CEJOR (2016) 24:231–261
DOI 10.1007/s10100-015-0417-4

ORIGINAL PAPER

Energy related system dynamic models: a literature review

Armin Leopold[1]

Published online: 1 September 2015

Abstract System dynamics is extensively used as a decision support method in the energy sector. There exists a wide body of applications worldwide that are used not only within power companies but also by governmental agencies at the regional and national level. This review includes most of the relevant energy publications related to system dynamics and presents them within a literature review table divided into four key energy topics. This literature review is carried out in a chronological way and focuses on the period since the year 2000. The main purpose of this study is to summarise the remarkable body of work and the latest system dynamics trends related to the energy sector, in particular renewable energy that system dynamics practitioners have accumulated in the last 15 years.

Keywords Literature review · System dynamics modelling · Energy

1 Introduction to system dynamics modelling

System dynamics (SD) was first developed during the late 1950's at The Massachusetts Institute of Technology under Jay. W. Forrester in 1958 (Forrester 1958). He analysed computationally a supply chain as a whole system. This system consists of three inventories (factory, distributors and retailers), and several order and delivery processes. This stock-and-flow concept, with feedback control and system thinking, lays the foundation of system dynamics methodology, which, since then, has been widely applied to many management issues, for instance strategic organisation development, and expanded to several other areas like urban development and environmental sciences (Forrester 1999, 1973, 1982, 1992; Meadows et al. 1972;

✉ Armin Leopold
armin.leopold@unibw.de

[1] Universität der Bundeswehr München, Neubiberg, Germany

Senge 1994). Consequently, SD has been fundamentally multidisciplinary from the beginning (Sterman 2000). An SD model consists mainly of a number of interconnected stock and flow variables. A stock is an accumulation, or integration, or level, to choose terminology from different fields. The flow changes the amount in a stock (Forrester 2009). As a methodology, SD can be implemented both for qualitative as well as for quantitative analysis. Because of the dominant impact of feedback loops, a model structure can be more briefly described for qualitative analysis using causal loop diagrams. Nowadays, an SD model is presented graphically using a variety of modelling and simulation environments (see e.g.: Ventana Systems 2009, XJ Technologies 2010) to facilitate both modelling and understanding. One of the main advantages of SD is that it provides a clear and transparent model structure, which can, besides other things, promote the cooperation between the SD modellers and decision-makers in the sense of participatory or group modelling (Anderson and Johnson 1997).

According to Wolstenholme (1983), SD considers both descriptive and quantified modelling ideas whilst preserving sufficient, relevant model content to provide explanations of system behaviour. Nevertheless, SD can be seen as a useful approach which can provide an initial qualitative overview that may be used in further steps to define the appropriateness of other more specific problem-orientated techniques, including its own simulation phase. To sum it up, SD can be presented as a system methodology, capable of assisting with practical problem definition, analysis and change in a broad range of systems, and with the potential to provide a significant contribution to current general system practice.

The challenge facing all people in the world is how to move from generalisations about system thinking to tools and processes that might help us to understand complexity better. Additionally, we need to design better operating policies, and guide change in systems from the smallest business to the planet as a whole. However, learning about complex systems when you are living in them is difficult. In particular, the collaboration needs to be strengthened within energy-related projects, in particular large infrastructure projects, by using the system dynamics method (Hu et al. 2015). Therefore, SD is a method to enhance learning in complex systems. However, learning about complex dynamic systems requires more than only technical tools to create mathematical models. Because we are concerned with the behaviour of complex systems, SD is grounded in the theory of nonlinear dynamics and feedback control, developed in mathematics, physics and engineering. Because these tools are applied to the behaviour of human as well as physical and technical systems, SD draws on cognitive and social psychology, economics and other social sciences (Sterman 2000).

According to Forrester, models can be regarded and used as a basis for experimental investigations at lower costs and in less time than trying changes in actual systems. Generally, social science models need to be models of systems, not merely of isolated components of an information feedback system. Our descriptive knowledge provides a wealth of material from which to formulate dynamic models (Forrester 1961).

2 Literature review on energy SD simulations

SD is a powerful method to gain useful insight into situations of dynamic complexity and policy resistance. SD is increasingly used to design more successful policies in the

field of energy policy and electricity-related policy settings. However, no one method is universal. The field of SD itself is very dynamic. Recent advances in interactive modelling, tools for representation of feedback structure and simulation software allow us to engage in the modelling process (Sterman 2000).

Within this chapter the main literature in the field of SD related to energy is presented. For each of the main topics, a literature review table is included at the end of the sub-chapters. Due to limitations, this review includes only studies published since 2000. These publications are categorised into the following four topics:

- Fossil fuels,
- Renewable,
- Electricity and
- Further energy-related resources.

2.1 Fossil fuels

In this part, we give an overview on the broad field of different fossil-resource SD-based models. The importance of fossil energy models for the US can be best demonstrated by Ford (2005). He uses SD to model and simulate the impacts of a strategic fuels reserve in California. Within this study, he describes a simulation analysis which he developed for the California Energy Commission. The simulation analysis evaluates the impacts of a strategic fuels reserve (SFR) designed to limit the increase in gasoline prices in the days following a refinery disruption. Additionally, the simulation method is notable for its clear display of price and storage dynamics, its representation of the long delays that limit responsiveness to both supply and demand, and the inclusion of unintended and intended impacts within the same model.

In a certain analogy, Fan et al. (2007) developed an SD model to capture the dynamics for coal investment in China. The SD model simulates the behaviour of the whole system driven by investment in mines and the impact of the investment in mines on the coal system is investigated. Moreover, the coal production capacity is predicted in various scenarios in 2020, based on which policy recommendations are proposed. To sum it up, with the model the impact of the investment in state-owned mines and geological prospecting is considered, and the optimal investment size is put forward.

Tao and Li (2007) developed an SD model of Hubbert Peak specifically to forecast China's oil reserves.[1] In other words, this paper proposes to use the generic SD model to simulate Hubbert Peak in a robust way, particularly for the Chinese oil production from 1950 until 2100. Their research comes to the result that during the coming 20 years, the crude oil demand of China will probably grow at the rate of 2–3 % annually, and the gap between domestic supply and total demand may be more than half of this demand.

Jeong et al. (2008) somewhat later developed a very specific SD model of the economic comparison between coal-fired and liquefied natural gas combined cycle power plants considering carbon tax for South Korea for the period of 2002 until 2027. This paper aims at making an economic analysis of South Korea's power plant utilities

[1] Hubbert Peak predicted in 1956 that the U.S. oil production would peak in the early 1970's.

by comparing electricity generation costs from coal-fired power plants and liquefied natural gas (LNG) combined cycle power plants with environmental considerations. In the authors' point of view, their results can help in deciding which utility in South Korea is economically justified in the circumstances of the latest environmental regulations.

Within the field of fossil energy, Chi et al. (2009) also described how dynamics affects the UK natural gas industry with a comprehensive SD modelling and long-term energy policy analysis. The focus of this study lies on the dynamic model of the indigenous natural gas industry in the UK, using several scenarios. They show the following result: the growing gas import-dependence in the UK is a direct result of the policies adopted by successive governments during the past two decades e.g. those aimed at promoting the fastest possible exploitation of indigenous gas reserves and large-scale exports.

Similar to the previous publication by Tao and Li (2007), Kiani et al. (2009) developed an SD model for examining the Hubbert Peak for Iran's crude oil reserves. The proposed model helps the Iranian decision-makers to evaluate different scenarios as well as performing sensitivity analysis, which gives them informative and useful forecasts about the time and value of the Hubbert Peak in different conditions.

Next, we will point out a basic paper by Kiani et al. (2010) composing an analyzing survey on the role of SD methodology on fossil fuel resources. Besides the illustration of the role of SD in fossil fuel resources analysis, their paper reviews in particular the pioneering SD models in this field of fossil fuels. Generally speaking, the SD approach can be considered for a variety of decision-making procedures. SD is capable of studying the causal dynamic relations between different sectors of energy systems, such as considerable delays in industry and new energy development, advanced varying technology, resource limitation and depletion, price fluctuation, increasing costs, growing demand, pollution and environmental concerns, political issues, etc.

