2016

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Original Publication Citation
Toba, A. L., & Seck, M. (2016). Modeling social, economic, technical & environmental components in an energy system. *Procedia Computer Science, 95*, 400-407. doi:10.1016/j.procs.2016.09.353

Available online at www.sciencedirect.com

ScienceDirect

Procedia Computer Science 95 (2016) 400 – 407

Procedia Computer Science

Complex Adaptive Systems, Publication 6
Cihan H. Dagli, Editor in Chief
Conference Organized by Missouri University of Science and Technology
2016 - Los Angeles, CA

Modeling Social, Economic, Technical & Environmental Components in an Energy System

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Abstract

Energy system models have become the main supporting tool for energy policy. Modern challenges in energy policy require energy systems models that integrate technical, environmental and societal aspects of the energy systems. In this paper, we introduce a conceptual model for an energy system model that specifies the relationships between social, technical, environmental, and economic aspects of an energy system. This conceptual model presented in the IDEF0 language will serve as a basis for a computational energy systems model.

Peer-review under responsibility of scientific committee of Missouri University of Science and Technology

Keywords: Energy system, environment, technology, society, economics, resource

1. Introduction

An energy system involves a sequence of processes and operations from the extraction of primary energy sources to the consumption of energy by society[1]. Society has become heavily dependent on highly advanced and complex technologies, which according to Castells[2], have come at a high environmental price, with increased needs in material and energy. These trends have led both social and technical systems to be strained to their capacity[3].

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Peer-review under responsibility of scientific committee of Missouri University of Science and Technology
doi:10.1016/j.procs.2016.09.353

In that regard, governments are trying to balance social needs, technological requirements and environmental considerations to manage efficient and more sustainable economies. For example, in his 2011 State of the Union address, president Obama called for a transition to a cleaner energy economy[4]. To succeed in this transition, we need tools that can analyze the complex and dynamic co-evolution of society, technology and nature. These tools will help assess the impacts of technological innovation and resource scarcity on the energy infrastructure, the societal demand, and the protection of the environment.

Energy system models capture relevant actors (producers, generators, suppliers and consumers), energy sectors (electricity generation, industrial, residential, commercial, transportation) and socioeconomic aspects (costs, prices, policy, social behavior) [5]. Over time, the focus of these models has progressively moved toward environmental issues, given the threat posed by climate change[6]. According to DOE[7], energy systems should be (1) secure, in terms of a value chain from supply (including energy resources, materials, and technologies) to operations (distribution, storage, and end use of fuels and electricity), (2) economically competitive (affordable and sustainable services) and (3) environmentally responsible (minimization of air, water and land pollution). An energy system model should therefore include components pertaining to these requirements.

Energy system modeling is critical, as an inadequate representation of energy systems can lead to inappropriate decision making[8]. Past researchers have presented several models, which can be categorized into two groups — optimization and simulation models—. Optimization models attempt to achieve set objectives, under given constraints, by either maximizing desired factors or minimizing undesired ones. Three prevalent models are MARKAL[9], TIMES[10] and MESSAGE[11]. These models are used to find a preferred mix of technologies, considering certain restrictions (minimization of costs, fuel usage, emissions, return on investment, etc.)[5]. Unlike optimization models, simulation models generate possible behaviors of the system, focusing on describing its likely evolution[1]. Most used models in this category are NEMS[12], PRIMES[13] and LEAP[14]. These models constitute an appropriate tool to explore alternatives, and more importantly assist decision makers in testing policies with “what-if” scenarios.

The domain of energy system modeling is not without challenges. Recurring issues encountered are the growing complexity of energy systems, the integration of human behavior and the transparency in models[15].

For Bale, Varga[16], the complexity in energy systems arises from what they call the “energy trilemma”. This trilemma consist in finding a way to (1) consistently provide affordable energy services, (2) achieve reliability of energy supplies and (3) reduce greenhouse gas from energy generation, all at the same time. Studies have taken on this challenge, using the systemic approach[17]. This approach offers a more global and unified view of the overall energy system. That way, the focus is on the system as a whole, which is built upon interactions between economy, society, technology and environment[16]. An approach focused on a single aspect would miss the required alignment between all other sectors, oversimplify the view of the energy system and thus limit the applicability of the results. Despite several suggestions for a more holistic energy model, no comprehensive model taking into account these aspects has been proposed.

