CHEMICAL ENGINEERING TRANSACTIONS
VOL. 35, 2013

A publication of
AIDIC
The Italian Association of Chemical Engineering
www.aidic.it/cet

Guest Editors: Petar Varbanov, Jiří Klemeš, Panos Seferlis, Athanasios I. Papadopoulos, Spyros Voutetakis

ISBN 978-88-95608-26-6; **ISSN** 1974-9791 DOI: 10.3303/CET1335108

Investigating the Causalities for Cleaner and Affordable Electricity Production Mix: A System Dynamics Methodological Approach

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Nowadays, environmental awareness and cleaner energy production are among the highest priorities of the European Union's (EU) sustainable energy policy agenda. Electricity sector, in particular, has a large share in the EU's energy roadmap 2050. Cleaner electricity production is highly depended on the generated energy balance. The latter is influenced by the penetration of renewable energy sources and the CO_2 emission directives. On the other hand, there is a major technological shift in the usage of energy sources for effective electricity generation. In such a setting, electricity price is becoming a factor which reflects the social acceptability of investments on cleaner production with a direct influence on demand and production levels.
So far, the determination of price in a steady state condition has been widely investigated under production mix, environmental, social and technological influences. However, the absence of dynamic strategic tools which can consider the causal influences as endogenous consequences of the embedded feedbacks is remarkable. From this central point, the objective of this paper is to propose a System Dynamics based methodological approach for examining the interrelations. This approach is illustrated through the aspect of social acceptability. This can be achieved by integrating the systems thinking approach and the simulation discipline into a holistic dynamic consideration of the cleaner and affordable electricity system.

1. Introduction

The 21st century is considered as the century of transition, where major changes are rapidly taking place. Institutional reforms towards environmental awareness and sustainable energy production are highlighted by the European Union (EU). It is stated that the current energy systems must be readjusted in order to be more efficient and able to deal with the challenges of sustainability (European Commission, 2012). Therefore, EU has set clear goals for the coming decades, namely: i) reduction of the greenhouse gas emissions in the next 30 years, ii) improvement of the energy efficiency, iii) purification of the energy production and iv) provision on energy of sustainability in a long-run (Roadmap 2050, 2010). Electricity generation sector, in particular, has been considered as one of the largest contributor to global greenhouse gas emissions due to its great reliance on fossil fuels (i.e. coal, gas, oil). In addition, modern civilizations have been built upon electricity as the main form of energy, thus affecting society's quality and standards of living. Hence, modeling and predicting electricity mix (i.e. the number of different sources employed to the electricity production) in respect of social acceptability is of great importance.
Prior to the liberalization of the electricity generation sector, the main concern of the electricity distributors was to determine the appropriate level of the generated capacity from the installed power plants and estimate the optimal energy production mix to ensure that the generated power capacity would serve the consumers' demand at the minimum cost and with an adequate level of reliability. Therefore, the determination of the cost was highly depended on the fossil fuel prices and the cumulative operating and investment costs of the power plants. Regarding the level of reliability, the electricity distribution networks were designed in order to provide electricity without disruptions and with the lowest possible energy losses within the physical network (Wacker and Billinton, 1989).

Please cite this article as: Tziogas C., Georgiadis P., 2013, Investigating the causalities for cleaner and affordable electricity production mix: a system dynamic methodological approach, Chemical Engineering Transactions, 35, 649-654 DOI:10.3303/CET1335108

After the liberalization, various attributes should be considered emphasizing on clean and sustainable electricity production (Larsen and Bunn, 1999). On the one hand, environmental legislation promotes cleaner production by applying severe taxation policies on primary production (i.e. coal) provoking high and uncontrolled emissions (). On the other hand, private initiatives are observed by adding capacity to the network, which are mainly related with the electricity that is produced by renewable recourses such as photovoltaic, geothermal, wind-farms, biomass, e.t.c. The electricity system is generally driven by uncertain demand. Moreover, the reliability of the system, regarding to the distribution, relies upon the reliable supply of the customers within the confines of the dynamic environment (Karakosta et al., 2009). Thus, the major drawback towards to sustainability refers to the inability to match the rather obsolete energy distribution system to modern needs in order to secure the efficient utilization of capital investments in the energy sector. Therefore, changes in the generated production mix and prices are significantly interrelated (Vogstrad et al., 2004). The side-effect of this interrelation reflects on the social acceptability expressed as the willingness for affordable electricity prices.