Tang et al. (2010) forecast the oil reserves and production in the Daqing oilfield, China, until 2060. In particular, this paper analyses the status of the Daqing oilfield, China's largest oilfield, and forecasts its ultimate recoverable reserves by use of a SD model. For Chinese policy-makers, it is worth paying attention to the problem of whether oil production in new oilfields can effectively make up for the decline in production of the large, old oilfields. Closely related, Li et al. (2011) forecast the growth of China's natural gas consumption until the year 2030. They estimate the gas consumption in China with the industry division method, which shows the different growth tendency of gas consumption in different industry fields. From a general point of view, the forecast results give some reasonable suggestions for the gas industry development in China.

Closely following the above, Ponzo et al. (2011) published an SD model about the regulation and development of the Argentinian gas market. This study shows that even short intervention in markets can have long-term impact, i.e. until 2025. Generally speaking, these simulations can help to understand the evolution of the Argentinian gas markets, which shows a future gas shortage.

Wu et al. (2011) introduced more or less at the same time the system's perspective on Taiwan's oil market after the liberalisation. In other words, this SD model analysis the effects of oil markets' floating price mechanism. The feedback loop of expected revenues could efficiently simulate a pricing mechanism. The model offers a virtual

management laboratory for policy-makers to conduct simulations of different policy scenarios. The findings indicate that the policy of lowering oil stockpiles have little effect on expected revenues of the oil company, and does not affect its pricing strategy.

Xu and Li (2011) study the dynamic complexities of one coal industry system in a fuzzy environment. Within this study a model was developed that integrates SD with fuzzy multiple objective programming that can be used to optimise sensitive parameters of the SD model. Based on the simulation, an effective policy related to the coal industry development can be established.

A model-based dynamic approach for construction of a fuel demand function portraying inter-fuel substitution in eight OECD countries is proposed by Abada et al. (2013). As result, a large number of simulations are conducted with the aim to propose an adapted single equation specification for the demand for fuel.

Hosseini et al. (2014) use SD methodology to model Iran's crude oil production peak and to evaluate the consequences. This is based on their previous work (Kiani et al. 2009). In this study, they examine the major factors influencing Iran's crude oil production peak with an SD approach. The developed model can help practitioners, especially policy-makers, in the oil sector to gain a systemic and comprehensive insight into influencing factors and the relationships which have caused Iran's crude oil peak.

The effect of strategic petroleum reserves (SPR) on the oil price in China is analysed with SD by Jiao et al. (2014). These authors develop an SD model on the Chinese system of the SPR and the oil price by simulating the effects of releasing 30, 60 and 90 days SPR on suppressing the oil price in 2015. They state that the greater the sensitivity of the domestic market to the respective oil price, the weaker the effect of the SPR on the oil price.

Recently, Yunna et al. (2015) published an SD analysis of the technology, the costs and policies that might affect the market competition of shale gas (SG) in China for the period until 2049. In details, they analyse the status quo of technology, policy, cost, and competition in the SG industry in China. Furthermore, they built an SD model to show various trends under different scenarios, which reveals the peak of competitors in the Chinese SG industry. They conclude with the following recommendations: the Chinese government should pay more attention to the perfection of laws and regulations of the shale gas industry. Furthermore, the research and development investments should be increased. This last recommendation can be taken as a general summary for all these fossil-based SD models. The following literature review table presents only the fossil fuel publications.

2.1.1 Conclusion

To conclude with, many of the presented publications are focusing on modelling and simulating central aspects related to the reserves of fossil resources. In particular, scientists in developing countries are applying SD for forecasting the potential oil reserves, some with the dependency on the resource price. To sum it up, SD is widely used in the whole world for fossil policy issues mainly with a national focus, some with a long-time horizon of more than 20 years and primarily to assist in estimating the limits of fossil resources and to forecast the economic effects.

Published	Author(s)	Title	Source	General purpose	Time horizon	Regional frame	Conclusion
2005	Ford	Simulating the impacts of a strategic fuels reserve in California	Energy Policy	Simulation analysis of the impacts of a strategic fuels reserve (SFR) developed for the California Energy Commission	None	California, USA	Method is notable for its clear display of price and storage dynamics
2007	Fan et al.	A system dynamics based model for coal investment	Energy	The behaviour of the whole system driven by investment in mines is simulated	2000–2020	China	The optimum investment in state-owned mines and geological prospecting is identified
2007	Tao and Li	System dynamics model of Hubbert Peak for China's oil	Energy Policy	Hubbert Peak model is used for the Chinese oil production	1950–2100	China	During the coming 20 years the gap between domestic supply and total demand may be more than half of this demand
2008	Jeong et al.	Economic comparison between coal-fired and liquefied natural gas combined cycle power plants considering carbon tax: Korean case	Energy	Economic analysis of Korea's power plant utilities	2002–2027	South Korea	Decision support justified in the circumstances of environmental regulations
2009	Chyong et al.	Dynamics of the UK natural gas industry: system dynamics modelling and long-term energy policy analysis	Technological Forecasting and Social Change	Indigenous natural gas industry in the UK	1987–2005	United Kingdom	The growing gas import-dependence in the UK
2009	Kiani et al.	Examining the Hubbert Peak of Iran's Crude Oil: a system dynamics approach	European Journal of Scientific Research	Helping Iranian decision makers to forecast Hubbert peak in different conditions	1962–2118	Iran	Production of crude oil in Iran will probably decrease to the rate of 3–4 % annually

Published	Author(s)	Title	Source	General purpose	Time horizon	Regional frame	Conclusion
2010	Kiani et al.	A survey on the role of system dynamics methodology on fossil fuel resources analysis	International Business Research	Reviews of SD models of fossil fuels	None	World	Showing the causal dynamic relations between different sectors of energy systems
2010	Tang et al.	Forecast of oil reserves and production in Daqing oilfield of China	Energy	Analysis of the status of China' largest oilfield	1960–2060	China	Forecasting its ultimate recoverable reserves
2011	Li et al.	Forecasting the growth of China's natural gas consumption	Energy	Forecasting the gas consumption in China with the industry division method	1997–2030	China	Different growth tendency of gas consumption in different industry fields
2011	Ponzo et al.	Regulation and development of the Argentinean gas market	Energy Policy	SD model for the development of the Argentinean gas market	2005–2025	Argentina	Decision support for the Argentinean gas markets
2011	Wu et al.	Effect of floating pricing policy: an application of system dynamics on oil market after liberalization	Energy Policy	Analysis of the effects of oil markets' floating price mechanism	2006–2010	Taiwan	A virtual management laboratory for policy-makers to conduct simulations of different policy scenarios
2011	Xu and Li	Using system dynamics for simulation and optimization of one coal industry system under fuzzy environment	Expert Systems with Applications	System dynamics with fuzzy multiple objective programming	2006–2020	None	Effective policy related to the coal industry development
2013	Abada et al.	Construction of a fuel demand function portraying interfuel substitution, a system dynamics approach	Energy	System Dynamics approach to capture fuel substitution in energy consumption	1978–2008	Canada, France, Germany, Italy, Japan, South Korea, the UK, the USA	Aim to propose an adapted single equation specification for the demand for fuel
2014	Hosseini et al.	Examination of Iran's crude oil production peak and evaluating the consequences: a system dynamics approach	Energy, Exploration and Exploitation	Iran's crude oil production peak	Until 2050	Iran	Help policy makers to gain a systemic and comprehensive insight of influencing factors in the oil sector

Published	Author(s)	Title	Source	General purpose	Time horizon	Regional frame	Conclusion
2014	Jiao et al.	The effect of an SPR on the oil price in China: a system dynamics approach	Applied Energy	Chinese system of the strategic petroleum reserves (SPR) and the oil price	2015	China	Effect of the SPR on oil price.
2015	Yunna et al.	A system dynamics analysis of technology, cost and policy that affect the market competition of shale gas in China	Renewable and Sustainable Energy Reviews	Shale gas industry in China	2009–2049	China	Laws and regulations of the shale gas industry

2.2 Renewable

Because of its fundamental importance we start with Ackere et al. (2005). They use the SD approach to model the management of a reservoir-based hydro-energy plant. To be more precise, this paper describes a modelling process at a Norwegian chemical producer which owns 20 % of a reservoir-based hydro-energy plant, and explains how this company has modified the way in which it ensures it has access to sufficient amounts of energy. The authors state that this approach forced the company to come to terms with a rather disturbing reality as they realised that in various instances the original product line was less profitable than the energy production and trading operations.