The social aspect is also missing from the previous studies. The impacts of social structure and policy in energy system are not examined. In their study, Bale, McCullen[18] look into the effects of social networks in the adoption of energy technologies. More specifically, they are interested in knowing how social influence can enhance technology diffusion. In another study, the influences of public values and norms on policy are discussed[19]. Strbac [20] analyzes the effects of demand side management in the transition toward a low-carbon energy system. Rydin, Devine-Wright[21] suggest the study of the co-evolution of social, economic, political and technological aspects of the energy system, as well as the impacts of built environment. However, no model is proposed in that sense. No model has provided insight, as to how society behavioral patterns can or may change, depending on the effects of technical, economic and environmental aspects from the energy system.

The challenge of transparency and traceability arises from the complexity of the energy system[22]. This lack of transparency is caused by the inability of modelers to describe in detail the inner work of the model. Pfenninger, Hawkes[1] link this inability to assumptions made in models. According to Klosterman[23], inadequate assumptions lead to poor results, which do not reflect the mechanism of the real system. Moreover, less complexity is generally an indication of more assumptions. If core assumptions are invalid or unjustified, then the methodology, the model and ultimately the results are of little or no importance[24]. Transparency implies thus traceability but also repeatability, through justified assumptions and established theories.

In this paper, we introduce a conceptualization of an energy system model. One particular form of energy that we are interested in is electricity. An electricity system is a network of components involved in the generation, transmission, distribution and consumption of electric power[25]. These activities necessitate the use of technology. However, we are mostly interested in technologies in the process of generation, as they are most critical in making the electricity system more secure, economically competitive and environment friendly. For example, the use of solar technology in a given area, say a community solar, would offer significantly different requirements, compared to the use of natural gas. The choice of generating technology may also dictate needs and requirements for transmission or distribution. Technologies used for consumption reflect consumers' preference, and only intervene after electricity is delivered. They are outside of the scope of our model and therefore, overlooked.

Generating electricity requires the availability of primary sources or natural resources (wind, coal, gas, water, etc.), as well as their use in the processes of transformation. These sources (renewable and non-renewable resources) are transformed by energy systems (plants, wind farm, hydroelectric stations, etc.) into electricity, under regulations[26]. These production processes have environmental effects, not only affecting nature[27], but also human health[28]. The consumption reflects the societal demands in electricity, which are met in exchange for money.

In light of these relationships, we consider the electricity system as a combination of four (4) subsystems, namely technical, environmental, social and economic. Our model captures and highlights the interplay of policy and regulations, economic, environmental, social and technological factors composing the electricity system.

We use IDEF0 (Icam −Integrated Computer Aided Manufacturing− DEFinition for Function Modeling) to present the conceptual model. This choice is motivated by 2 reasons. One, it offers a perspective from high to low level (with more details) views, indicating the various degrees of abstraction or assumption made to satisfy the purpose of the model. This structure reinforces the integrity of the design, which can be verified at each level. Two, at each level, it offers a functional view of the system, presenting all functions and activities enabling the system operations. In that sense, it helps in specifying and documenting every relationship within the model. This function-based design (1) facilitates the correspondence between activities or processes represented and their counterpart in reality, and (2) enables the model design to be tracked back to the main objective. IDEF0 is thus adequate to face the challenges of transparency and traceability evoked earlier, in energy system modeling. Its clarity helps assist in communicating the application design to users and easily build understanding.

Section 2 gives a brief definition of the conceptual model, using the IDEF0 approach and introducing the subsystems and their operations. Section 3 summarizes the paper and discusses future works.