This paper proposes a System Dynamics (SD)-based methodological approach to develop dynamic tools to cope with the structural and functional complexity of the electricity system on the dimension of social acceptability under different electricity system settings. The rest of the paper is organized as follows. Section 2 presents a brief literature review on the existing modelling approaches, and justifies the appropriateness of the SD approach. Section 3 presents the basic background of the SD methodology, while the conceptual modelling of the proposed approach is given in Section 4. The modelling of social acceptability is given in Section 5, which presents the causal-loop diagram and provides discussion of the main. Finally, in Section 6 we wrap-up with conclusions and future research aspects.

2. Literature review

During the last century, electricity had a pivotal role and was inherently correlated to the technological advancements and prosperity of the humanity. However, the rapidly increasing demand for energy, along with the imposed regulations over green energy production issues (indicatively the EU adopted the Climate and Energy Package in December 2008 and several energy efficiency measures in 2008 and 2009) and the technological obsolescence of the existing electricity generation and distribution infrastructure, have fostered the scientific research upon this field (EU, 2010). In a recent study, Payne (2010) provides a rather comprehensive review of the existing research efforts that examine the underlying causal relationship between electricity consumption and economic growth. Based on an international survey the author highlights the modern need and the research potential towards the electricity consumption-growth relationship across neighbouring countries. Nevertheless, electricity consumption greatly depends upon the electricity price, especially within the present fragile global economic landscape. To that end, Papadelis et al. (2012), elaborated the Business Strategy Assessment Model to examine the dynamics of existing socio-economic systems in shaping effective energy policies. The researchers highlight that a convergence between policy assessment evaluation and business strategy assessment models could assist regulators in deriving reflexive policy assessment techniques. Furthermore, Sarica et al. (2012) developed a simulation model that embraces the agents involved in a power distribution system. Their optimization efforts reveal that the physical network parameters, from the electricity generator to the end user, have a detrimental impact on the electricity pricing policies and the volatility of the prices.

From a SD perspective, the literature suggests dynamic approaches for the modelling of energy systems. However, in the majority of existing studies, the system boundaries limit the examination to myopic approaches, thus failing to cope with the structural and mainly functional complexity of the actual system. Under this context, Botterud et al. (2002) leveraged the SD approach to capture the main factors that influence the long-term development of the power markets in terms of electricity price and relevant investments. Their analysis over a Norwegian case study concludes that investments in energy infrastructure are primarily driven by high electricity prices. Furthermore, Pereira and Saraiva (2011) employed the SD methodology to characterize the long-term evolution of electricity demand and prices as to tackle the investment and profit maximization problems of power generation agents. They applied their model in the generation expansion planning problem of wind parks and solar systems in Portugal and Spain (Pereira and Saraiva, 2013). Moreover, Ojeda et al. (2009) proposed a SD model to investigate the role of interconnector between two electricity markets. Their research outcomes indicate the beneficial intervention of an interconnector operator both in terms of electricity supply reliability and in electricity merchant prices. Recently, Cepeda and Finos (2011) examined the dynamics among interdependent electricity markets. Their results indicate that the existence of heterogeneity in the price capping and capacity institutional settings between interconnected power markets can lead to market distortions. In the renewable energy sources domain, Vogstrad et al. (2002) investigated the sustainable energy production from different renewable sources and assessed the optimum power generation mix. The authors introduced a simulation model taking into account the stochasticity of electricity markets and the dynamics of the financial economics. In particular, the authors investigated the role of new technologies towards renewable energy production and their effect in achieving equilibrium in the energy market, while promoting the best pricing policies for the consumers. Considering the social aspect of energy sources, Cowell et al. (2011) examined the social acceptability of wind energy in Wales and concluded that the provision of community benefits increases the sustainability of wind farm development areas.

3. System dynamics approach

The SD methodology is reported as an appropriate tool to embrace the plethora of parameters within the energy sector (Ford, 1996). The theory of SD methodology was developed during the fifties and sixties by Forrester (1961) as a policy design tool for complex management business problems. Despite traditional discrete event simulation-based approaches, the SD methodology provides an understanding of changes focusing on the interaction between physical flows, information flows, delays and policies that create the dynamics of the variables of interest and thereafter searches for policies to improve system performance. This is justified by its ability to control the increased complexity, deriving in particular from the sources of uncertainty and the causal influences.