An SD-based simulation of the price patterns for tradable green certificates to promote electricity generation from wind is elaborated by Ford et al. (2007). Their study focuses on the simulation of the price dynamics of a market designed to support an aggressive mandate for wind generation in the north-western USA. With the growing interest in carbon allowances, the authors believe it is important to anticipate the performance of a combination of markets for tradable green certificates and carbon allowances until the year 2020.

Leaver and Unsworth (2007) develop an SD model of the behaviour of a geothermal field in New Zealand. In this very specific case, SD was used to obtain mass and thermal balances of a spring in the Orakeikorako geothermal field, New Zealand, based on geothermal field measurements. Nevertheless, the geothermal steam inflow estimated from the model confirms the existence of a weak hydraulic connection with a deeper geothermal reservoir.

Also Tu et al. (2009) study the dynamic complexities of launching the planting- and livestock-breeding biomass energy industry. To be more precise, by the integrated application of the SD feedback dynamic complexity analysis method and agricultural engineering, environment engineering and other disciplines, the authors exploit the "Pig-biogas-energy" circular engineering in the base. After the whole systems engineering was put into practice, the region obtained comprehensive benefits for the environment, economy and society, and promotion of the building of a harmonious society.

For evaluating SD models of risky projects using decision trees, alternative energy projects are analysed as an illustrative example by Tan et al. (2010). Generally speaking, SD models may be used to estimate the cash flow resulting from these projects for any given predetermined sequence of decisions. However, this approach has the virtue of combining SD's capability to cope with dynamic complexity with that of decision analysis to model managerial flexibility.

Zhao et al. (2011) propose a hybrid agent-based simulation approach for policy evaluation of solar power generation systems in the USA. The goal of this research is to develop a decision-making support tool to analyse the effectiveness of various policies (both incentives as well as regulations) on the proper growth rate of distributed photovoltaic (PV) systems avoiding the instability of the transition system or steep

rising of the electricity price. The proposed models have been developed for residential areas in two different regions of the US based on real data, which have been used to illustrate the impact of policies in different regions.

Closely following the above, Château et al. (2012) introduce an SD group modelling approach for building a stakeholder's vision of an offshore wind-farm project. For that purpose, all the involved local stakeholders are directly integrated in this study about an offshore wind-farm. According to the authors, the insight gained from the study can provide valuable information to produce feasible strategies for the green energy technique to meet local expectations.

Besides this, Hosseini et al. (2012) describe how changes impact the near future of wind power development in Iran. In order to explain the current situation as well as the future trends of the wind power market in Iran, an SD model was developed. The authors state that results of the simulation are representative of the fact that the development of Iran's wind power sector requires serious and effective supportive policies as well as reformulating the industry's vision and goals.

Hsu (2012) uses the SD methodology to assess the effects of capital subsidies and feed-in tariffs on solar PV installations in Taiwan until 2030. This study uses the SD approach to develop a simulation for assessing these promotion policies. Additionally, policy-makers can carry out cost/benefit analyses for different combinations of promotion policies, CO_2 emission reduction goals, and budget limitations.

Closely related to this, Jones (2012) investigates the dynamic growth in a photovoltaic market in the USA. The author presents an SD model of the growth of a new industry based on the features of a local photovoltaic market. The analysis reveals important lessons for policy and strategy: building strong feedback and coordinated and sustained action are the highest advantage interventions for growth.

Hu et al. (2013) develop an SD model to capture the dynamics of the transition towards renewable energy supply in Germany until 2025. This SD model depicts the development of the energy market in an aggregated form and is used to compare different possible pathways of the impending energy transition. They come to the result that a more effective GHG mitigation of about 40 % can be achieved at a lower cost by making use of higher wind and photovoltaic capacities in combination with the capability to produce synthetic natural gas using excess electricity from wind and solar energy.

Movilla et al. (2013) develop a preliminary SD model for the photovoltaic energy market in Spain with a time horizon until 2020. They describe a simulation model of the photovoltaic energy sector in Spain, whereby the model allows analysis of the dynamic behaviour of the photovoltaic sector under different scenarios. Generally speaking, the model allows an understanding of the sector's behaviour under the latest policies of the Spanish government, thus helping to design future public policies.

A fuzzy SD approach for the adoption of renewable energy technologies was published by Mutingi (2013). The aim of this study was to develop a fuzzy SD approach to improve the usefulness of energy policy system models characterised with linguis-

tic variables. However, it is anticipated that the application of fuzzy SD models to real world energy-economy policy problems will bring model realism into energy-low carbon models.

An SD study on the long-term impact of wind power generation on the Iberian day-ahead electricity market price is elaborated by Pereira and Saraiva (2013). In this paper, the authors describe a long-term generation expansion model that includes an optimisation module to build generation expansion plans and a dynamic model used to obtain estimates for the evolution of the demand, the electricity price and the capacity factors of candidate technologies. For that reason, they use an SD model, which is applied to the Iberian generation system using different shares of wind power capacity to quantify the impact of wind power on the day-ahead electricity market price.

Reddi et al. (2013) introduce an SD model of hybrid renewable energy systems (HRES) and combined heating and power (CHP) stations within the USA. In their paper, they develop a comprehensive system dynamics model, which includes data from a manufacturing company of HRES and CHP stations. The model can be a platform to further simulate and study the composition and operating strategies of organisations that are venturing to adopt new or additional HRESs.

A new SD approach which focuses on simulating the effect of feed-in tariffs on renewable energy penetration in Malaysia until 2050 was published by Akhwanzada et al. (2014). The objective of this study is to develop an SD model for assessment, which can evaluate the FIT scheme for solar PV systems. The main outcome is the fact that managing continued investments and payments is a complex task for the government due to the uncertainty, nonlinearity, and dynamics involved.

Aslani et al. (2014) analyse the renewable energy development of power generation in the US. To be more precise, this paper discusses the role of the renewable portfolio in the US energy action plan during 2010–2030 with an SD model, which is constructed to evaluate different costs of renewable energy utilisation by 2030. The authors estimate that the total value of renewable energy promotion and utilisation in the US will be more than 170 billion $.

Closely related to this, a dynamic model-based analysis of the green power in Ontario, Canada is achieved by Qudrat-Ullah (2014). For a better understanding of the long-term dynamics of Ontario's electricity system until the year 2030 in socio-economic and CO_2 emissions dimensions, this research develops, validates, and applies a dynamic simulation model. Some of the model-based results point to an alternative plan, focused on the reduction of thermal generation, addition of renewable generation, and investments in research and development of the electricity system, which can lead Ontario towards a future with "more" and affordable "green power".

Still staying in Northern America, Rendon-Sagardi et al. (2014) focus on the dynamic analysis of feasibility in the ethanol supply chain for biofuel production in Mexico. This research includes an analysis of the main variables of the ethanol supply chain, as well as the feasibility for its use and the development of an SD model

based on an idea suggested by the Secretariat of Energy in Mexico. The obtained results predicted the following until 2030: Mexico will face a fuel shortage in the future and the amount of the biofuel produced and accumulated will collaborate little to meet the domestic fuel demand.

Robalino López et al. (2014) recently did an SD modelling case study of Ecuador for renewable energy and CO_2 emissions. The authors have developed an SD model based on a relationship, which is a variation of the Kaya identity, and on a GDP that depends on renewable energy, which introduces a feedback mechanism in the model. Nevertheless, this study offers useful lessons for other developing countries, and might be used as a policy-making tool because it is easily transferable to any other period or region.

Recently, Barisa et al. (2015) used SD to forecast the potential future biodiesel policy designs and consumption patterns in Latvia. For that reason, the authors developed an SD model to capture the overall Latvian biodiesel industry within the road transportation sector. The major results obtained from model simulations confirm that promoting biofuel acceptance among end-users is the primary key issue.

Recently, a model-based analysis of biomethane production in the Netherlands and the effectiveness of the subsidisation policy under uncertainty was published by Eker and Daalen (2015). In this research, the authors study the dynamics of the Dutch biomethane production and analyse the effects of subsidisation policy with an SD model. The authors state that in the future research, different policy options, such as subsidising other biomass-based renewable energy options and policies affecting the biomethane demand can be tested.

