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# Sustainable Energy Security: Critical Taxonomy and System Dynamics Decision-Making Methodology

Charalampos Tziogas*, Patroklos Georgiadis

Department of Mechanical Engineering, Aristotle University of Thessaloniki, Greece
ctziogas@auth.gr

Today, social and economic well-being of nations greatly depends upon the availability, accessibility, affordability, and environmental acceptability of the provided energy services to the end-users. Therefore, effective energy policies and utilized technologies need to be leveraged as to improve and sustain a system's energy security with reference to threats from external and internal events. To that end, energy supply diversity is often regarded as an essential approach that could assist in promoting energy security of an energy consuming system. Indeed, energy supply diversity is often regarded as a proxy for energy security. Moreover, despite the fact that many research efforts have been developed thus far to model energy security, a comprehensive approach that could capture the complex nexus of dynamics that transcend energy secure systems does not yet exist.

In this context, in this manuscript we present a critical taxonomy of the state-of-the-art literature and practices that apply to all major issues that stakeholders need to address for the design of energy secure systems. More specifically, we first present the generic system components along with the unique characteristics of potential energy secure systems. Following this, we recognize and present the most critical issues for the design and planning of energy secure systems, while we provide a respective classification of the related research efforts. Following that, we propose a conceptual System Dynamics approach upon the energy sector that could assist policy-makers and regulators in strategically planning energy security systems for the society. Finally, we wrap-up and discuss major gaps in the existing literature, while propose a future research agenda.

## 1. Introduction

Nowadays, more pronouncedly than ever before, every jurisdiction is closely related to energy systems in order to meet the demand for a wide range of diverse services like electricity, transportation, heating and cooling (IEA, 2014). At a greater extent, social and economic well-being of a jurisdiction greatly depends upon the availability, accessibility, affordability, and environmental acceptability of the provided energy services to the end-users (Shin et al., 2013). Therefore, effective energy policies and utilized technologies need to be leveraged so as to improve and sustain a system's energy security with reference to threats from external and internal disruption events (Hughes and Ranjan, 2013). To that end, diversity in energy supply is often regarded as an essential strategy that could assist in promoting energy security of an energy consuming system (Cooke et al., 2013). Indeed, energy supply diversity is often regarded as a proxy for energy security (Kruyt et al., 2009).

Notably, Europe faces major challenges regarding its energy security both in terms of energy production (Sanz-Casado et al., 2014), power transmission and electricity distribution (Chyong and Hobbs, 2014). The increased risks and uncertainties stem mainly from the fact that the European Member States greatly depend upon imported energy supplies that render their energy sufficiency vulnerable, particularly for the less integrated and connected regions like the Baltic and Eastern Europe. In fact, European Union (EU) imports around 53 % of the energy it consumes (EU, 2014). Except for the social implications, the European energy insecurity associates with significant economic impact. More specific, the EU external energy bill accounts more than €1 billion per day (around €400 billion in 2013) and more than a fifth of the total EU imports (EU,

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2014). Taking into consideration the fact that the energy demand in the EU region is expected to increase by 27 % by 2030, energy security has to be reviewed under a novel, sustainability context that may affect the energy supply and trade flow schemes. Therefore, new energy policy agendas and strategies need to be drafted (EU, 2014) as to address the growing energy demand through embracing the plethora of the associated economic, environmental, social (Sacchelli, 2014) and technological factors. Nevertheless, despite the fact that many research efforts that tackle the issue of energy insecurity have been developed, a solid approach that documents the critical factor of energy security and the adoption of System Dynamics (SD) approaches in the energy sector are very limited (Tziogas and Georgiadis, 2013). Such limitations mainly stem from data unavailability and poorly customized models (Shin et al., 2013).
In this context, the purpose of this research is to highlight critical dimensions of energy security. Therefore, in Section 2 we present a critical taxonomy of the state-of-the-art literature and practices that apply to all major issues that stakeholders need to address for the design of energy secure systems across the entire energy supply chain. Following that, in Section 3 we propose a conceptual SD approach upon the energy sector that could assist policy-makers and regulators in strategically planning energy security systems. Finally, we wrap-up and discuss major gaps in the existing literature, while we propose a future research agenda.