The causal loop (influence) diagrams capture the major feedback mechanisms. The objective of these diagrams is twofold. Firstly, they simplify the representation of the model and secondly, address the hypothesis of the model. The structure of a dynamic system model contains stock (state) and flow (rate) variables. Stock variables are the accumulations (i.e. Resource Availability), within the system, while flow variables represent the flows in the system (i.e. Electricity Price). The structure of a system in SD methodology is captured by linking the stock and flow structure with feedback mechanisms. The direction of the influence lines (causal links) displays the direction of the effect. The sign (+) or (-) at the upper end of the influence lines shows the sign of the effect. When the sign is (+), the variables change in the same direction, having positive or negative influence (Sterman, 2000). Through the causal analysis, the dominant feedback loops (balancing and/or reinforcing) will be exhibited, as mechanisms governing the mode of the dynamic behavior of the system.

4. Methodological framework

The generic methodological framework towards a holistic modeling approach is given in Figure 1.

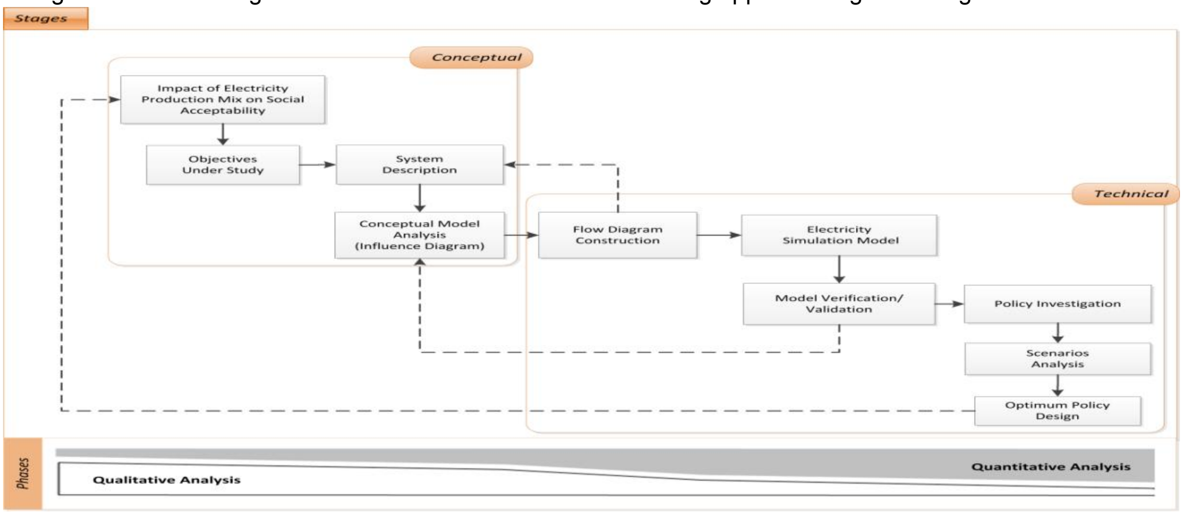

Figure 1: System Dynamics methodological framework approach

Specifically, in order to reveal best policies, the modeling follows a qualitative and quantitative approach, which includes ten stages closely connected with each other. The qualitative phase contains the development of causal-loop diagrams, depicting the interrelations among the system elements, under system objectives, within specific system boundaries. The quantitative phase follows the qualitative phase and contains the development of the flow diagrams. Thereafter, the diagrams will be translated into simulation programs that will be verified and tested. The simulation discipline is further utilized to conduct what-if scenario analysis. This analysis is supported by special software packages such as DYNAMO®, ithink®, Powersim®, Vensim®, e.t.c. Based on the results obtained by simulation runs, policies that improve the dynamic behaviour of the system are revealed. The following sections present the conceptual modeling of this approach dealing with the electricity generation sector under the scope of social acceptability, taking explicitly into consideration: i) electricity production mix, ii) electricity demand, iii) pricing policy, iv) CO_2 emissions through operational costs, v) investments, vi) technological advances, vi) energy sources availability, and vii) distribution networks.