2.2.1 Conclusion

Within the energy SD modelling field, the renewables show great promise. As shown in the table, renewable energy issues are modelled with SD all around the globe, and mainly with a long time horizon of 20 years and more. To sum it up, there exists the general notion that the recent research and its subsequent impact might change the near future of renewable power development in a sustainable and significant way.

Published	Author(s)	Title	Source	General purpose	Time horizon	Regional frame	Conclusion
2005	Ackere et al.	Managing a reservoir-based hydro-energy plant: building understanding in the buy and sell decisions in a changing environment	Energy Policy	Modelling process at a Norwegian chemical producer	1997–1998	Norway	Focus on energy production and trading operations
2007	Ford et al.	Simulating price patterns for tradable green certificates to promote electricity generation from wind	Energy Policy	Simulation of the price dynamics of a market designed for wind generation in the northwestern USA	2006–2020	USA	Markets for tradable green certificates/ carbon allowances
2007	Leaver et al.	System dynamics modelling of spring behaviour in the Orakeikorako geothermal field, New Zealand	Geothermics	Obtain mass and thermal balances of a spring in a geothermal field in New Zealand	None	New Zealand	Model confirms the existence of a connection with a deeper geothermal reservoir
2009	Tu et al.	Theory and application research on construction of planting and livestock breeding biomass energy industry based on system dynamics	Systems Engineering--Theory and Practice	Exploitation the "Pig-biogas-energy" circular engineering	None	China	The region obtains comprehensive multiple benefits
2010	Tan et al.	Evaluating system dynamics models of risky projects using decision trees: alternative energy projects as an illustrative example	System Dynamics Review	To estimate the cash flow resulting from projects for any given predetermined sequence of decisions	20 years	USA	Combining SD' capability to cope with dynamic complexity
2011	Zhao et al.	Hybrid agent-based simulation for policy evaluation of solar power generation systems	Simulation Modelling Practice and Theory	Develop a decision support tool to analyse the effectiveness of policies on photovoltaic	20 years	USA	Illustration of the impact of policies in different US regions

Published	Author(s)	Title	Source	General purpose	Time horizon	Regional frame	Conclusion
2012	Château et al.	Building a stakeholder's vision of an offshore wind-farm project: a group modelling approach	Science of the Total Environment	An offshore wind-farm study which directly involves local stakeholders	1990–2030	Taiwan	Provide feasible strategies for the green energy technique to meet local expectations
2012	Hosseini et al.	A study on the near future of wind power development in Iran: a system dynamics approach	ICREDG	Modeling future trends of wind power market in Iran	2004–2015	Iran	Energy policy support tool for Iran's wind power sector
2012	Hsu	Using a system dynamics model to assess the effects of capital subsidies and feed-in tariffs on solar PV installations	Applied Energy	Assessing promotion policies, CO_2 emission reduction goals, and budget limitations	2011–2030	Taiwan	Policymakers can carry out cost/benefit analyses for different combinations of promotion policies
2012	Jones	Dynamic growth in a photovoltaic market	International Journal of Technology, Policy and Management	Model of the growth of a local photovoltaic market	None	USA	Analysis reveals important lessons for policy and strategy
2013	Hu et al.	Transition towards renewable energy supply—a system dynamics approach	Green Growth and Sustainable Development 2013	A SD model depicts the development of the energy market in an aggregated form	Until 2025	Germany	Used to compare different possible pathways of the impeding energy transition
2013	Movilla et al.	A system dynamics approach for the photovoltaic energy market in Spain	Energy Policy	Modelling the photovoltaic energy sector in Spain	2004–2020	Spain	Helping to design future PV public policies in Spain
2013	Mutingi	Adoption of renewable energy technologies: a fuzzy system dynamics perspective	Energy Policy Modeling	Developed a fuzzy system dynamics approach to improve the usefulness of energy policy system models	25 years	None	Fuzzy system dynamics models bring model realism into energy-low carbon models

Published	Author(s)	Title	Source	General purpose	Time horizon	Regional frame	Conclusion
2013	Pereira et al.	Long term impact of wind power generation in the Iberian day-ahead electricity market price	Energy	Long term generation expansion model	1997–2010	Spain and Portugal	Long-term SD based model, applied to the Iberian generation system
2013	Reddi et al.	System dynamics modelling of hybrid renewable energy systems and combined heating and power generator	International Journal of Sustainable Engineering	SD model of hybrid renewable energy systems and combined heating and power generator	None	USA	Platform for organisations that are venturing to adopt new HPG
2014	Akhwanzada et al.	Simulating the effect of feed-in tariff on renewable energy penetration: a system dynamics approach	Proceedings of the international conference on science, technology and social sciences	Model based evaluation the FIT scheme for solar PV system.	2012–2050	Malaysia	Managing continued investments and payments is a complex task
2014	Aslani et al.	Role of renewable energy policies in energy dependency in Finland: System dynamics approach	Applied Energy	Evaluating renewable energy policies on dependency in Finland	Until 2020	Finland	To test scenarios related to renewable energy polices
2014	Aslani and Wong	Analysis of renewable energy development to power generation in the United States	Renewable Energy	The role of renewable portfolio in the US energy action plan during 2010–2030	2010–2030	USA	The total value of renewable energy promotion and utilization
2014	Qudrat-Ullah	Green power in Ontario: a dynamic model-based analysis	Energy	Long-term dynamics of Ontario's electricity system	2000–2030	Ontario, Canada	Focused on the reduction of thermal generation, addition of renewable generation, and investments in R&D

Published	Author(s)	Title	Source	General purpose	Time horizon	Regional frame	Conclusion
2014	Rendon-Sagardi et al.	Dynamic analysis of feasibility in ethanol supply chain for biofuel production in Mexico	Applied Energy	Analysis of the main variables of the ethanol supply chain in Mexico	2014–2030	Mexico	Prediction of a fuel shortage in the future in Mexico
2014	Robalino López et al.	System dynamics modeling for renewable energy and CO_2 emissions: A case study of Ecuador	Energy for Sustainable Development	Model based on a relationship, which introduces a feedback mechanism	Until 2020	Ecuador	Policy-making tool for other developing countries
2015	Barisa et al.	Future biodiesel policy designs and consumption patterns in Latvia: a system dynamics model	Journal of Cleaner Production	Latvian biodiesel industry within the road transportation sector	Until 2020	Latvia	Promoting biofuel acceptance among end-users
2015	Eker and Daalen	A model-based analysis of biomethane production in the Netherlands and the effectiveness of the subsidization policy under uncertainty	Energy Policy	Dutch biomethane production	2000–2050	The Netherlands	Subsidizing other biomass-based renewable energy options affecting the biomethane demand

2.3 Electricity

A basic simulation study of power plant construction in California was developed by Ford (2001). This paper describes a computer simulation model constructed to simulate the general patterns of power plant construction that might appear in an electric system with approximately the same loads, resources and markets as those in California. In general, forecasting is a hazardous business, and the simulation model described in this article was designed for general understanding, not for year-by-year forecasting. Nevertheless, the model shows certain dominant patterns, which can help us think about the duration of difficult times.

A similar case study was presented by Qudrat-Ullah and Davidsen (2001) about the dynamics of electricity supply, resources and pollution in Pakistan. This research, using SD methodology, provides an assessment of the existing policy subject to the constraints of environmental concerns and available, but limited, resources. The authors identify that the unchanged prolongation of the existing policy seems to effectively attract independent power producers investments but not without potentially adverse consequences for the environment and the economy.

The transition from fossil-fuelled to renewable power supply in the deregulated Nordic electricity market is discussed by Vogstad et al. (2002). The authors investigate the trade-offs between the long-term and short-term effects of energy planning within the context of a deregulated power market. The simplified model is to be used to improve the communication and understanding of results, in contrast to the comprehensive, quantitative model version. Therefore, the main objective with models is to improve the mental models of decision-makers because if they do not understand the results or the behaviour, they will not accept or be able to use it for decision-making.

Closely related to this, Vogstad (2005) published "A System Dynamics Analysis of the Nordic Electricity Market: The Transition from Fossil Fuelled Towards a Renewable Supply Within a Liberalised Electricity Market." In this comprehensive study, a system dynamics model to analyse the long-term versus short-term implications of various energy policies within the context of the Nordic electricity market is developed. The model itself is designed to study energy and environmental policies for the transition from a fossil-fuelled towards a renewable electricity supply.