## 2. Energy security

### 2.1 Definition

The term “energy security” is extensively used in the literature during the last years. However, an integrated system that captures the dynamics of an energy security phenomenon incorporating alternative energy sources has been less pronounced. This can be attributed to the complexity of the issue and the plethora of the entities involving in such a system. Furthermore, there is not any taxonomy that maps the relevant sustainability indicators at each echelon of an energy supply chain. An energy supply chain comprises of the “whole set of industrial and commercial activities that contribute to supplying energy and energy related goods and services, to ultimately provide energy services” (Blum and Legey, 2012).
It is well accredited that no energy system can be completely secure (Ekins et al., 2011). To that end, a key priority for the global policy-making is energy security. Notably, in recent years, the reports and publications about energy security are increasing due to the significance to both the developed and developing world. The term is being perceived with a diverse meaning from different stakeholders and, therefore, it is often characterized as ‘polysemic’ and ‘slippery’ providing the denotation that it incorporates multiple dimensions at the same time (Chester, 2010). Indicative dimensions under the ‘polysemic’ and ‘slippery’ prism include: (i) decentralisation of supply and energy intensity, (ii) national differences like for example the level of energy autonomy of a stakeholder’s country, and (iii) country focus like the emphasis on market solutions or state involvement.
Specifically, Chester (2010) very early recognized that “Energy security is ubiquitous to contemporary discussion about energy issues and climate change. The term is commonly found embedded in discussions framed around a handful of notions, which denote unimpeded access or no planned interruptions to sources of energy, not relying on a limited number of energy sources, not being tied to a particular geographic region for energy sources, abundant energy resources, an energy supply which can withstand external shocks, and/or some form of energy self-sufficiency”. Generally, four (4) components of energy security are recognized, namely (1) Availability, (2) Accessibility, (3) Affordability, and (4) Acceptability. Nowadays, taking into account the population growth, the global financial crisis and the fundamental evolutions that has taken and taking place in the energy market since the early 1990’s, the preservation of the energy security, while considering economic, environmental and social parameters, still remains an open challenge for policy makers. In the subsection follows a critical taxonomy of related up-to-date and seminal studies is presented, as these are mapped on the aforementioned components.

### 2.2 Critical taxonomy

Based on an extensive synthesis of the literature, we provide a first generic draft of all the major issues and the reported indicators that need to be tackled in designing sustainable energy supply chains that foster energy security. The inclusive critical taxonomy is presented in Table 1. This framework is not an exhaustive list of all related studies, but rather comprises a synthesis of all issues that have been identified as part of our on-going research.

*Table 1: Critical taxonomy of existing research*

| Study | Ener. Security Comp. | | | | Indicators | Research Approach | Sustainability | | |
|---|---|---|---|---|---|---|---|---|---|
| | Av. | Ac. | Af. | Ap. | | | Env. | Soc. | Ecn. |
| Shin, Shin, and Lee (2013) | • | • | • | • | – Gas Price<br>– Gas Import Volumes ($M^3$)<br>– $CO_2$ Emissions<br>– Market Liquidity | QFD, SD | • | | • |
| Chuang and Ma (2013) | • | | • | | – Energy Supply Mix (MT)<br>– $CO_2$ Emissions | HHI, SWI | | • | • |
| Becker and Fischer (2013) | | | • | | – Electricity Price (€/MWh) | Theoretical Analysis, Comparative Analysis | | | • |
| Bazmi and Zahedi (2011) | • | | • | • | – Citations (#) | Literature Review | • | • | • |
| Abada, Briat, and Massol (2013) | • | | | | – Fuel Demand (Mtoe/year)<br>– Fuel Price ($/utoe) | SD | | | • |
| Blum and Legey (2012) | • | | • | | – Energy resilience<br>– Energy adaptability<br>– Energy transformability | Theoretical Analysis | • | | • |
| Hinrichs-Rahlwes (2013) | • | | | | – Share of renewable energy sources to fuel in Germany | Theoretical Analysis, Descriptive Statistics | • | • | |
| Li (2005) | • | | | | – Fraction of energy sources to world market | Theoretical Analysis | • | • | • |
| Genus and Mafakheri (2014) | • | • | | • | – None | Theoretical Analysis, Descriptive approach | • | | |
| Katinas et al. (2014) | • | | | | – Share of renewable energy sources for energy production in Lithuania (ktoe; MW; TWh)<br>– $CO_2$ Emissions (kt) | Theoretical Analysis, Descriptive Statistics | • | • | |
| Luthra et al. (2015) | • | | | | – Ranking of barriers to sustainable energy technologies adoption | AHP | • | • | • |

