14] (Forrester, 1961) takes a feedback perspective to describe and explain the dynamics (i.e., changes over time) of complex systems. The fundamental premise of system dynamics is that the structure of a system drives its dynamic behaviour – endogenous view [15]. For instance, fluctuations in the price of crude oil (behaviour of the oil supply-demand system) are due to internal factors (e.g., disruptions in oil production, delays in the transportation of oil – internal structures of the oil supply-demand system). Thus, as per SD view, it is imperative that a better understanding and control of the (internal) structures of an energy system, should lead to better (behaviour s) outcomes (e.g., adequate and affordable supply of electricity). Likewise, a utility company's loss of market share, according to SD perspective, is due to internal (to the company) factors (e.g., low level of investments and low innovation rate in customer service sector – *the stocks and flows of the system*).

In fact, system dynamics models has been serving energy policy domain for more than five decades. For instance, in 1973, Fossil, a system dynamics model, was developed in the US for energy policy design, with the explicit focus on all the sources of energy and energy demand [16]. Building on the successes of Fossil, later on IDEAS model was developed and was the official Department of Energy' energy planning model for the United Sates until 1995 and the energy demand, electricity generation, oil, gas, and coal production, renewables, and environmental emissions were explicitly modelled in IDEAS [17]. Ford's work on the Pacific Northwest Hydroelectric System and electric utility is a solid body of system dynamics modelling (for an excellent review of Ford' work and other electricity related system dynamics modelling and applications, please see [18]). Adding the climate change context to the existing energy-economy interactions focused system dynamic models, FREE is a model that tests the implications of climate change related feedback processes [19]. Another well-known system dynamics model, ENERGY 2020 has been actively used by regional and national governments to conduct energy and emission related policy analysis in the US and Canada [17].

In early 1990s, the increased deregulation and liberalization in the energy sector of various countries introduced new uncertainties for the energy planners and decision makers – giving rise to even the higher demand of system dynamics models. As expected much of the modelling activity took place in the context of regional and national energy policies, liberalization and privatization of electricity systems, and environmental concerns. Table 2 list major system dynamics models that have been developed and applied to various energy policy related issues across the globe.

Table 2: System Dynamic Energy Policy Models

Energy Policy Modelling Themes	**Sources**
Design and assessment of regional and national energy and electricity policies	[5], [16-17], [19]
Privatization of electricity and firms' investment behavior	[23-26]
Energy efficiency analysis and management	[10], [21], [25]
Electricity market design and responses	[10], [20]
Generation capacity expansion	[20], [22], [26]
Renewables and environmental emissions	[19], [20], [22]

4. Concluding remarks

Overall, modelling and simulation has well served the energy domain for several decades. The existence of non-linear and uncertainty intensive variables, several inherent time lags, and intertwined feedback loops in an energy system pose serious modelling challenges. Now, the increasing

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liberalization and privatization, heightened emphasis on environmental issues including global warming and climate change, complexity of multi-dimensional and conflicting interests of stakeholders, and unprecedented technological disruptions have only added to the complexity of the task of the energy policy decision makers across the globe. In the context of these forceful developments, the traditional econometric and linear programming methods alone are not adequate to deal with the complex, dynamic nature. System dynamics methodology does rise to this challenge.

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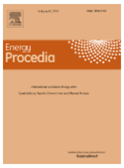

Biography

Hassan Qudrat-Ullah is associate professor of management science, the School of Administrative Studies, York University, Canada. Dr. Hassan has 18 years of teaching, research, and consulting experience in the USA, Canada, Singapore, Norway, UK, Korea, China, Saudi Arabia, and Pakistan. His research interests include system dynamics modeling and energy policies.