Kilanc and Or (2006) also use an SD model to describe how changes impact the decentralised Turkish electricity market. To visualise the dynamics of the competitive electricity power, a simulation model based on the SD philosophy is developed in this study. With the help of such a decision-making tool, companies and regulators have a better opportunity to understand possible consequences of different decisions that they may make under different policies and market conditions.

Closely following the above, Olsina et al. (2006) introduce the system's perspective. They are modelling the long-term dynamics of electricity markets. In order to gain significant insight into the long-term behaviour of liberalized power markets, an SD-based model was proposed and the underlying mathematical formulations extensively discussed. These results might be of significant value in the firm's strategic planning as well as in investment appraisals of power plant projects based on the Real Option approach.

Dimitrovski et al. (2007) use SD methodology to model the power system expansion. This article describes an interdisciplinary approach to computer modelling of large-scale power systems over a long-term horizon, and to simulate the interplay between the economic, technical and environmental factors in the system. The major results might be of significant value in the firm's strategic planning as well as in investment appraisals of power plant projects based on the Real Option approach.

Later, Ford (2007) studied the dynamic complexities of global climate change and the electric power industry. He explains the potential for the electric power industry to play a pivotal role in the coming years, the reducing CO_2 emissions during the 10–20 years following the adoption of mandatory carbon markets. Furthermore, the policy options include a combination of targets, regulations, and financial incentives to "put a price on carbon."

Based on their previous work (Kilanc and Or 2006), Kilanc and Or (2008) published a study about a decision-making support tool for the analysis of pricing, investment and regulatory processes in a decentralised electricity market. In this study, an SD model is developed to better understand and analyse the decentralised and competitive electricity market dynamics in the long run. Consequently, public regulators and power companies are potential users of the model, for learning and decision-making support in policy design and strategic planning.

Sánchez et al. (2008) combine SD, credit risk theory and game theory to model long-term investments in electricity generation in Spain until 2025. In other words, their paper provides a new multidisciplinary approach to model the long-term planning of electricity generation. This approach can be used as a tool to analyse the long-term dynamics of electricity markets and the way the new generation capacity enters into these markets under different hypotheses of companies' strategies and regulatory policies.

Balnac et al. (2009) develop a preliminary SD model of the Mauritian power sector. This particular study documents the first iteration in the development of a power sector model for Mauritius based on "Threshold 21" models by the Millennium Institute. The aim is to provide a description of the Mauritian power landscape and translate the same into an SD model. The authors mention that future work might include the expansion of the model to cover the whole of the Mauritian energy system and to do policy analysis.

Jäger et al. (2009) propose a model-based dynamic approach for the German electricity market. This paper includes an impact study of economic- and environment-related constraints on the German electricity spot market, which was carried out using the SD-based model for the German electricity market called "Zertsim". Mainly due to the variation of input parameters and immediate presentation of results, the model supports discussions regarding the future of electricity markets in workshops and conferences; additionally the model is suitable to provide decision-making support for investments in decentralised and renewable energies.

Related to this, Ochoa and Ackere (2009) analyse the policy changes and the dynamics of capacity expansion in the Swiss electricity market. In other words, the authors evaluate the dynamics of capacity expansion in the Swiss electricity market and the impact of different policies such as nuclear phase-out and management of electricity exchanges—imports and exports—policies. Additionally, the authors illustrate the

need for explicit policies for managing the imports and exports of electricity to avoid import dependence on neighbouring countries.

Genoese (2010) analyses in his PhD thesis "Energiewirtschaftliche Analysen des deutschen Strommarkts mit agentenbasierter Simulation" the German electricity market with an agent-based simulation. This study describes the development and application of an agent-based simulation model for the German electricity market. The agent-based simulation seems to be a promising approach to take account of the new aspects in an appropriate manner.

Later, Jalal and Bodger (2010) developed an SD model to capture the dynamics to evaluate electricity generation expansion in New Zealand. This research studies the electricity generation expansion issue in New Zealand and makes projections to investigate whether capacity cycles will happen here in the future. The SD approach captures the dynamic relationship between the electricity market and generation investment. In other words, it gives an ability to study a system as a whole rather than as different sections, providing an understanding on how all the objects in a system interact with one another.

System modelling for the large-scale diffusion of multiple electricity technologies in an urban distribution network is elaborated by Dykes et al. (2011) for a midsized US city until 2030. Hence, an SD model is developed which allows the simulation of a wide range of scenarios in order to analyse the diffusion and impact of compound technological changes on the electrical distribution system. The model attempts to capture the role of several key technologies that are likely to affect the distribution system in the near future.

The main objective of the publication by Arto et al. (2012) is to evaluate separate portfolio concepts of electricity generation in Germany in a comparative way. In other words, combining SD model simulation and data analysis it is possible to observe the long-term development of the electricity industry and anticipate its reliability and total production cost under different assumed scenarios. According to the results produced with the help of the SD model, load management produces significant potential savings on production costs at acceptable reliability and helps to achieve the political goal of reducing GHG emissions.

Closely related to this, Hu et al. (2012) use SD as an IT-based decision-making support for turning on Germany's energy transition. With the help of SD, they started to analyse how the upcoming Nord.Link project will contribute to a reliable, efficient and sustainable electricity supply in Germany. By modelling the latest project, Nord.Link, within the actual electricity system with the help of SD, the active public should be able to understand the complex interactions.

A model and simulation of a power grid engineering project based on SD with the backdrop of a smart grid is explained by Li et al. (2012). Based on defined key factors and their mutual relations, a dynamic model with the fundamental structure of casual loop and stock-flow diagrams is built to simulate the management process of the power grid-engineering project. The simulation results shows that the SD model can be used efficiently in the modelling and optimisation of power grid engineering project management for its clear causality, suitable complexity and exact description characteristics.

Hoffmann et al. (2013) published an SD-based analysis of performance losses of thermal power plants in Germany. In this, the authors analyse the impact of climate change on the output of thermal power plants using an SD modelling approach. For power plant operators the plant availability plays a major role in the planning of production and optimisation of plant revisions.

Qudrat-Ullah (2013) analyse the dynamics of electricity generation capacity in Canada. A system dynamics model of the electricity supply and demand system of Canada is constructed, validated and applied. By utilizing this developed model for simulations, future research can investigate other related issues in the context of alternative policy design for the Canadian electricity sector.

Another system dynamics approach was established by Saysel and Hekimoğlu (2013) for exploring the options for carbon dioxide mitigation in the Turkish electric power industry. In their research, an original dynamic simulation model is built, validated and analysed to explore the options for carbon mitigation in the Turkish electric power industry. Generally, the model can serve as an experimental platform for further analysis of problems related to carbon mitigation in the Turkish electricity sector.

Closely following the above, Niu and Song (2014) forecast the medium- and long-term load based on SD and the electricity elasticity coefficient method in China. The paper develops the traditional electricity elasticity coefficient method in the power load forecasting field to set up an SD model based on the principle of the electricity elasticity coefficient, whose purpose is to improve the medium- and long-term power load forecasting accuracy. The study concludes that the SD model built here leads to a superior accuracy and better perspective.

Finally, Franco et al. (2015) published an SD-based simulation of the new British electricity-market reform. This paper presents an SD model that supports analysis of long-term effects of the various policy instruments that have been proposed in the "GB Electricity Market Reform", focusing on environmental quality, security of supply and economic sustainability. Using lessons learned from simulation, the paper concludes that effectively achieving the GB EMR objectives requires this comprehensive intervention or a similar one that includes the promotion of low carbon electricity generation through the simultaneous implementation of various direct and indirect incentives.

2.3.1 Conclusion

Still, it is very difficult to sum up all the different aspects of electricity-based SD models including their variety of intentions, time horizons and goals, depending on the region taken into account. However, the research on electricity SD models has a certain similarity across the world, demonstrating the need for optimization of planning, production and use of power plants.