**Abbreviation list**

| | | | |
|---|---|---|---|
| **Av.**: Availability | **Ac.:** Accessibility | **Ecn.**: Economic | **SD**: System Dynamics |
| **Af.**: Affordability | **Ap.:** Acceptability | **QFD**: Quality Function Deployment | **SWI**: Shannon–Wiener Index |
| **Env.**: Environmental | **Soc.**: Social | **HHI**: Hirschman–Herfindahl Index | **AHP**:Analytical Hierarchy Process |

A plethora of studies investigating energy security and sustainability exists. To that end, Bazmi and Zahedi (2011) provide an update over the role of optimization modelling in the global power sector though leveraging

publications over the past decade, with a specific focus on electricity-generating technologies and the related distribution or supply systems. In addition, in order to promote energy security, the role of alternative and renewable energy sources in the energy mix has been investigated. For example, Abada et al. (2013) investigate the alternative energy substitution opportunities for natural gas in the industrial sector. Specifically, the authors provide a SD model to study the role of prices towards substitutions between three main fuels namely, oil, coal and natural gas, in eight OECD economies during the period 1978-2008. Their developed SD tool proves to be a realistic formulation of the natural gas demand function. Their model captures both fuel substitution and the dynamic adjustment of the natural gas demand to past prices. Moreover, Li (2005) identifies the significance of diversification and localization of energy systems towards promoting energy security and he further claims that these ideas foster bio-diversity and investment returns. Furthermore, Shin, Shin, and Lee (2013) elaborate the Quality Function Deployment (QFD) approach to identify key energy security factors in the gas sector of the Republic of Korea and combine the SD methodology to monitor the impact of intervention policies upon energy security. The authors conclude that the implemented Korean energy policies are ineffective, mainly characterized by incoherency which leads to increasing energy insecurity in market liquidity along with and excess of $CO_2$ emissions. Within the context of the Asian countries, Chuang and Ma (2013) leverage the Hirschman–Herfindahl Index (HHI) and the Shannon–Wiener Index (SWI) to investigate the contribution of different energy sources to the energy system in Thailand. Their findings support that the utilization of a diversified energy mix can secure national energy systems' stability through reducing price fluctuations and environmental pollution.
Further, recognizing the key role of energy towards economic development, Blum and Legey (2012), motivated by the failure of developed economies to maintain a maximum welfare state among their citizens based upon the provision of affordable, sufficient and environmentally sustainable energy services, by introducing the notion of energy security gap. To that end, they prescribe the indicators of energy resilience, adaptability and transformability in order to assess and foster the energy security of an economy. Under this context, Hinrichs-Rahlwes (2013) describes best practices examples from Germany and the European Union to facilitate the successful drafting of reliable investment frameworks and policies for the future development of renewable energy technologies. Also, Genus and Mafakheri (2014) adopt a neo-institutional perspective to illustrate the pivotal role of institutional arrangements along bioenergy supply chains for the understanding and the improving of energy security state in the UK. In addition, Katinas et al. (2014) review the current state and the potential of renewable energy options in Lithuania. The authors claim that the drafting of national support schemes could increase the utilization of renewable energy to ameliorate energy security in Lithuania. On regard of the developing countries, Becker and Fischer (2013), by comparing feed-in tariffs and auction-based tariffs of solar photovoltaic systems in China, India and South Africa, report that countries need to assess various policies that promote low-cost electricity generation from renewable energy sources. Further, the authors argue that to render electricity from renewable sources affordable, the designed generation-based policies need to be tailored to the specific country's economic and social structure. Specifically, with refer to social aspects, India despite accounting for 17 % of the world's population, it accounts for only 4 % of the world's energy consumption (Pillai and Banerjee, 2009). In order to fulfil its increasing energy demand, Luthra et al. (2015) propose that the country has to invest in renewable energy sources and therefore provide sustainable energy services. However, the extensive literature review provided by the authors identified twenty-eight barriers considering the adoption of renewable/sustainable energy technologies in India. Further, an indicative incident revealing the energy insecurity of the country was "The Great Indian Outage", stretching from New Delhi to Kolkata, that occurred on July 30 and 31, 2012, and which is characterized as the world's largest blackout. The power failure occurred due to the collapse of the northern power grid and affected approximately 700 million people (twice the population of the United States) (Luthra et al., 2015).