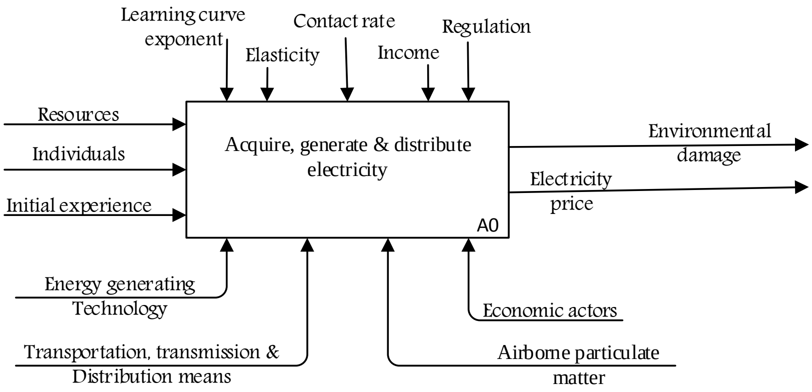
2. Model conceptualization

2.1 Model description

IDEF0 specifies the functions (activity, process, or transformation) performed in the system and indicates the mechanisms or means by which those take place. IDEF0 models are composed of 'graph diagrams', 'text' (textual information, such as 'purpose' and 'viewpoint', added to clarify the model) and 'glossary' (definitions of processes, inputs, controls, outputs and mechanisms). The graphic diagram contain 'boxes', with 'inputs' (concept capturing components that trigger the activity) shown as arrows entering the 'box' from the left side, outputs (concept capturing components that result from performing the activity) exiting the box from the right side, controls (concept capturing components that guide or regulate the activity) entering the 'box' from the top, and 'mechanisms' (concept capturing components that enable the activity to be performed) entering 'box' from the bottom[29]. The diagram at the highest level provides most general descriptions of the subject represented. It also defines the 'purpose' (the goal) as well as the 'viewpoint' (the perspective and the context within which an energy system is looked at) of the model. This diagram is split into a series of child diagrams providing more details. These diagram types are cross-referenced to each other.

The A-0 diagram displayed in figure 1 represents the top-level context of the model. It sets the model scope or boundary as well as its orientation, with main 'inputs', 'outputs', 'controls' and 'mechanisms'. The main function of the model is *Acquire, generate & distribute electricity*. This function derives from Jaccard[30], who defines an energy system as "*the combined processes of acquiring and using energy in a given society or economy*." These processes would require resources that are extracted, refined, transported, stored, and converted, using technologies, into end product for individuals' use[31]. We also account for regulations governing these operations[26], environmental damages created by emissions generated from the operations[32] and their economic implications[33], which are key components in the electricity system.

The A0 diagram displayed in figure 2 represents the electricity system at a lower level. In this figure, we can see the components of this system. The '*boxes*' shown represent the main functions or activities performed by the technical (box A1), environmental (box A4), social (box A2) and economic (box A3) subsystems.



Purpose: To describe the interactions between social, economic, environmental and technical aspects of the electricity system as a basis to understand its behaviour.
Viewpoint: Electricity system modeller

A-0	Acquire, generate & distribute electricity	

Fig. 1. Graphic diagram of the electrical system, top-level

2.1.1 Technical system

The technical system is defined as a set technologies and all possible operations carried out to produce electricity. The main function is to *produce electricity*. Operations include processing and transportation of resources[34]. The qualifications of the workforce is also a requirement in this process, as workers training affects the productivity during production[35]. On the producer's side, increases in the technology performance help lower the costs of the technology through certain mechanisms, namely economies of scale in production (mass production) and learning by workforce[36]. On the user's side, growth in the technology performance will reduce the uncertainty of its merits and generate more enthusiasm of society into adopting it[37]. Technologies in the model refer to all techniques used for the transformation of both renewable and non-renewable resources. Those techniques, which include turbines (water, gas, wind), reciprocating engines, photovoltaic panels, etc., vary therefore, based on the nature of the resource used. Besides the learning growth, regulations[33], demands, and economic investments, the level of environmental damages[38] emerging from emissions is also controlling factors to the technical processes. Once produced, electricity is transported, transmitted and distributed using appropriate means.