Published	Author(s)	Title	Source	General purpose	Time horizon	Regional frame	Conclusion
2001	Ford	Waiting for the boom: a simulation study of power plant construction in California	Energy Policy	Simulation of the general patterns of power plant construction in California	2000–2008	California, USA	Simulation model designed for general understanding
2001	Qudrat-Ullah and Davidsen	Understanding the dynamics of electricity supply, resources and pollution: Pakistan's case	Energy	An assessment of the existing resource policy	1980–2030	Pakistan	The existing energy policy attracts investments in an unsustainable way
2002	Vogstad et al.	The transition from fossil fuelled to a renewable power supply in a deregulated electricity market	Proceedings of the International System Dynamics Conference	Long-term and short-term effects of energy planning within the context of a deregulated power market	2000–2030	Nordic electricity market	Improve communication and understanding of results - to improve the mental models of decision makers
2005	Vogstad	A system dynamics analysis of the nordic electricity market: the transition from fossil fuelled towards a renewable supply within a liberalised electricity market	NTNU	Analysis of various energy policies within the Nordic electricity market	Until 2030	Nordic electricity market	Studying the energy and environmental policies for the transition from a fossil fuelled towards a renewable electricity supply
2006	Kilanc and Or	A system dynamics model for the decentralized electricity market	International Journal of Simulation: Systems, Science and Technology	To visualize the dynamics of the competitive electricity power market	Next 20 years	Turkey	Decision support tool for companies and regulators under different policies and market conditions
2006	Olsina et al.	Modeling long-term dynamics of electricity markets	Energy Policy	The long-term behaviour of liberalized power markets	Next 20 years	None	Strategic planning of power plants projects

Published	Author(s)	Title	Source	General purpose	Time horizon	Regional frame	Conclusion
2007	Dimitrovski et al.	An interdisciplinary approach to long-term modelling for power system expansion	International Journal of Critical Infrastructures	Interdisciplinary modelling approach of large-scale power systems over a long-term horizon	2005–2025	USA	Importance of simulation models designed for interactive use
2007	Ford	Global climate change and the electric power industry	Competitive Electricity Markets	Potential for the electric power industry	10–20 years	Global	Combination of targets, regulations, and financial incentives
2008	Kilanc and Or	A decision support tool for the analysis of pricing, investment and regulatory processes in a decentralized electricity market	Energy Policy	Decentralized and competitive electricity market dynamics in the long run	20 years	Turkey	Decision support in policy design and strategic planning
2008	Sánchez et al.	A multidisciplinary approach to model long-term investments in electricity generation: combining system dynamics, credit risk theory and game theory	Power and Energy Society General Meeting-Conversion and Delivery of Electrical Energy in the 21st Century	SD combined with credit risk theory and game theory	2005–2025	Spain	To analyse long-term dynamics of electricity markets
2009	Balnac et al.	A system dynamics model of the Mauritian power sector	Proceedings of the International System Dynamics Conference	Development of a power sector model for Mauritius based on T21 models	1997–2007	Mauritius	Provide a description of the Mauritian power landscape
2009	Jäger et al.	A system dynamics model for the German electricity market–model development and application	Proceedings of the International System Dynamics Conference	Impact studies of economic and environment related constraints on the German electricity spot market	1998–2025	Germany	Provide decision support for investments in decentralized and renewable energies

Published	Author(s)	Title	Source	General purpose	Time horizon	Regional frame	Conclusion
2009	Ochoa and Ackere	Policy changes and the dynamics of capacity expansion in the Swiss electricity market	Energy Policy	Analysis of capacity expansion in the Swiss electricity market	Next 20 years	Switzerland	Illustration of the impact of different energy policies in Switzerland
2010	Genoese	Energiewirtschaftliche Analysen des deutschen Strommarkts mit agentenbasierter Simulation	Nomos	An agent-based simulation model for the German electricity market	Until 2030	Germany	An approach to take into account the new aspects in an appropriate manner.
2010	Jalal and Bodger	The development of a system dynamics model to evaluate electricity generation expansion in New Zealand	AUPEC	Electricity generation expansion issue in New Zealand	2008–2050	New Zealand	Projections to investigate about energy capacity cycles
2011	Dykes et al.	System modeling for the large-scale diffusion of multiple electricity technologies in an urban distribution network	IEEE Power and Energy Society General Meeting	Analysis of the diffusion and impact of compound technological changes on the electrical distribution system.	2005–2030	Midsized US city	Captures the role of several key technologies affect the future distribution system
2012	Arto et al.	Germany's electricity industry in 2025: evaluation of portfolio concepts	Proceedings of the International System Dynamics Conference	SD model simulation and data analysis for the long-term development of the German electricity industry	The year 2025	Germany	Load management produces significant potential savings on production costs

Published	Author(s)	Title	Source	General purpose	Time horizon	Regional frame	Conclusion
2012	Hu et al.	IT-based decision support for turning on Germany's Energy Transition	Operations Research Proceedings	Analysis of the contribution of the Nord.Link project	Next 20 years	Germany	The active public should be able to understand the complex interactions of the Nord.Link project
2012	Li et al.	Modelling and simulation of power grid engineering project based on system dynamics on the background of smart grid	Systems Engineering Procedia	Model based simulation of the management process of the power grid-engineering project.	40 months	None	Used for modelling and optimization of power grid engineering project management
2013	Hoffmann et al.	Analysis of performance losses of thermal power plants in Germany—a system dynamics model approach using data from regional climate modelling	Energy	Analysis of the impacts of climate change on the output of thermal power plants	2011–2070	Germany	Planning of production and optimisation of plant revisions
2013	Pereira and Saraiva	A long term generation expansion planning model using system dynamics—case study using data from the Portuguese/Spanish generation system	Electric Power Systems Research	Long-term generation expansion model	Long-term	Portugal, Spain	Getting more insight on the possible long term evolution of the electric power system
2013	Qudrat-Ullah	Understanding the dynamics of electricity generation capacity in Canada: a system dynamics approach	Energy	Model of the electricity supply and demand system of Canada is constructed, validated, and applied	2000–2025	Canada	Future research can investigate other related issues in the context of alternative policy design for Canadian electricity sector

Published	Author(s)	Title	Source	General purpose	Time horizon	Regional frame	Conclusion
2013	Saysel and Hekimoğlu	Exploring the options for carbon dioxide mitigation in Turkish electric power industry: System dynamics approach	Energy Policy	Explore the options for carbon mitigation in Turkish electric power industry	2000–2030	Turkey	Experimental platform for problem analysis related to carbon mitigation in Turkish electricity sector
2014	Niu and Song	Medium and long-term load forecasting based on system dynamics and electricity elasticity coefficient method in China	Energy Education Science and Technology Part A: Energy Science and Research	Development of system dynamics model based on the principle of electricity elasticity coefficient	2014–2020	China	Improve the medium and long-term power load forecasting accuracy.
2015	Franco et al.	Simulating the new British electricity-market reform	European Journal of Operational Research	Analysis of long-term policy instruments proposed in the "GB Electricity Market Reform"	2013–2030	Great Britain	Promotion of low carbon electricity generation

2.4 Further energy-related resources

Concerning the nuclear industry in the United Kingdom, Carhart (2009) investigates the potential use of SD as a tool for event analysis. Commonly, SD is proposed and investigated as a tool to provide an alternative, more holistic view of their development to complement the present one. The major findings suggest that un-simulated qualitative models are relatively quick and easy to produce and can provide additional insight. However, those conducting the investigations rarely have the time or resources to collect data and produce models suitable for simulation.

Ma et al. (2010) study the dynamic complexities of the hydrogen demand in China. Based on both China's future economic development and relative economic theory and SD theory. Their contribution qualitatively analyses the internal factors and external factors of hydrogen energy demand. Additionally, it makes assumptions about China's medium- and long-term hydrogen demand according to the different speeds of China's economic development. Generally speaking, the change of Chinese hydrogen demand scale, based on its economic growth, cannot be effectively explained by the Chinese economic growth rate, and other influencing factors and mechanisms need further investigation.

Kunsch and Friesewinkel (2014) apply the SD methodology to model the latest nuclear energy policy in Belgium after Fukushima. In this, policy investigations are made with SD: a premature nuclear phase-out will not serve the deployment of renewable energy sources and rational use of energy. With the support of system-dynamics analyses confirming previous studies, the authors come to the firm belief that the nuclear phase-out schedule should be reconsidered. Nuclear power should be kept as a transition source until the renewables become more competitive and can provide a more significant share of Belgian energy.

Thematically related, Lisse (2014) apply SD for a general nuclear power plant design. This study analyses an SD model for outsourcing engineering services in a large and complex project whose organisational structure that is typically associated with nuclear power plants. The main results indicate that the decision to insource/outsource engineering work on nuclear power plant projects may have significant cost and time impacts which should be considered by decision-makers.