5. Causal relationships and social acceptability

Today population growth and the global financial crisis have induced great changes in the electricity demand scheme. In addition, a large portion of the population is environmentally conscious, thus raising the demand for renewable energy sources. Generally, consumers request the provision of clean electricity in low price. Nevertheless, existing technologies and infrastructure cannot often accommodate market request (Anderson and Taylor, 1986). In addition, power system operators try to design and assess different pricing mechanisms and incentives in order to increase their market penetration and their profits. The present study extents the existing decision support model developed by Botterud et. al (2002). In particular the proposed model of the previous is extended by Vogstrad et. al (2005). However, in the approaches proposed the issues of social acceptability are not taken into consideration. Therefore, the latter constitutes the main contribution of our modelling approach. In our study, we emphasize the vital role of social acceptability as the key factor of policy making decisions and therefore encourage the public to embrace sustainable energy policies and turn them into practice. As presented in Figure 2, the level of social acceptability is expressed through the social response to the electricity price. As the Electricity Price decreases the Social Acceptability increases due to customers' satisfaction. On the one hand, the public has positive influence on the system about the electricity production mix. On the other hand, the Electricity Production Mix is highly correlated with the Electricity Price, translated on the willingness to pay for low cost electricity. Clean and Affordable Energy comprises by plethora of structural elements shown in Figure 2.

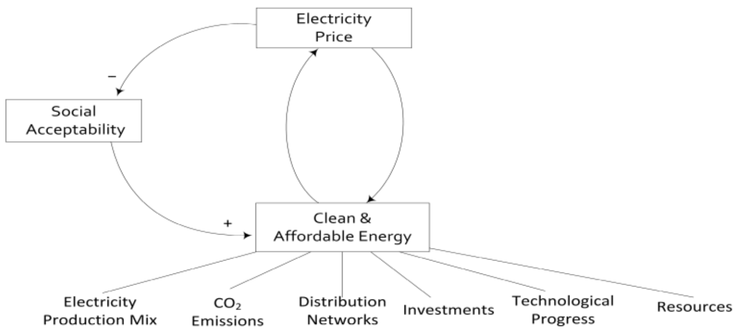

Figure 2: Social acceptability in electricity sector

Interestingly, the polarity of causal relationship between Clean and Affordable Energy and Electricity Price is not profound. In particular, a careful experimental design under alternative policy settings for each structural element dictates a combination of number of applicable policies (scenarios). The causal effect of Clean and Affordable Energy in terms of the Electricity Price depends on the selected scenario. Given that the Electricity Price directly affects the policy matrix for Clean and Affordable Energy raises open question for policy makers and regulators to define the best policy mixture which capture the equilibrium. In this paper we present the conceptual modelling of this approach, focusing on the interrelations deriving from the Social Acceptability as illustrated in Figure 3. As Electricity Demand increases, Electricity Price decreases and vice versa. Increase in Gross Domestic Product (GDP) per Capita increases the Electricity Demand through the Intensity of Electricity Use. Except the demand sector, in Figure 3 six (6) key areas can be identified for policy interventions affecting the Social Acceptability.

Policy 1: The Electricity Production Mix affects the Electricity Price which negatively affects the *Social* Acceptability. Specifically, the diversification of the energy production sources increases. Electricity Prices due to the need for extended and efficient electricity networks, and innovative sustainable technologies. However, an increase in Electricity Price decreases the Social Acceptability as consumers are generally interested in the undisrupted supply of electricity but not willing to pay a premium price depending on the nature of the energy resources (Reinforcing Loop R_1 : Electricity Production Mix → Electricity Price → Social Acceptability).

