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Application of system dynamics approach in electricity sector modelling: A Review

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Abstract: Electricity has become a vital source of energy for social and economic development in modern era. Likewise, the issues of its planning and management have grown complex. To address complexity in decision making, researchers have chosen system dynamics (SD) modelling and simulation technique. A state-of-art of such studies published during the period 2000-2013 is presented in this paper. The contribution of this review lies in categorizing the literature based on the important and contemporary researched areas. These research areas include models developed for policy assessment, generation capacity expansion, financial instruments, demand side management, mixing methods, and finally micro-worlds. Review shows that policy assessment and generation capacity expansion are the two most modelled topics. Financial instruments models evaluate different mechanism to support renewable technologies whereas mixing-methods channelize descriptive approach of SD into evaluating a single objective. Demand side management and micro-worlds are the least focused categories in SD. This paper also discusses the individual models in each category highlighting their construct, outcomes and any deficiencies.

Keywords: electricity; modelling; system dynamics;

1. Introduction

Energy planning has been classified as a complex issue due to its interaction with other sectors of the society [1]. These interactions include production, demand, technology, fuel security, affordability and environmental concerns. With an increasing dependence of modern society on energy, a myriad of models have been developed to facilitate energy planning process. The aim of these models is to understand and analyse the complexity surrounding the energy issue so that not only resources are managed efficiently but also demand is met adequately with minimal damage to environment. These models come from disciplines like economics [2, 3], operational research [4, 5,6], and social sciences [7,8]. Jebaraj and Iniyan [9] reviewed energy models in the literature, and grouped them as follows: energy planning, energy supply–demand, forecasting, optimization, neural networks and fuzzy theory based ones. Bazmi and Zahedi [10], Baños et al. [11], and Foley et al. [12] reviewed optimization-based models for energy system planning. Furthermore, Connolly et al. [13] reviewed computer simulation models that allow analysis of integrating renewable energy sources. This review paper is distinct from previously mentioned ones as it reviews models particularly developed using System Dynamics (SD) approach.

In this review, only one form of energy, electricity, is focused. The reason for this emphasis is because electricity is the newest form of energy human society has embraced [14]. Also, the demand of this commodity has increased at a dramatic pace of 3.5% annually [12]. Moreover, due to its importance, electricity has been the prime focus of many energy related studies as well [15]. Beside this, to maintain a secure, reliable and affordable supply of electricity, decision making process in the sector has become a challenge for investors and policymakers, alike, due to uncertainties surrounding electricity sector. The sources of uncertainties are: (i) delays in generation and related infrastructure construction; (ii) choice and advancement in technology; (iii) resources limitation; (iv) price and demand fluctuations; (v) pollution and environmental concerns, and, last but not least, (vi) regulatory and political issues. Further, electricity sector is dynamic in nature; it is continuously evolving over time. The aforementioned sources of uncertainty are also inherently dynamic in nature. The decision making landscape becomes even more intriguing when a competitive electricity market structure is considered [16].

As proposed by McIntyre and Pradhan [17] while developing any decision making model in electricity sector, a holistic approach must be adopted. This requires that not only technical but also social, economic and environmental issues to be considered. The well-known models like MARKAL/TIMES, LEAP, WASP, EGEAS, MESSAGE, RETScreen and many more, rooted in the above mentioned disciplines, do adopt a holistic approach but ignore feedbacks, delays and nonlinearities related to factors being modelled. Furthermore, non-SD models rely on equilibrium or energy balance framework. This assumption in long-run cannot be maintained. The reason for this shortcoming is the continuously evolving nature of social, economic, environmental and technological factors involved. To cater for the deficiencies, researchers resolved to SD approach of modelling, analysis, and evaluation. SD approach has a number of merits over other modelling approaches. This includes:

1. Allowing researchers to model complex energy system from cause-effect perspective, rather than relying on statistically significant relationships;
2. Enabling a modeller to identify feedbacks which enrich analysis capabilities of the model; and
3. Relaxing the linearity hypothesis, thus allowing modellers to include nonlinear relationships.

Over years numbers of researchers have used SD to model electricity sector. Therefore, there is a need to glean information on those models.

The layout of this paper is as follows. Section 2 describes the objectives and research design, followed by a brief introduction of SD methodology in Section 3. Section 4 reviews in detail the studies done using SD. The paper concludes with major findings in Section 5.

2. Objectives and Research Design

The motivation of this survey is to highlight SD contribution to electricity sector modelling. The objectives of this research include: (i) to review electricity sector modelling done using SD and (ii) to serve as a critical reference on issues and construct of those SD models. The period of interest for this review started in January 2000 and ended in December 2013. The choice of time period is based on the fact that a review prior to 2000 has been published by Ford [18].A year by year search was made on Elsevier SCOPUS, Springerlink, and EBSCOhost online databases using key phrases. The key phrases used were: SD and electricity, computer simulation and electricity, electricity and policy modelling. Each database search was then limited (discipline wise) to full length peer-reviewed articles. Conference papers, communications, and book reviews, master and doctoral theses were excluded. Selection of articles was limited to journal articles only because journal article represent the top-echelon of research [19]. Scrutiny of articles resulted in 55 papers of which 35 fall under the scope of this review. Table 1 shows the distribution of reviewed papers by journals.