## 3. System dynamics conceptual modelling approach

### 3.1 System dynamics theory

The SD methodology is grounded in the theories of linear/nonlinear dynamics and feedback control loops and is well documented as an approach for studying the dynamic behaviour of complex systems. It was developed by Jay W. Forrester during the fifties and sixties as a policy design tool for managing complex business problems. The dynamic complexity arises because systems are dynamic, tightly coupled, governed by feedback, nonlinear, history-dependent, self-organizing, adaptive, counter-intuitive, policy-resistant, and characterized by trade-offs (Sterman, 2000). Through analysing the processes of information feedback, the SD methodological approach reveals 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.

The structure of a system in SD methodology is based on causal loop diagrams. A causal loop diagram represents the major feedback mechanisms. These mechanisms have either a negative (balancing loop) or positive (reinforcing loop) effect. A balancing loop exhibits goal-seeking behavior: after a disturbance, the system seeks to return to an equilibrium state. In a reinforcing loop an initial disturbance leads to further change, suggesting the presence of an unstable equilibrium. Further, the SD methodology structure is captured by linking stocks and flows with the aforementioned feedback mechanisms. The direction of the influence lines (causal links) displays the direction of the effect. The positive (+) or negative (-) polarity demonstrates shows the direction of the effect. In positive causal links, the variables change in the same direction, having positive or negative influence (Sterman, 2000). Finally, a negative causal link demonstrates a change at the opposite direction.

### 3.2 Causal-loop diagram of the system under study

The causal-loop diagram of the system showing the interrelations among energy security and sustainability pillars is illustrated in Figure 1.

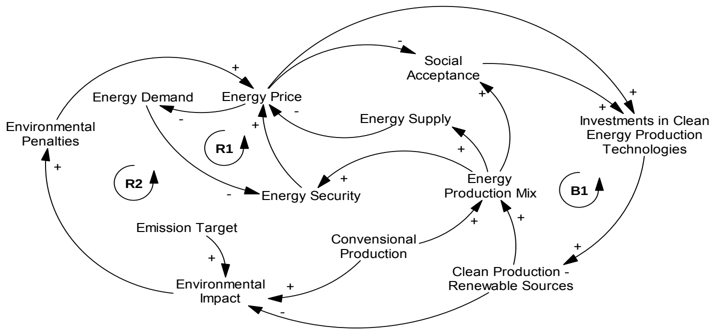


*Figure 1: Causal-loop diagram of the system under study*

Initially, the energy price affects the current consumers' energy demand and therefore as the energy cost increases the respective demand decreases and the social acceptability of the existing energy production mix is decreased as well. Following that, the increase in energy demand further challenges the energy security status at the system under study (Reinforcing Loop, R1). To that end, investments in clean energy production technologies could increase the energy production from renewable energy sources thus enhancing the energy production mix. Therefore, the energy supply increases, while the energy security status is safeguarded thus lowering energy supply price (Balancing Loop, B1).

Energy production mix comprises of conventional and renewable energy production sources. On the one hand, conventional energy production technologies increase the negative impact on the environment through hazardous emissions from the elaborated fossil fuels. On the other hand, eco-friendly technologies bring the environmental system in balance through lowering greenhouse gas emissions. Hence, investments in clean energy production technologies are further dictated by the environmental impact of the specific energy production mix. In case the set emissions' target is surpassed, environmental penalties apply thus causing an increase in the supplied energy price (Reinforcing Loop, R2).

## 4. Conclusions

Energy security is an emerging field stemming from the increasing concerns of both academia and authorities. Furthermore, research focus is directed towards the key performance indicators (KPIs) that should be elaborated upon monitoring and assessing energy security level in conjunction with sustainability performance. In the present study, we briefly reviewed up-to-date and seminal scientific works while emphasizing on the key issues that determine energy security strategy design, along with the indicators and indexes that have been elaborated to measure it.

Moreover, our developed SD framework highlights that formulated national energy policies need to consider all the sustainability dimensions as to ensure that effective and balanced energy security strategies are implemented. However, a robust approach in the energy security literature is currently lacking. Therefore, a potential research field could be the development of comprehensive and rigorous decision-making framework upon the manner energy security is linked to various competing ends. Our on-going research focuses on incorporating SD approach that could capture the dynamic nature of the interrelated factors that shape national energy security landscape.

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