Recently Kasada et al. (2015) show an SD model for the stock and flow of tritium in a fusion power plant in Japan. In this, an SD model of the tritium fuel cycle is developed for analysing stock and flow of tritium in fusion power plants. Still, the model is also used for considering operation scenarios to avoid excess stock of tritium, which must be produced at a tritium breeding ratio over unity. As we can easily see from the few examples, further modelling of energy simulations refers mainly to nuclear energy policy.

2.4.1 Conclusion

To conclude with, many of the presented papers are focusing on nuclear energy. In particular, in highly developed countries SD is used to investigate the future policies of nuclear energy and the possibility for a phase-out. However, there exist some publications that focus on alternatives, like hydrogen- and fusion power plants.

Published	Author(s)	Title	Source	General purpose	Time horizon	Regional frame	Conclusion
2009	Carhart	Investigating the potential use of system dynamics as a tool for event analysis in the nuclear industry	IET International Conference on System Safety	SD is used to provide an alternative, more holistic view of their development	None	United Kingdom	Qualitative models can provide additional insight
2010	Ma et al.	Study on the hydrogen demand in China based on system dynamics model	International Journal of Hydrogen Energy	Analysis of internal and external factors of hydrogen energy demand system	Until 2050	China	Assumptions of China's medium and long-term hydrogen demand
2014	Kunsch and Friesewinkel	Nuclear energy policy in Belgium after Fukushima	Energy Policy	Energy policy investigations with SD in Belgium	2005–2030	Belgium	Nuclear power should be kept as a transition source and can provide a more significant share of Belgian energy
2014	Lisse	Applying system dynamics for nuclear power plant design	ASME 2014 Small Modular Reactors Symposium	Analysis of the outsourcing engineering services in a large and complex project organizational structure	70 days	None	Decision support tool for nuclear power plants outsourcing management initiatives.
2015	Kasada et al.	A system dynamics model for stock and flow of tritium in fusion power plant	Fusion Engineering and Design	SD model focusing on the stock and flow of tritium in fusion power plants	None	Japan	Decision support for operation scenario of tritium

3 Conclusion

The applications of the system dynamics methodology on energy have become more diverse since 2000. Within the reviewed studies, system dynamics mainly shows a noteworthy role in modelling dynamic aspects for dynamic studies and policy analysis, all over the world. However, in particular in China and in other leading nations SD is applied for forecasting fossil fuel reserves, according to the actual and upcoming energy demand. Referring to the literature review table, one can conclude that the SD approach can be applied for a diverse variety of decision-making situations within the energy sector. Nevertheless, SD is capable of studying not only the causal dynamics of dynamic relations within different energy systems, but also in showing specific analyses of energy transitions. In this paper, not only the relevance of SD in the energy field is presented, but also a vast variety of SD models in this field are reviewed and might be used for further analysis in this area.

To conclude, there are some research areas, which necessitate further research, in particular, transformation processes within energy system, and transition issues to renewable energy, energy-consumer centric modelling and modelling-based assessment of alternative energy technology potentials.

References

Abada I, Briat V, Massol O (2013) Construction of a fuel demand function portraying interfuel substitution, a system dynamics approach. Energy 49:240–251

Ackere AV, Ruud M, Davidsen P (2005) Managing a reservoir-based hydro-energy plant: building understanding in the buy and sell decisions in a changing environment. Energy Policy 33(7):39–947

Akhwanzada SA, Tahar RAM, Cheng J (2014) Simulating the effect of feed-in tariff on renewable energy penetration—a system dynamics approach. In: Wan Omar K et al (eds) Proceedings of the international conference, pp 717–721

Anderson V, Johnson L (1997) Systems thinking basics. From concepts to causal loops. Pegasus Communications, Cambridge, Mass, ISBN: 1883823129

Arto K, Dolgopolova I, Hu B, Leopold A, Pickl S (2012) Germany's electricity industry in 2025: evaluation of portfolio concepts. In: The 212 international conference of the system dynamics society proceedings. St. Gallen, Switzerland, pp 22–26

Aslani A, Wong KFV (2014) Analysis of renewable energy development to power generation in the United States. Renew Energy 63:153–161

Aslani A, Helo P, Naaranoja M (2014) Role of renewable energy policies in energy dependency in Finland: system dynamics approach. Appl Energy 113:58–765

Balnac K, Bokhoree C, Deenapanray P, Bassi A (eds) (2009) A system dynamics model of the Mauritian power sector. In: Proceedings of 27th international conference of the system dynamics society. Albuquerque, NM, USA, pp 26–30

Barisa A, Romagnoli F, Blumberga A, Blumberga D (2015) Future biodiesel policy designs and consumption patterns in Latvia: a system dynamics model. J Clean Prod 88:71–82

Carhart NJ (eds) (2009) Investigating the potential use of system dynamics as a tool for event analysis in the nuclear industry. IET international conference on system safety: IET

Château P-A, Chang Y-C, Chen H, Ko T-T (2012) Building a stakeholder's vision of an offshore wind-farm project: a group modeling approach. Sci Total Environ 420:43–53

Chi KC, Nuttall WJ, Reiner DM (2009) Dynamics of the UK natural gas industry: system dynamics modelling and long-term energy policy analysis. Technol Forecast Social Change 76(3):339–357

Dimitrovski A, Ford A, Tomsovic K (2007) An interdisciplinary approach to long-term modelling for power system expansion. Int J Crit Infrast 3(1–2):235–264

Dykes KL, Bean M, Cook J (2011) System modeling for the large-scale diffusion of multiple electricity technologies in an urban distribution network. IEEE power and energy society general meeting proceedings
Eker S, Daalen EV (2015) A model-based analysis of biomethane production in the Netherlands and the effectiveness of the subsidization policy under uncertainty. Energy Policy 82:178–196
Fan Y, Yang R-G, Wie Y-M (2007) A system dynamics based model for coal investment. Energy 32(6):898–905
Ford A (2001) Waiting for the boom: a simulation study of power plant construction in California. Energy Policy 29(11):847–869
Ford A (2005) Simulating the impacts of a strategic fuels reserve in California. Energy Policy 33(4):483–498
Ford A (2007) Global climate change and the electric power industry to appear in competitive electricity markets: design, implementation and performance. In: Sioshansi FP (ed), pp 499–542. doi:10.1016/978-008047172-3.50018-0
Ford A, Vogstad K, Flynn H (2007) Simulating price patterns for tradable green certificates to promote electricity generation from wind. Energy Policy 35(1):91–111
Forrester JW (1958) Industrial dynamics: a major breakthrough for decision makers. Harv Bus Rev 36(4):37–66
Forrester JW (1961) Industrial dynamics. MIT press, Cambridge
Forrester, JW (1973) World dynamics, 2nd edn. Wright-Allen Press, Cambridge
Forrester JW (1982) Global modelling revisited. Futures 14(2):95–110
Forrester JW (1992) Policies, decisions and information sources for modeling. Eur J Oper Res 59(1):42–63
Forrester JW (1999) Urban dynamics. Pegasus Communications, Waltham (System dynamics series). ISBN 10: 1883823390
Forrester JW (2009) Some basic concepts in system dynamics. Sloan School of Management, Massachusetts Institute of Technology, Cambridge
Franco CJ, Castaneda M, Dyner I (2015) Simulating the new British electricity-market reform. Eur J Oper Res 245(1):273–285
Genoese M (2010) Energiewirtschaftliche Analysen des deutschen Strommarkts mit agentenbasierter Simulation. Nomos, Berlin
Hoffmann B, Häfele S, Karl U (2013) Analysis of performance losses of thermal power plants in Germany—a system dynamics model approach using data from regional climate modelling. Energy 49:193–203. doi:10.1016/j.energy.2012.10.034
Hosseini SH, Shakouri GH, Akhlaghi FAR (2012) A study on the near future of wind power development in Iran: a system dynamics approach. Second Iranian conference on renewable energy and distributed generation, ICREDG 2012
Hosseini SH, Kiani B, Mohammadi Pour M, Ghanbari M (2014) Examination of Iran's crude oil production peak and evaluating the consequences: a system dynamics approach. Energy Explor Exploit 32(4):673–690
Hsu C-W (2012) Using a system dynamics model to assess the effects of capital subsidies and feed-in tariffs on solar PV installations. Appl Energy 100:205–217
Hu B, Leopold A, Pickl S (2012) IT-Based decision support for turning on Germany's energy transition. Operations research proceedings, pp 449–454
Hu B, Leopold A, Pickl S (2013) Transition towards renewable energy supply—a system dynamics approach. In: Growth and sustainable development. Springer, Berlin, pp. 217–226
Hu B, Leopold A, Pickl S (2015) Concept and prototype of a web tool for public-private project contracting based on a system dynamics model. Cent Eur J Oper Res 23(2):407–419
Jäger T, Schmidt S, Karl U (eds) (2009) A system dynamics model for the german electricity market (No. 21500045). EcoMod
Jalal TS, Bodger P (eds) (2010) The development of a system dynamics model to evaluate electricity generation expansion in New Zealand. Universities power engineering conference (AUPEC), 20th Australasian. Universities power engineering conference (AUPEC)
Jeong S-J, Kim K-S, Park J-W, Lim D-S, Lee S-M (2008) Economic comparison between coal-fired and liquefied natural gas combined cycle power plants considering carbon tax: Korean case. Energy 33(8):1320–1330
Jiao J-L, Han K-Y, Wu G, Li L-L, Wei Y-M (2014) The effect of an SPR on the oil price in China: a system dynamics approach. Appl Energy 133:363–373
Jones CA (2012) Dynamic growth in a photovoltaic market. Int J Technol Policy Manag 12(2–3):101–114