With the design intent in mind, SD and electricity sector, individual articles were reviewed thoroughly to identfy the focus, uniqueness, any shortcomings. Each article was then grouped in the ‘most appropriate’ category and before comparing it with other papers within the same category.

Table 1:   Distribution of reviewed papers by journal

Journals	**Number of papers reviewed**
Energy Policy	13
Energy	5
Renewable Energy	2
Socio-economic Planning science	2
International Journal of Electricity Sector Management	2
European Journal of Operations research	1
International Journal of Critical Infrastructures	1
International Journal of Simulation	1
Simulation Modeling Practice and Theory	1
Sustainability	1
System Research and Behavioural Science	1
System Dynamics Review	
Ecology and Society	1
Applied Energy	1
IEEE systems journal	
Kybernetes	1

3. System Dynamics Modelling Approach

The modeling and simulation method of SD was first developed by Prof. J.W. Forrester, MIT, in 1950s to analyze complex behaviors in social sciences, distinctively in management, through computer simulations [20]. Prior to the SD, decisions made to tackle a problem often resulted in unexpected outcomes; hence there was a pressing need for developing a new methodology [21]. This counter intuitive behavior of the system is attributed to the structure in which they are influencing each other, rather than to the variables of the system [21].

SD modelling process starts with problem articulation to determine the boundary of the system. Causal loop diagrams are then drawn with major variables linked together in feedback fashion. Causal loop diagram (CLD) links system variables by arrows. These arrows show the direction of influence while the polarity accompanying arrows depicts the effect of influence: positive for direct, and negative, for an inverse influence. A CLD schematic is depicted in Figure 1. A mathematical stock and flow diagram (SFD) is then developed for simulation purpose followed by a testing phase. The final stage of modelling process is policy design and evaluation. This stage consists of 'what-if' analysis and sensitivity tests.

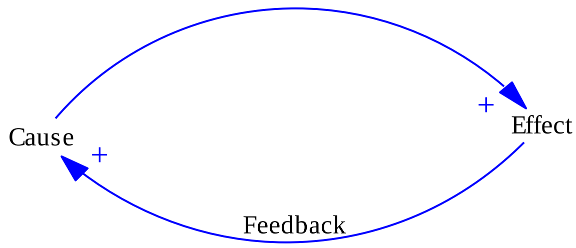
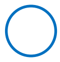


Figure 1: The Causal Loop Diagram. Adapted from [21]

To develop a quantitative SFD from qualitative CLD, four building blocks are used: stock, flow, auxiliary, and a connector (see Table 2). A stock shows the level of any system variable at a specific time instant and can be of two kinds: tangible or intangible. Tangible stock includes natural stocks, goods or capital, whereas intangible stock can be information, psychological or any indexed value. Flow or 'valve' is attached to a stock. Flow is responsible for increasing or depleting stock's level. An auxiliary or a converter can be parameters or values calculated from other variables within the system. Finally, a connector or an arrow denotes connection and control between system variables.

Table 2: Basic building blocks used in system dynamics with icons

Building block	Symbol	Description
Stock (level)		It shows an accumulation of any variable.
Flow (rate)		Attached to a stock. Alters stock level by an inflow or an outflow
Auxiliary(convertor)		Connects stock and a flow in a complex setting. Used for intermediate calculations.
Connector		Link different building blocks, showing the causality

In Figure 2, an SFD built in iThink® shows the icons used for various building blocks. The cloud icons that are at the start and at the end of the inflow and the outflow represent the system's boundary.

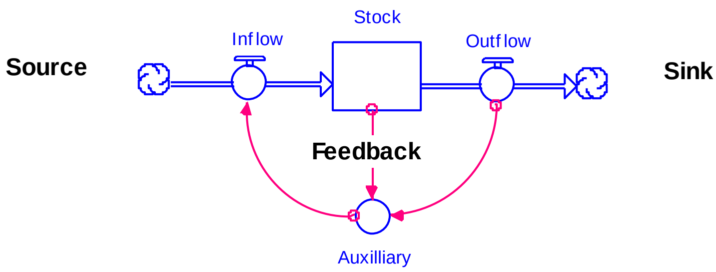


Figure 2: Stock and Flow diagram in iThink®. Adapted with modification from [21]

4. System Dynamics and Electricity Sector Modelling

In this section, a review of models using SD methodology is presented. The categorical distribution of articles is presented in Table 3.

Table 3: Distribution of reviewed papers by categories.

Categories	Number of papers reviewed
Policy Assessment	12
Generation Capacity Expansion	9
Financial Instruments	5
Mixing-methods	3
Demand Side Management	4
Micro-Worlds	2

4.1. Policy Assessment Models

A policy assessment model evaluates an intended or implemented policy in a country. These models investigated support policy for private investors [23,24]; policies for power market deregulation [25,26,27]; cross-border trading of electricity [28,29]; comparing policies to promote renewable power sources reducing dependency on fossil fuels [30,31, 32, 33], and environmental savings [34].