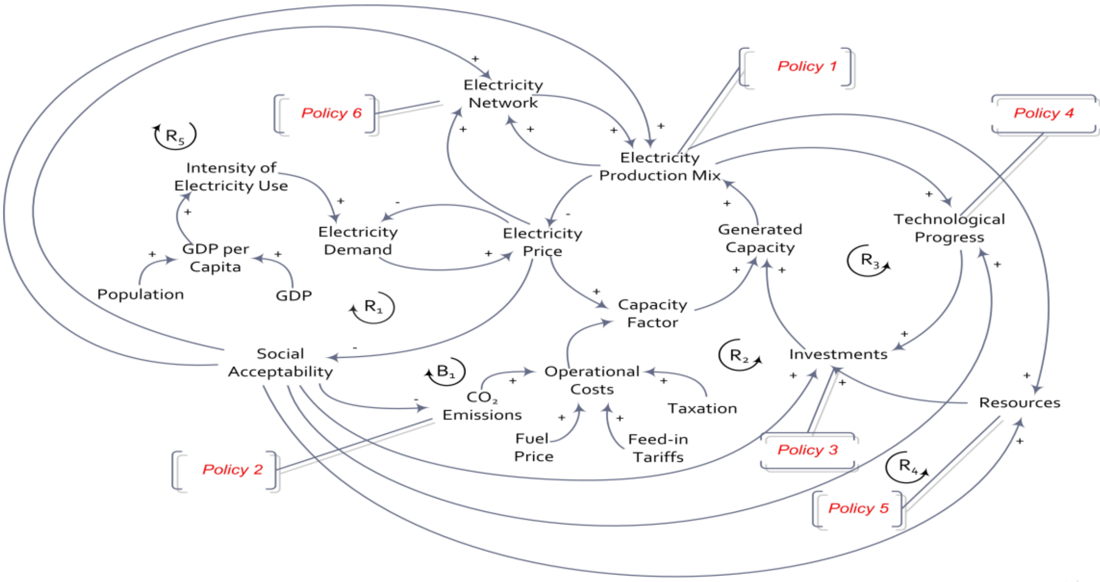

Figure 3: Main causal loop diagram of the conceptual system under study

Policy 2: The introduction of regulations, regarding the CO_2 Emissions, cause an increase in Operational Costs, thus increasing the Capacity Factor, highlighting the need for more diversify portfolio on energy production sources (Generated Capacity). However, the introduction of renewable energy sources, changes the Electricity Production Mix thus provokes an increase in Electricity Price and reduces Social Acceptability (Balancing Loop B_1 : CO_2 Emissions → Operational Costs → Capacity Factor→ Generated Capacity → Electricity Production Mix → Electricity Price → Social Acceptability).

Policy 3: Regulations pressure regarding sustainable Electricity Production Mix foster Investments in the relative sector thus increasing the existing Generated Capacity and therefore introducing new modes of Electricity Production Mix at a lower Electricity Price. The latter increases the Social Acceptability (Reinforcing Loop R_2 : Investments → Generated Capacity→ Electricity Production Mix → Electricity Price → Social Acceptability).

Policy 4: A great burrier for the electricity sector is the inability to store the generated energy in order to cover future demand, due to the obsolesce of the existing energy production technologies. The aforementioned implementation leads to volatile production and frequently in mismatch to the corresponding demand. To this effect research and development in relevant Technological Progress promotes the utilization of novel applications that can increase the effectiveness of the energy production and distribution systems. This increased performance reduces the risk related to the financial returns thus keeping electricity prices at reasonable levels and therefore enhances Social Acceptability of sustainable energy production systems (Reinforcing Loop R_3 : Technological Progress → Investments → Generated Capacity → Electricity Production Mix → Electricity Price → Social Acceptability).

Policy 5: Following the previous analysis the availability of alternative energy production sources (Resources) along with a prosperous institutional environment can foster Investments in sustainable energy production systems using different renewable and/or non-renewable resources. Consequently, the Electricity Production Mix is increasing which leads to the provision of the electricity commodity to the public in favourable pricing policies (Reinforcing Loop R_4: Resources → Investments → Generated Capacity → Electricity Production Mix → Electricity Price → Social Acceptability).

Policy 6: The distribution of the electricity presumes the existence of the Electricity Network in adequate capacity (causal links between Electricity Network and Electricity Production Mix, in Figure 3) However, the serving and the maintaining of the supply raises bi-lateral agreements between countries and interconnected Electricity Network (Reinforcing Loop R_5 : Electricity Network →Electricity Production Mix → Electricity Price → Social Acceptability).

6. Concluding discussion

Our analysis denotes that the study of social acceptability is vital and of great importance for policy making decisions. Due to the complexity and the continuously increasing number of the factors that directly relate to electricity production and distribution systems, the SD methodology seems to be an effective approach towards the articulation and evaluation of alternative related policies. On the one hand, investments and

technological progress in electricity production sector have a positive appeal in public opinion and drive the demand for active interventions in this sector. Within this context appropriate regulator environments may promote the exploitation of alternative electricity production sources and an expanding upgrade of the electricity distribution networks. On the other hand, emphasizing on the diversification of the electricity production mix or the limitations of CO_2 emissions may yield opposite results and discourage the public from embracing sustainable energy strategies and practices. Therefore with the scope of increasing public social acceptability of electricity, the implementation of relative decision making policies seems imminent.
In conclusion, this approach can be used for policy formulation towards cleaner and affordable electricity production mix. However, such an approach calls for further research in the fields of dynamic modeling validation, policy analysis and testing.

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