Technical regulations refer to laws governing the production of electricity. *Emission* refer to the discharge of gas and other substances resulting from technical processes. *Initial experience* refer to the initial training of the workforce. *Resources* refer to all substances transformed into electricity. *Learning curve exponent* refer to the learning rate of the workforce, in getting familiar with technologies. *Transportation, transmission & distribution means* refer to all means used to transport and distribute resources and electricity (power line, trucks, etc.). *Technical costs* refer to all costs, fixed and variables, attached to the transportation, production, transmission and distribution of resources and electricity. *Electricity generating technology* refer to technologies used transform resources into electricity.

2.1.2 Social system

Social system captures society or parties represented by individuals or organizations, interacting with one another, all forming the consumer sector (customers constituting the electricity market). The main function is to *form societal needs*, which are emerging from interactions between individuals and determinant of actions. Actions involve making decisions, formulating regulations and reinforcing them[39]. Actions also involve the use of technology. Following the theory of 'innovation diffusion', Von Tunzelmann[40] support that changes in technology and regulations alternate in response to each other. In that sense, society takes advantage of technologies and socially adhere to them if its needs are met. The evolution of society, in terms of needs and regulations, fuels technology evolution, and vice versa. Electricity demand is therefore derived from preferences in the quality of services, which depend on technology efficiency, environmental friendliness[41] as well as costs[42, 43]. The price of electricity is also influential in demand generation and technology acceptance from society, as it depends, not only on the profitability and survival of firms[44], but also individuals' income.

Individuals refer to social entities in a given location. *Income* refers to earnings of individuals in society. *Demand* refer to the societal consumption or needs in electricity. *Contact rate* refers to the interactions between social entities.