By anticipating the effect of changing policies on the electricity market, Qudrat-Ullah and Davidsen [23] developed an SD model of electricity generation sector of Pakistan. The model investigated the impact of government's policy of boosting private sector investments in power generation. Demand, investments, resources, production capital, production, environmental, and finally the financial sub-sectors were modelled. The interaction of these sub-sectors with the Gross Domestic Product (GDP) driving electricity demand was assumed to produce dynamic behaviour of industry. The model simulations revealed that government's continuous support to Independent Power Producer (IPP) resulted in fossil-fuel based capacity investments, and consequently CO_2 emission. Simulations further revealed that with a new policy in place, hydroelectric development would be impeded. The model effectively showed the side effects of a policy. However, overly relying on a single exogenous variable (GDP) as the driver of long-term demand seems not that appropriate. Other macro-economic factors, like population and electrification rate could be more appropriate for inclusion in a model of a developing country. With similar sub-sectors and policy focus, the study by Qudrat-Ullah and Karakul [24] revealed that investments in generation sector seemed not sufficient to meet the growing demand in the long-term. Though both studies model revealed ramifications of new policy effectively, they ignored any environmental or demand reduction measures on the system. Further, both of these studies ignored renewable technologies for power generation, apart from large hydropower. In addition, future investments were made dependent on the identification of a least-costing technology (also adopted by Pasaoglu Kilanc and Or [26]). This narrowed down the scope of technology evaluation as oppose to one from multi-perspectives, which is more holistic.

In the back-drop of electricity industry deregulation, Kilanc and Or [27] developed a model to observe the future composition of Turkey's electricity generation sector. Though the model has similarities in model sub-sectors to Qudrat Ullah and Davidesn [23] and Qudrat-Ullah and Karakul [24], however, investors were divided into three categories: incumbent, IPPs, and new entrants. Also, a bidding mechanism for export of electricity to grid was introduced. The model was capitalised by Pasaoglu Kilanc and Or [26]. Simulation exposed the imperfect foresight of investors in decision making and power plant construction delays resulting in generation capacity and electricity price fluctuations. A technology lock-in to natural gas and hydropower plants was also observed. Moreover, despite government's support, simulations showed under investments in wind power and no explanation for this finding was provided. Further, no mechanism was provided in the model which could avoid market power of investors. This shortcoming was highlighted in simulations when generation companies can decide to withhold their capacities, subsequently raising electricity price.

Set in a regulated electricity market, Ochoa [28] presented a qualitative SD model for Switzerland. A CLD was developed to identify the repercussions of different policies. Particularly, the model was concerned with identifying the influence of nuclear power phase out and bilateral electricity exchanges on installed generation capacity and electricity price. On the basis of the conceptual model, the author claimed that withdrawing nuclear power from supply chain would not only increase import dependency but also electricity price. In case policy bans import, only then capacity expansion could be expected ensuring security of supply and earning from export of electricity. The qualitative model ignored the environmental and transmission network constraint of the system along with considering renewable technologies for power generation. Ochoa and van Ackere [29] expanded the scope of Ochoa [28]. Simulation demonstrated that international electricity exchanges were essential for meeting demand, keeping cost of electricity low and in generating income for utility companies. In case of a nuclear phase out, simulations revealed that the capacity gap could only be filled by gas based technologies. Fluctuations in generating capacity were observed in model's output, similar to Pasaoglu Kilanc and Or [26]. The study elaborated the model through CLD only and the lack of any description of mathematical formulations used. The CLD used by Ochoa and van Ackere [29] is shown in Figure 3.

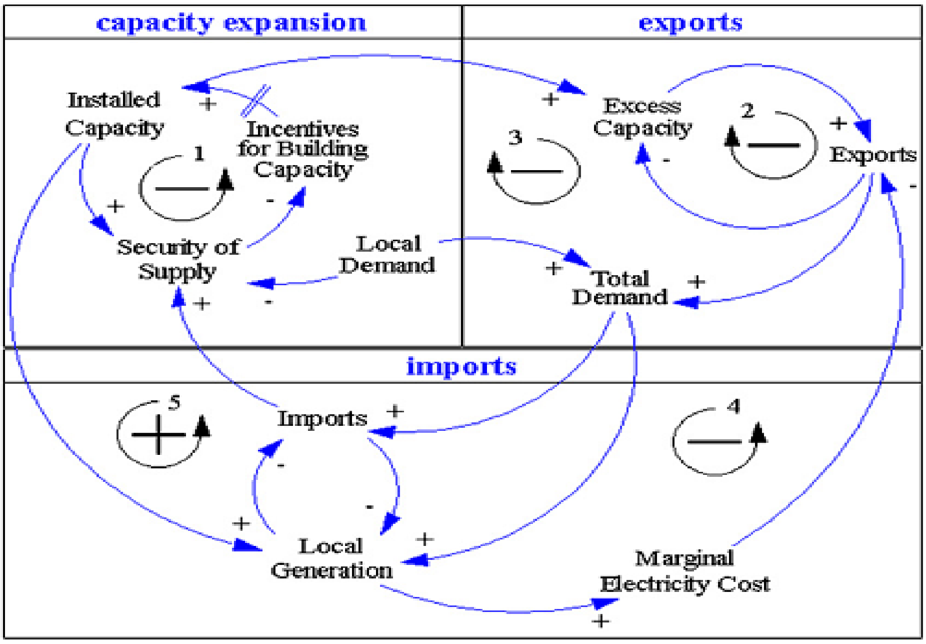


Figure 3: Causal loop diagram to model Swiss. Source [29]