Kasada R, Kwon S, Konishi S, Sakamoto Y, Yamanishi T, Tobita K (2015) A system dynamics model for stock and flow of tritium in fusion power plant. Fusion Eng Des. doi:10.1016/j.fusengdes.2015.03.047

Kiani B, Hosseini SH, Amiri Roozbeh H (2009) Examining the Hubbert peak of Iran's crude oil: a system dynamics approach. Eur J Sci Res 25(3):437–447

Kiani B, Mirzamohammadi S, Hosseini SH (2010) A survey on the role of system dynamics methodology on fossil fuel resources analysis. Int Bus Res 3(3):84–93

Kilanc GP, Or I (2006) A system dynamics model for the decentralized electricity market. Int J Simul Syst Sci Technol 7(7):40–55

Kilanc GP, Or I (2008) A decision support tool for the analysis of pricing, investment and regulatory processes in a decentralized electricity market. Energy Policy 36(8):3036–3044. doi:10.1016/j.enpol.2008.03.034

Kunsch PL, Friesewinkel J (2014) Nuclear energy policy in Belgium after Fukushima. Energy Policy 66:462–474

Leaver JD, Unsworth CP (2007) System dynamics modelling of spring behaviour in the Orakeikorako geothermal field, New Zealand. Geothermics 36(2):101–114

Li J, Dong X, Shangguan J, Hook M (2011) Forecasting the growth of China's natural gas consumption. Energy 36(3):1380–1385

Li C, Zhou L, Na LI, Zeng M (2012) Modelling and simulation of power grid engineering project based on system dynamics on the background of smart grid. Syst Eng Proc 3:92–99

Lisse SD (2014) Applying system dynamics for nuclear power plant design. ASME 2014 small modular reactors symposium, SMR 2014

Ma T, Ji J, Chen M-Q (2010) Study on the hydrogen demand in China based on system dynamics model. Int J Hydrogen Energy 35(7):3114–3119

Meadows DH, Meadows DL, Randers J, Behrens WW (1972) The limits to growth. Universe Books, New York (A Potomac Associates book)

Movilla S, Miguel LJ, Blázquez LF (2013) A system dynamics approach for the photovoltaic energy market in Spain. Energy Policy 60:142–154

Mutingi M (2013) Adoption of renewable energy technologies: a fuzzy system dynamics perspective. In: Qudrat-Ullah Hassan (ed) Energy policy modeling in the 21st century. Springer, New York, pp 175–196 (Understanding Complex Systems)

Niu D, Song Z (2014) Medium and long-term load forecasting based on system dynamics and electricity elasticity coefficient method in China. Energy Educ Sci Technol Part A Energy Sci Res 32(3):2085–2094

Ochoa P, Ackere AV (2009) Policy changes and the dynamics of capacity expansion in the Swiss electricity market. Energy Policy 37(5):1983–1998

Olsina F, Garces F, Haubrich H-J (2006) Modeling long-term dynamics of electricity markets. Energy Policy 34(12):1411–1433

Pereira AJC, Saraiva JT (2013) Long-term impact of wind power generation in the Iberian day-ahead electricity market price. Energy 55:1159–1171

Ponzo R, Dyner I, Arango S, Larsen E (2011) Regulation and development of the Argentinean gas market. Energy Policy 39(3):1070–1079

Qudrat-Ullah H (2013) Understanding the dynamics of electricity generation capacity in Canada: a system dynamics approach. Energy 59:285–294

Qudrat-Ullah H (2014) Green power in Ontario: a dynamic model-based analysis. Energy 77:859–870

Qudrat-Ullah H, Davidsen P (2001) Understanding the dynamics of electricity supply, resources and pollution: Pakistan's case. Energy 26(6):595–606

Reddi KR, Li W, Wang B, Moon Y (2013) System dynamics modelling of hybrid renewable energy systems and combined heating and power generator. Int J Sustain Eng 6(1):31–47

Rendon-Sagardi MA, Sanchez-Ramirez C, Cortes-Robles G, Alor-Hernandez G, Cedillo-Campos MG (2014) Dynamic analysis of feasibility in ethanol supply chain for biofuel production in Mexico. Appl Energy 123:358–367

Robalino López A, Nieto M, Isidro Á, García Ramos JE (2014) System dynamics modeling for renewable energy and CO_2 emissions: a case study of Ecuador. Energy Sustain Dev 20:11–20

Sánchez JJ, Barquín J, Centeno E, López-Pea A (eds) (2008) A multidisciplinary approach to model long-term investments in electricity generation: combining system dynamics, credit risk theory and game theory: IEEE

Saysel AK, Hekimoğlu M (2013) Exploring the options for carbon dioxide mitigation in Turkish electric power industry: system dynamics approach. Energy Policy 60:675–686

Senge PM (1994) The fifth discipline. The art and practice of the learning organization. Doubleday, Currency, New York

Sterman JD (2000) Business dynamics: systems thinking and modeling for a complex world, vol 19. Irwin/McGraw-Hill, Boston

Tan B, Anderson E, Dyer J, Parker G (2010) Evaluating system dynamics models of risky projects using decision trees: alternative energy projects as an illustrative example. Syst Dyn Rev 26(1):1–17

Tang X, Zhang B, Höök M, Feng L (2010) Forecast of oil reserves and production in Daqing oilfield of China. Energy 35(7):3097–3102

Tao Z, Li M (2007) System dynamics model of Hubbert peak for China's oil. Energy Policy 35(4):2281–2286

Tu G-P, Jia R-A, Wang C-X, Jia X-J, Deng Q-Z, Peng Y-Q (2009) Theory and application research on construction of planting and livestock breeding biomass energy industry based on system dynamics. Syst Eng Theory Pract 29(3):1–9

Vogstad K (2005) A system dynamics analysis of the nordic electricity market: the transition from fossil fuelled towards a renewable supply within a liberalised electricity market. NTNU, Trondheim

Vogstad K, Botterud A, Maribu KM, Grenaa S (2002) The transition from fossil fuelled to a renewable power supply in a deregulated electricity market. In: Proceedings of the international conference on system dynamics

Wolstenholme EF (1983) System dynamics: a system methodology or a system modelling technique. Dynamica 9(2):84–90

Wu J, Huang Y-L, Liu C-C (2011) Effect of floating pricing policy: an application of system dynamics on oil market after liberalization. Energy Policy 39(7):4235–4252

Xu J, Li X (2011) Using system dynamics for simulation and optimization of one coal industry system under fuzzy environment. Expert Syst Appl 38(9):11552–11559

Yunna W, Kaifeng C, Yisheng Y, Tiantian F (2015) A system dynamics analysis of technology, cost and policy that affect the market competition of shale gas in China. Renew Sustainable Energy Rev 45:235–243

Zhao J, Mazhari E, Celik N, Son Y-J (2011) Hybrid agent-based simulation for policy evaluation of solar power generation systems. Simul Model Pract Theory 19(10):2189–2205