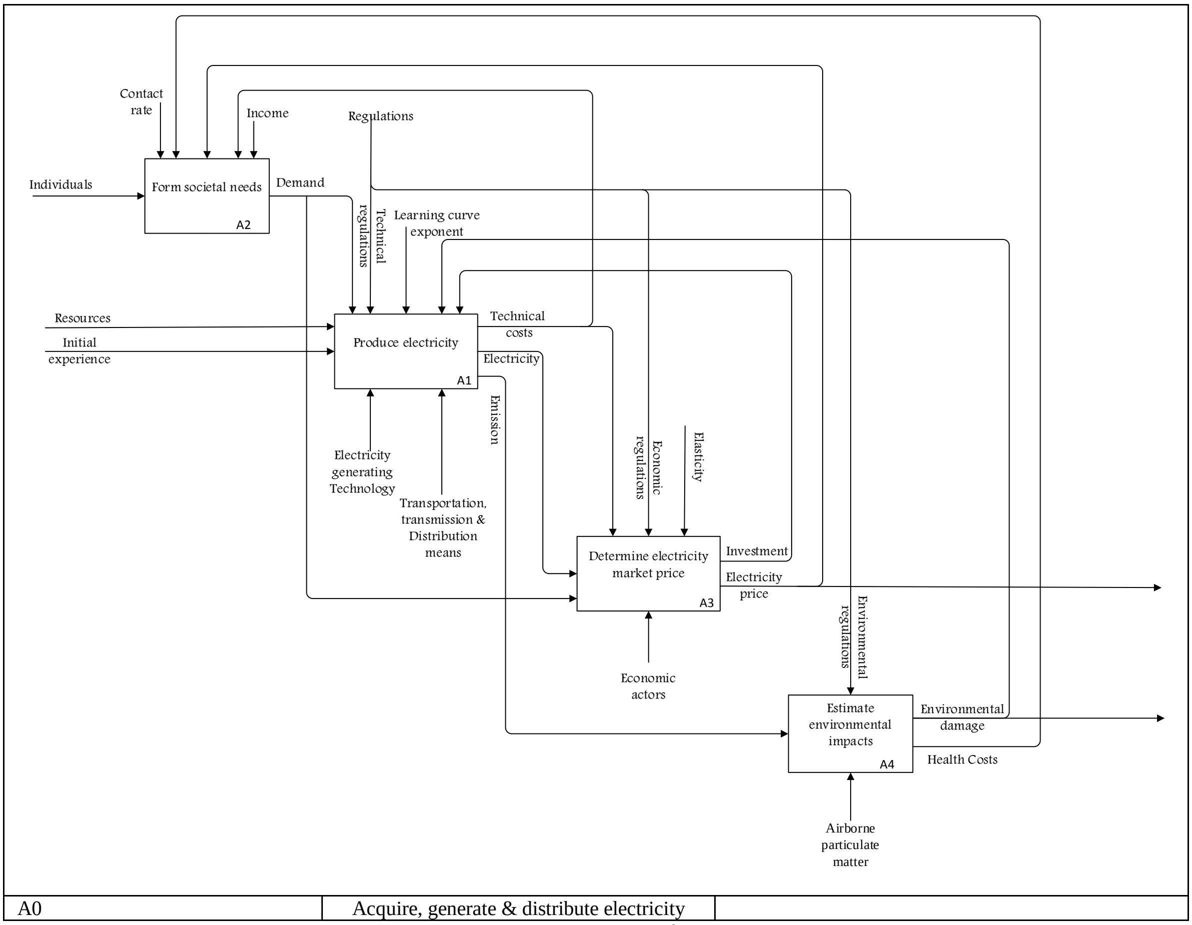


Fig. 2. Graphic diagram of the electricity system

2.1.3. Economic system

Economic system is defined as a market economy, in which decisions regarding production, transmission and distribution depend on supply and demand[45]. The main function is to *determine electricity price.* In this market, all economic actors trade with one another, searching for the price at which products and services related to electricity can be agreed upon. This pricing mechanism depends on the market share (market concentration, competitiveness, etc.), the demand and supply elasticity[46]. In a competitive market, a given technology product can only survive if it produces revenues which can cover all costs associated with its production[43]. For example, when a technology is competing in a market, firms continually adjust price in an effort to increase chances of profits[47] and opportunities of investments. This market price is referred as “cost price” [47], as it depends on the technology costs regulated by desired profit margin. This mechanism is controlled by regulations[44].

Economic regulations refer to regulations governing trades between economic agents. *Electricity price* refer to the price at which at which electricity suppliers and consumers agree to trade in an open market, at a particular period of time. *Elasticity* refer to the responsiveness of a product in relation to changes of another one. *Economic actors* refer to actors making economic decisions (firms, individuals, governments, etc.). *Investments* refer to money allocated to technology development in the expectation of future benefits.

2.1.4. Environmental system

Environmental system captures the environmental and health impacts of technological processes. The main function of this system is *estimate the environmental impacts*. Emissions may turn into pollution, depending on the concentration distribution —number and size of emission sources—[48]. The presence of airborne particulate matter is also responsible for spread of pollution, with links to adverse pulmonary health effects and respiratory distress, for both children and adults[49,50]. This function is controlled by environmental regulations. EPA[51] set two types of standards, namely primary and secondary standards. Primary standards set safety threshold regarding human health and the secondary ones, regarding environmental and property damage. Pollution, if occurring, generate health related costs. Emissions from coal-fired power plants, for example, are recognized as contributing factors to breathing difficulties[52], hospital admissions[53] and premature mortality[54].

Environmental damages refer to the degradation that both nature and human health suffer, as a result of electricity production emissions. *Health costs* refer to the costs incurred due to health issues created by emissions. *Environmental regulations* refer to regulations addressing the effects of electricity generations on the nature and society’s health. *Airborne particle matter* refers to extremely small breathable particles moving through air.

2.2. Electricity model: Technical system

In this section, we present the structure of the technical system, displayed in figure 3. The diagram presented shows 5 ‘boxes’, illustrating the functions or activities performed in the technical system. As supported by Keirstead, Jennings[31], these processes include resource extraction, refining, transportation and conversion to end product (electricity) for society’s use.