Stemming from the sustainability framework, Cimren et al. [30] developed a model to analyze waste-to-electricity policy for Ohio, USA to curb CO_2 emissions as well as its potential in creating new jobs. Incorporating job creation in the model was a novel idea used in this study. This was in contrast to Qudrat-Ullah and Davidsen [24], Pasaoglu Kilanc and Or [265], and Ochoa and van Ackere [29], who focused more on economics of technology and meeting demand as the prime factors for selecting a technology. The analysis found that the said policy not only reduced greenhouse gases but it also created new jobs. Though results were presented in the paper, model development was significantly lacking in the study. Also, the study assumed all available biomass to be co-fired with coal for power generation while neglecting other uses of biomass, for example, as fertiliser. Furthermore, split between biogas and biomass for electricity generation was neglected in the model.

Zhao et al. [31] model focused on assessing two incentive policies for promoting solar photovoltaic (PV) in residential sector. These policies included investment tax credit (ITC) and feed-in tariff (FiT). The developed model used Bass model of technology diffusion at its core. However, the introduction of two new variables, i.e. the payback period of investments, and the household monthly income extended the classical Bass model. Unlike Qudrat-Ullah and Davidsen [23], the driver of increasing demand was not made explicit. The model pivoted on calculating the payback period for investment decision which was then used in macro-level setting to highlight the PV adoption process. Simulations showed that an incentive policy did sped up the technology adoption process. However, no significant difference was found between either policy - FiT or ITC. On methodological side, the study lacked presenting feedback structure used in relating both policies. Also, the model treated solar PV technology as a mature technology with no link to cost reduction (either by using technology or by technology advancement) as the one studied by Hsu [35].

Despite the interdependency of electricity and water, there is a lack of frameworks guiding policy developments [36]. To encourage researchers to deal with this issue, Newell et al. [32] proposed a qualitative SD model for Australia. The issues of water scarcity, emissions and electricity production were dealt with in the model. Unlike Elias [37] who relied on focussed groups, this study used secondary data to highlight the problem through various CLDs. On the contrary to Qudrat-Ullah and Davidsen [23], Cimren et al. [30] and Saysel and Hekimoglu [34], the study included the issue of food security related to electricity production through water scarcity, not just CO_2 emissions. However, in the same way as Pasaoglu Kilanc and Or [26], the study modelled imperfect foresight of decision-makers in dealing with the issue. The study proposed to policy makers to readily change the structure of Australian market and increase cross sector dialogue in dealing with electricity and water issues comprehensively. In comparison to Ochoa [28], the CLDs presented lacked coherence. Furthermore, no proper justification was given for electrification of transport sector as the only factor for an increase in electricity demand. Electricity demand can be modelled by many macro-level indicators like, population, changing life style and economic growth of the country. Also, the study excluded consideration of renewable technologies for power generation which are very pertinent to policy-makers in the described scope of work.

Ahmad and Tahar [33] presented a model that assessed renewable capacity target for five different technologies in Malaysia. The model relied on modelling delays in planning and construction while ignoring how various factors (e.g. demand, cost, reserve margin etc.) influenced investment decision as modelled by others (see Refs. [23,24,34]). Though the findings were very useful for future policy development, the lack of feedback between capacity expansion plan and cost of technology made the model to be less dynamic.

Fuentes-Bracamontes [25] developed a model named REFELECTe. The model focussed on Mexican electricity generation sector only in the context of deregulation policy. Like Qudrat-Ullah and Karakul [24], the model used demand, price, investment-decision and environmental sub-sectors. The main driver of the model- electricity price- was modelled as follows in Equation (1).

$$\textit{electricity price} = f\,(\textit{fuel cost, reserve margin}) \qquad (1)$$

The output of the model revealed that the competition in fossil-fuel technologies - while keeping the control of hydro and nuclear capacity with the government - achieved environmental and security of supply target, along with keeping the price within acceptable range. Unlike Qudrat-Ullah and Davidsen [23] and Qudrat-Ullah and Karakul [24], REFELECTe used IF-THEN-ELSE statements for choosing between various generation technologies being modelled. This approach, though simple and less computational, served the purpose effectively. The model assumed future capacity investments as a function of capacity retirements. This setting ignored capacity investments which were needed due to rise of demand. REFELECTe's algebraic equations were provided but the lack of causal loop diagrams undermined the confidence in the model. Finally, assuming an accelerated depreciation of a power plant on the basis of underutilization seemed an unrealistic assumption. Though a particular technology power plant may be lower in the merit-order of scheduling, dismantling it before the lapse of its useful life was uneconomical, as power plants have almost no salvage value [38].

In a study undertaken by Saysel and Hekimoglu [34], contribution to carbon mitigation policy by electricity generation from renewable resources was discussed. The model allocated future demand onto five renewable and two fossil-fuel technologies based on the cheapest production cost basis. The same approach of choosing a particular technology has been adopted by Qudrat-Ullah and Davidsen [23] and Fuentes-Bracamontes [25]. Though logical, this approach failed to account for externalities (e.g. social and technological advancements) in renewable technologies. In addition, the study assumed capacity replacements prompted by price driven incentives, like Fuentes-Bracamontes [25], which was also not possible as power generation technologies were capital intensive with almost no salvage value. The study showed that emission reduction policy can be successful, if power generation was shifted to renewable resources.

The models used for policy assessment are summarized in the Table 4.

Table 4. Policy assessment model summary.

Model focus	Reference	Weakness
Deregulation	Fuentes-Bracamontes [25]	Ignored capacity investments due to rise in

		demand
	Pasaoglu Kilanc and Or [26]	Formulation to limit market power of competitors was not modelled
	Kilanc and Or [27]	Sparse description of mathematical model
Support policy for private investors	Qudrat-Ullah and Davidsen [23]	Overly relying on one variable for driving the model
	Qudrat-Ullah and Karakul[24]	Environmental ramifications were being ignored
Environmental saving	Saysel and Hekimoglu [34]	Social and technological advancement were ignored
Cross-border trading of electricity	Ochoa [26]	Reference- mode behaviour of key variables was not provided
	Ochoa and van Ackere [27]	Environmental and transmission network constraints were ignored
Promote renewable power sources	Cimren et al.[30]	Other uses of biomass were ignored
	Zhao et al. [31]	An analysis of combination of two incentive policies was neglected
	Newell et al. [32]	Integration of concept was difficult due to lack of coherence between various models
	Ahmad and Tahar [33]	Narrowly focussed model on policy target

4.2. Generation Capacity Expansion Models

Articles falling under this category comprise of models that were developed to address the generation capacity expansion (GCE) problem in the electricity sector. GCE decision is crucial to decision makers as the entry and exit barriers in power generation sector are high. Therefore, vigorous analyses are needed before committing to generation capacity expansion. The main focus of GCE models was to find out which technologies for power generation will constitute the system in a long-run i.e. in the context of being the most profitable as well as serving the demand. Some GCE models investigated multi technologies (e.g. Olsina et al. [38], Hasani-Marzooni and Hosseini [39] and Qudrat-Ullah [40]), while others were focussed on a single technology expansion (e.g. Gary and Larsen [41], and Ford [42]). Moreover, as GCE models consider perfect market conditions (i.e. where a quick recovery of profits is paramount), only mature technologies were considered. Within these generation technologies, fossil-fuel technologies were preferred mostly. The only exception for the choice of technologies can be seen in the models by Hasani-Marzooni and Hosseini [39] and Qudrat-Ullah [40]. The former included wind power whereas the latter used aggregated renewable technologies alongside nuclear power.

The generic causal structure used by GCE models is presented in Figure 4. According to this structure, GCE decisions were made based on the profitability assessment of a particular investment. There was a delay between the investment decision being made and the actual generation capacity coming into operation. The supply-demand gap along with technology capital cost and market price of electricity were the crucial factors to be considered for the return on investment.

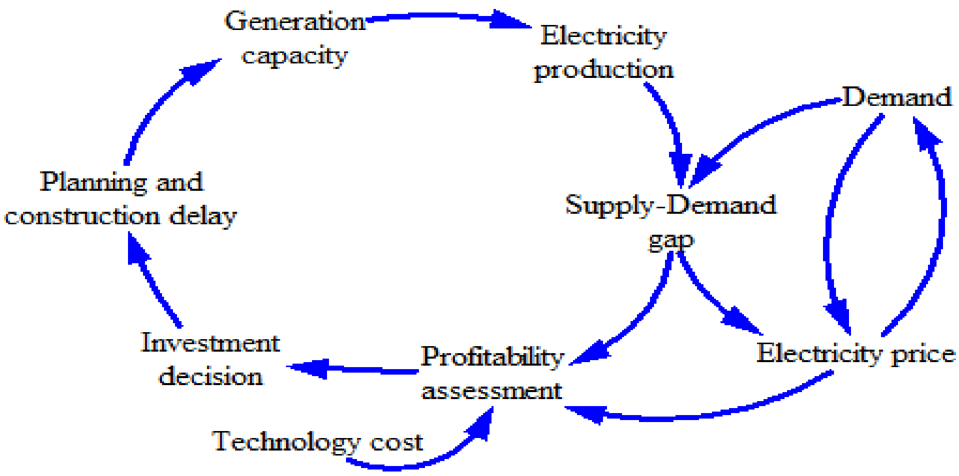


Figure 4: Generic causal structure used in GCE models.

Though the general structure presented in Figure 4 is at the core of GCE models, each study tailored it to suit its own focus. Gary and Larsen [41] disregarded capacity retirements which could send a flawed signal of total capacity to decision makers, thus undermined the effectiveness of the model's behavioural approach in decision making. Likewise, Olsina et al. [38] incorporated variable efficiencies over the operational life of technologies for electricity generation. Other studies chose to consider a fixed efficiency value.