The activity of transport would only apply to transportable sources, not solar or wind for example. The means of extraction & transportation are specific to the nature of the resources to be extracted and transported. Constraints of safety control the good course of these activities[55]. The transformation of the resources into electricity is done through technologies, which processes vary with the nature of the resource in hand. As hinted earlier, the processes of electricity production generate costs [15] and environmental effects via emissions[56]. An increase in production leads to an increase in labour efficiency. According to Arrow[57], labour efficiency is improved by repeating the generation processes. This is what the author calls “learning-by-doing”. The *experience from production* gained by workers accumulates and results in a more enhanced and improved technology know-how. This improvement, along with investments contribute to new improved processes and changes in production methods[58]. The energy conversion efficiency improves as a consequence of these changes, which is translated through technology advances or innovation. This is what Arrow[57] calls “technological learning”. This principle also assumes that an increase in conversion efficiency leads to an increase in cumulative production, which ultimately leads to a decrease in production costs.

Enhanced production methods refer to the innovation in production techniques. *Experience from production* refers to the learning acquired by labour from mass production.

3. Conclusion

We have presented an IDEF0 conceptualization of an electricity system that describes the functions and interrelations between the social, technical, environmental and economic aspects of an energy system. The aim of this conceptualization is to develop an energy system model that is comprehensive and transparent so that it can be used to effectively support energy policy decisions.

We have shown a high level view of the whole energy system and delved into the technical system. Further work will involve the implementation of this conceptual model using Systems Dynamics and Agent Based Modeling approaches, as well as the application of the resulting models on policy decision case studies.

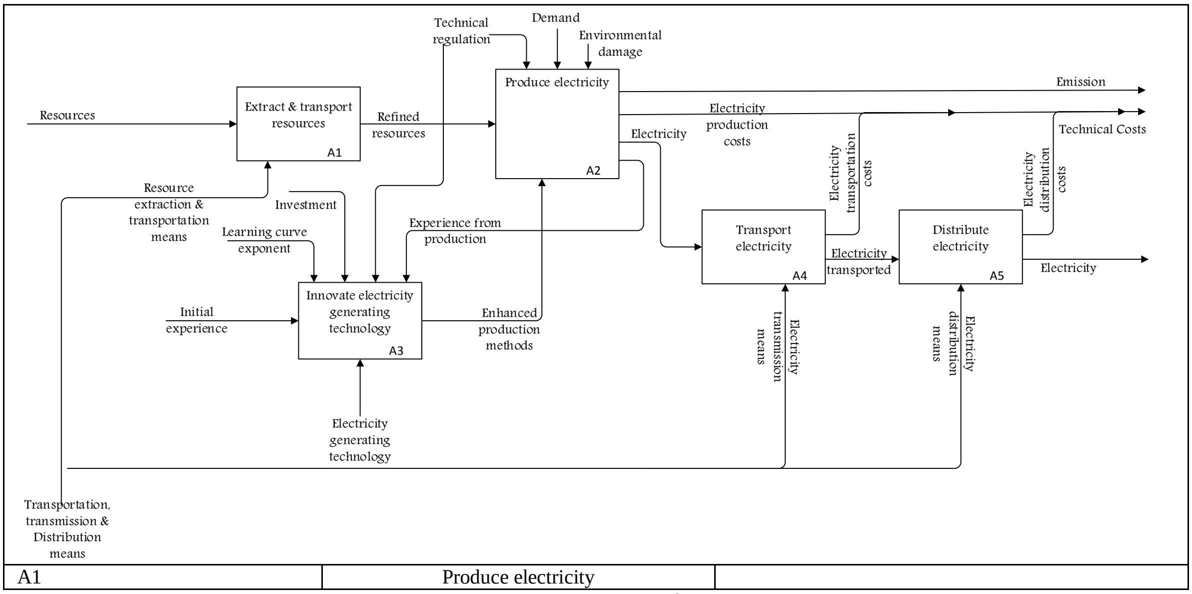


Fig. 3. Graphic diagram of the technical system

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