The price estimation of electricity by Olsina et al. [38] was modelled by the interaction of demand and supply curves while the one developed by Ford [42] relied on average price of electricity. Furthermore, Olsina et al. [38] considered the demand to be price inelastic. This was a weak presumption as it neglected long-run changes in demand which may result due to adopting energy efficiency measure. This drawback was improved by Hasani-Marzooni and

Hosseini [39] in their model by considering the demand to be elastic. In the same context of price of electricity, Hasani-Marzooni and Hosseini [39] used the total electricity generation to influence the price of electricity instead of using the supply demand gap of the system. Though it served the purpose, it made the model to be less strategic and more operationally inclined - a contradiction to the focus of GCE models.

It was also found that each of the GCE model was focusing on a particular national market. For example, Gary and Larsen [41] focussed on the UK, Ford [42] modelled the USA market, Olsina et al.[38] developed a GCE model for Argentina, Qudrat-Ullah [40] for Canada, and Park et al. [43] for Korea, to name a few. This trend seemed to be very logical as each country's market has some distinctive characteristics. Despite the geographical difference, all models reported a similar result. Simulations showed a cyclic behaviour in the total operational capacity and the price of electricity. This output was endorsed to power plant construction delays, and cognitive limitation of investors' ability to foresee the market trend.

Generation capacity expansion issue also deals with a topic of capacity payment mechanism. This mechanism serves as an incentive for expanding generation capacity. The objective of this payment, from regulator to generator, is to ensure a certain capacity above peak demand to hedge any risk of supply deficit. Description of various capacity mechanisms can be found in [44]. The main variable to define a capacity payment mechanism was supply-demand gap; the larger the gap, the higher is the payment from regulator to investor. To identify the level of capacity payment, various approaches were being used. These include probabilistic approach adopted by Park et al., [43] and Arango [45], a market oriented one by Assili et al. [46], and finally a hybrid of fixed and market oriented one by Hasani and Hosseini [44]. Table 5 summarizes the studies and the approaches used.

Table 5: Capacity payment mechanism result comparison

Capacity payment mechanism	**Prime decision variable**	**Reference**
Probabilistic-fixed	Supply-demand gap	Park et al.[43]
Fixed-variable hybrid	Supply-demand gap	Hasani and Hosseini [44]
Market oriented variable	Supply-demand gap	Arango [45]
Probabilistic-variable	Supply-demand gap	Assili et al.[46]

Park et al. [43] modelled the capacity payment mechanism based on identifying loss of load probability (LOLP) calculations. Equation (2) and Equation (3) show the relationships.

$$LOLP = f\,(demand,\ installed\ capacity) \quad (2)$$

$$LOLP\ based\ capacity\ payment = LOLP*(Value\ of\ Loss\ of\ Load - Marginal\ Price) \quad (3)$$

The study assumed a fixed Value of Loss Load to be flawed. There were two different classes of generators in a system; ones that supply a base load and those supplying the peak load. Value of Loss of Load for peak generators was much higher than for the base load suppliers. Arango [45], on the other hand proposed deterministic market oriented approach for capacity payment. The model relied on interactions between price, demand, economic dispatch, bidding price, installed capacity, and investment decisions fashion. However, there was lack of mathematical formulations for the proposed model specifically in a feedback setup.

Assili et al. [46] in their study used a probabilistic approach to calculate LOLP. However, instead of using an exponential decay for LOLP calculation as used by Park et al. [43], a binomial distribution function was used in the model. Hasani and Hosseini [44] used a hybrid of fixed and variable capacity payment mechanism. Fixed payment values were set in accordance to the supply-demand gap while the variable part was made contingent upon the extra generation capacity anticipated.

GCE models with capacity payment mechanism showed that the cycles or oscillations seen in GCE problem were reduced irrespective of the type of capacity payment mechanism employed. Furthermore, it seemed that variable capacity payments were better than fixed payment mechanisms.

Models reviewed in this category explained that it was difficult to balance supply and demand in electricity sector. It was found that investor needed a continuous financial support in order to ensure safety margin of capacity. At present, it seemed that fossil fuel technologies were the preferred over renewable technologies in GCE models. Finally, planning and construction delays in the expansion of generation capacity were critical to be considered.

4.3. Financial Instrument Models

Financial instruments category comprises of studies that modelled various mechanisms to promote investments in renewable generation capacity. The need for such instruments was due to high cost of renewable technology [47], and to be able to shift electricity generation on a more sustainable track [48]. These instruments comprised of two quite similar entities, namely, Tradable Green Certificates (TGC) [49, 50] and Zero-Emission Certificate (ZEC) [51], along with the FiT scheme [35], and a general investment incentive scheme by Alishahi et al. [52]. Table 6 summarizes the core structure used by various models in this category followed by a comprehensive discussion.

Table 6. Financial instrument model core structure and weaknesses

Financial Instrument	**Reference**	**Core Model Structure**	**Technology**	**Weakness**
TGC	Ford et al.[49]	Supply and Demand of certificates	Wind	Wind capacity retirements were ignored making certificates prices to reach to stable level quickly
ZEC	Kunsch et al. [51]	Supply and Demand certificates	Wind	Only one renewable power technology modelled. The intermittency of renewable was disregarded.
TGC	Hasani-Marzooni and Hosseini [50]	Expected profitability of investment	Wind	No mention of how wind power will supply base load only.
Feed-in Tariff	Hsu [35]	Expected profitability of investment	Solar PV	Capacity retirements as well as permitting and construction delays were ignored.
General incentive	Alishahi et al. [52]	Expected profitability of investment	Wind	No mechanism presented can match the timing of wind power and peak demand

The financial instrument of TGC by Ford et al. [49] and ZEC by Kunsch et al. [51] relied on a generic supply and demand structure for the certificates. Both generators and distributors can trade these certificates in the market. It was assumed that the investors will be able to generate extra income to expand their renewable generation capacity by trading these certificates. Kunsch et al. [51] modelled the ZEC market more comprehensively as compared to the TGC market by Ford et al. [49]. Six technologies for electricity generation were considered, five being fossil-fuel based, and wind power from renewable side were modelled for ZEC, while only wind was chosen for TGC market. The simulations showed that by trading ZEC, both generation and distribution companies would be able to reduce their cost of operation, increase their renewable technology capacity along with reducing emissions. In contrast to Ford et al. [49], ZEC model considered power plant decommissioning which was a realistic way to model generation sector. However, Kunsch et al. [51] considered substitution between fossil and wind power based on the high price of ZEC was misleading. This consideration was a misrepresentation because there is a long lead-time from making a decision to invest in a new technology and actual operation of technology, during which the market conditions may change.

Seeing the drawback of substitution between fossil and renewable technologies in context of TGC, Ford et al. [49] and Hasani-Marzooni and Hosseini [50] focussed on just one renewable technology, namely, wind power. Unlike Ford et al. [49], the price of electricity and the TGC were both modelled by Hasani-Marzooni and Hosseini [50]. Furthermore, the issue of intermittency of wind power that was disregarded by Ford et al. [49] in their model was tackled by considering a variable capacity factor for the technology by Hasani-Marzooni and Hosseini [50].

Both these simulation studies on TGC showed that TGCs attained high prices when there was a gap between the operating capacity and the targeted wind capacity. However, when the capacity target is achieved, the price of certificates plummeted. This rise and fall of TGC prices resulted in wind capacity oscillations. TGC price oscillations were attributed to decision-makers imperfect foresight of future, and project construction delays. This situation gave an important insight that there is a limit to certificates market. Hence, the support mechanism needs to be restructured for continuance.

Similarly, Alishahi et al. [52] evaluated various financial incentive settings for promoting wind power capacity. These settings include fixed incentive, and a market based incentive. The authors used probabilistic wind resource availability in contrast to Ford et al. [49] and Hasani-Marzooni and Hosseini [50]. The model relied on expected profitability of investment for decision making. The expected profitability is given in Equation (4).

Expected profitability = f (fixed incentive, market-based incentive, investment cost) (4)

Fixed incentive, a portion of investment cost, was taken exogenous to the system while market-based incentive depended upon the market price of electricity. Simulations showed that fixed incentives resulted in higher wind capacity as compared to market-based ones. Authors recommended on the basis of their analysis that the electricity should be supplied to the consumers only when electricity price is high. Unless there is a physical mechanism to store wind power, the recommendation seems less practical.

Finally, in this category, Hsu [35] developed a model to evaluate the FiT scheme in promoting solar photovoltaic (PV) investments in Taiwan. FiT is an advanced form of fixed incentives [52]. The model performed the cost-benefit analysis of FiT and subsidies under various scenarios. Simulation showed that by increasing FiT rate, solar PV investments increased exponentially. Like Ford et al. [49], Hsu [35] also did not consider solar PV capacity retirements. Considering capacity retirements as well as permission and construction delays can substantially surface different dynamics, rather than exponential rise in PV capacity. Beside this, the effect of electricity demand on solar PV investments was also ignored. This linkage is crucial as it shows how much renewable technologies are able to sustain demand.

The SD model developed in this category seemed inclined to discuss financial barriers to renewable power technology. Other barrier to promotion like technical, institutional, public acceptance and awareness [53] were largely ignored. As for the choices of technology to be modelled, wind power was given preference over other renewable technologies, except solar PV.

4.4. Mixing-methods Models

Mixing methods of modelling techniques enriches the analysis of a study. In the same context, SD has been mixed with other modelling methods. These studies were evaluated in this subsection. Model structure and results were excluded from the discussion as they were not in scope of this category.

The first of mixing method studies was reported by Dimitrovski et al. [54]. The authors combined engineering optimisation and causal feedback approach of SD. The hybrid model used western electricity market of USA as a case. The hourly wholesale electricity prices were modelled in MATLAB/Simulink routines. These routines were then called in the SD model built in VENSIM® software. The study results showed the likelihood of synergy between shorter time resolution engineering approach and longer time resolution approach of SD models.

Periera and Saraiva [55] reported a novel approach of combining SD with an artificial intelligence technique of genetic algorithm (GA). Like Dimitrovski et al. [54], the model attempted for optimization. SD model provided information on long-term price and demand dynamics of electricity, along with share of various capacities for power generation. This information was used to devise optimised expansion plans using GA. The GA was implemented in MATLAB whereas SD model was implemented in POWERSIM®. The interface between the two software packages was provided by Microsoft EXCEL. The study highlighted that the descriptive nature of SD can effectively be transformed into a prescriptive optimization one.

SD and decision tree approach were combined by Tan et al. [56]. The proposed methodology tested wind power investment decision by a hypothetical firm. The cash flow data generated by simulation model was subjected to a decision tree. Unlike Dimitrovski et al. [54] and Periera and Saraiva [55], no interface was mentioned to have been developed between SD and decision tree model. However, the study successfully showed flexibility of SD model's output being channelized into sequential characteristic of a decision tree.

Finally, Zhao et al. [31]'s model employed SD and Agent-based modelling (ABM) approach. The study was divided in two levels: lower and upper. At the lower level, payback period for solar power investments was calculated while at higher level, a general adoption process was evaluated. At both levels, SD and ABM were applied. This setting proved advantageous as it gave flexibility in bringing extra details, in this case, hourly distribution of electricity load; providing enriched results.

The mixing methods category showed the compatibility of SD with other modelling methods. It can be inferred that the motivation of combining SD with other techniques was to compress substantial amount of information into a specific decision action. However, there is lack of literature in electricity sector modelling that combines SD model with a multi-criteria approach, and extending a static approach to a dynamic one.

4.5. Demand-side Management Models

This category includes models that focus on the demand-side management (DSM) of electricity supply chain. DSM covers all those policies or actions that intended to reduce electricity consumption, either by substitution of higher efficiency end-use technology, or altering the time of use of energy [57].

Substitution of higher efficiency devices was modelled by Dyner and Franco [58] and Ben Maalla and Kunsch [59]. The former study used SD approach to model fluorescent lamps adoption while the latter tried to highlight the adoption of domestic combine heat-power (μ-CHP) technology. Dyner and Franco [58] relied on the price of technology as the main variable to choose between incandescent and fluorescent lamp technologies. According to this structure, if the number of fluorescent lamp user increased then the number of incandescent lamp user decreased. This reduction further enhanced the fluorescent lamp users' adoption rate.

On the other hand, Ben Maalla and Kunsch [59] employed a well-structured Bass model of technology diffusion. μ-CHP diffusion model showed an S-shaped growth curve; typical for the adoption of new technology.

Finally, Elias [37] developed a model for identifying ways to curtail escalating electricity demand in New Zealand's residential sector. Unlike Dyner and Franco [58] and Ben Maalla and Kunsch [59], a focus group approach was used to develop the casual loop diagram for the problem. This approach proved to be more comprehensive as compared to one followed by Ochoa [28] for developing a qualitative model. The iterative process resulted in a unanimously agreed model. Analysis of model revealed that public behavioural changed to use of electricity as the most effective mode to reduce demand. This finding is in contrast to previous studies in DSM which proposed substitution by more efficient appliances.

There was a limited SD literature on DSM. The reason for this scarcity could be power generation, due to its association with security of supply, takes priority over efforts to curtail demand.

4.6. Micro-world Models

Micro-worlds provide laboratory setting where users can conduct experiments, improve their proficiency in decision-making, and learn about dynamic complexity of a problem. In the electricity sector, so far only two studies have reported the use of a micro-world;. i.e. Dyner et al [60] and Paşaoğlu [61].

Dyner et al. [60] named the micro-world as EnerBiz. The micro-world focused on the Colombian electricity market. The micro-world facilitated trading and risk management capabilities of market participants. The second micro-world, developed by Paşaoğlu [61], named Liberalised Electricity Market Micro-world (LEMM) was indented for an academic environment for Turkey. EnerBiz and LEMM were tested by real users in their respective countries, but the outcome of the exercise was the same. Each group of users valued respective micro-worlds for increasing their understanding of the feedbacks, delays and dynamics in the electricity sector. Both these micro-worlds focused on the generation side only which facilitate decision making but they lacked in assessing technologies for generation especially the renewable ones.

5. Conclusions

In this paper, an effort has been made to highlight the contribution of SD modelling of electricity sector. The review revealed that policy assessment and generation capacity expansion were the two most modelled issues. Policy assessment models were developed at national level to gain insight on effect of new policies. These policies include encouraging private sector investments, nuclear phase out or deregulation of sector. Generation capacity expansion addressed the reliability and affordability of generation system. Simulations highlighted the dependence and interaction of investment decisions on profitability calculations. A market based capacity payment was found to ensure timing generation expansions yet this mechanism was unable to eliminate investment cycles. Models in financial instruments category were concerned with boosting renewable technologies for electricity generation in a competitive market. In mixing methods category, flexibility of SD with other tools and techniques was confirmed. In demand side management category, it was found that information dissemination regarding rational use of energy is crucial for influencing demand. Finally, in the micro-worlds category the importance of learning and experimenting in electricity markets was asserted. Due to the commercial value, not many articles reported on micro-worlds. Furthermore, the review revealed that there is a generic supply-demand structure underlying all models. The changing market conditions and regulations, which disturb the supply-demand equilibrium, were the prime motive of using SD approach.

From the review future direction for researchers using SD can be suggested in the energy sector. These include developing models focusing on phase-out of fossil fuel technology in general, and nuclear technology in particular. On capacity expansion side, transmission and distribution networks factors could be included. This inclusion would bring richness to the model. Likewise, it is suggested to have more hybridization of SD and artificial intelligence techniques. Finally, side management public's attitude towards time-of-use could be modelled.

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