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Procedia Environmental Sciences 28 (2015) 27 – 36

Procedia Environmental Sciences

The 5th Sustainable Future for Human Security (SustaiN 2014)

A policy-oriented approach to energy security

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Abstract

Modern energy systems are increasingly complex and face ever-changing demands. As energy markets become increasingly global and interdependent, the issues affecting energy systems have also increased in number and complexity. Geopolitical events, natural disasters, severe weather, public acceptance of energy activities, increasingly automated and integrated energy systems, and the impact of climate change are just some of the factors impacting on energy systems. Consequently, the assessment of risks, threats and vulnerabilities in energy systems has become more urgent and more challenging.

Studies of energy security have been criticized on various grounds, including that they employ a narrow conception of energy security and rarely use a systematic approach. Various conceptual models have been proposed to evaluate energy security but are usually limited to the effect of supply disruptions. There are few examples of models that clearly define the broad range of risks faced by contemporary, complex energy systems.

This paper seeks to address these issues by taking a broader, policy-oriented approach to the factors affecting modern energy systems. We employ a complex systems perspective in conceptualizing the energy system and a more comprehensive approach to identifying risks, threats and vulnerabilities for energy security assessment purposes.

Peer-review under responsibility of Sustain Society

Keywords: Energy security; risk; uncertainty; assessment framework; complex adaptive system; system of systems; policy

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Peer-review under responsibility of Sustain Society
doi:10.1016/j.proenv.2015.07.005

1. Introduction

Studies of energy security have been criticized on various grounds, including that they rarely use a systematic approach, are arbitrary and cannot be applied universally from country to country[1]. Many studies fail to explain the concept of risk adequately, focus on only one part of the energy system or define the system so narrowly that the range of risks under study is limited[2]. The literature lacks frameworks incorporating a broader range of response strategies capable of dealing with the increasing uncertainties facing modern energy systems[3]. Research on energy security assessment often tends to focus on the behavior of energy subsystems (such as the electricity grid) rather than the behavior and performance of the energy system as a whole[4]. As a result, response strategies from a "whole of system" perspective are under-represented in the literature on energy security.

The purpose of this paper is to develop a policy-oriented approach to identifying and evaluating vulnerabilities, risks, threats and response strategies for the energy system. A policy-oriented approach is one that is inclusive of a broad range of factors – whether internal or external to the energy system – that can potentially impact on energy security policy. We take a complex adaptive systems perspective of the energy system which we also view as an interdependent "system of systems". We believe this approach is unique in the literature on energy security and offers a more comprehensiveperspective for describing the behavior of and vulnerabilities in modern energy systems.

2. Background: a broader view of energy security

As energy markets become increasingly global and issues affecting energy systems increase in number and complexity, the concept of energy security is being challenged to accommodate these developments. The increasing demand and competition for energy resources, along with fears of potential resource depletion, high prices and the effects of climate change are at the root of why energy security has become so important recently[5].

There is much debate among academics concerning the definition of energy security. The literature suggests that many current definitions of energy security are too narrow to encompass issues that many policymakers and researchers believe are essential to a full and complete definition for current use[5,8,9]. Others have pointed out that a narrow conception of energy security can pose serious challenges to energy policies[10].

As energy systems have become more complex and pervasive in societies, the issues arising from the role of energy have increased in number and complexity. As a result, a growing number of authors subscribe to a broader and more comprehensive definition of energy security that considers economic, technological, environmental, social, and geopolitical factors[3,5,8,11,12].

3. Discussion

3.1. Defining the energy system

It is necessary to define the energy system, its components, relationships and general behaviors as a prerequisite to identifying vulnerabilities, risks and threats. We adopt a complex adaptive systems (CAS) approach to describing the behavior of the energy system[13]. Our view is that a complex systems view of the energy system can better explain the multi-dimensional nature of energy security. This necessitates viewing the energy system from various dimensions or scales.

At the micro level, complexity is expressed in terms of a large number of "agents"– human or technological components –that interact with each other in a non-linear fashion. The agents learn and adapt their behaviour based on these interactions and as a result, new patterns of behaviour for the system as a whole emerge and shape the environment, which in turn affects the behaviour of the agents. This process of coevolution of the agents and the environment is a distinctive characteristic of complex adaptive systems[14].

At the meso (intermediate) level, an energy system can be defined as the interconnected components of human systems, technology and infrastructure that convert natural sources of energy into energy services and amenities. The energy system can therefore be viewed as a supply chain consisting of three main subsystems: primary energy procurement, transformation and final energy demand. This view of the energy system is useful for understanding the relationship between subsystems and the flows of energy demand and supply.

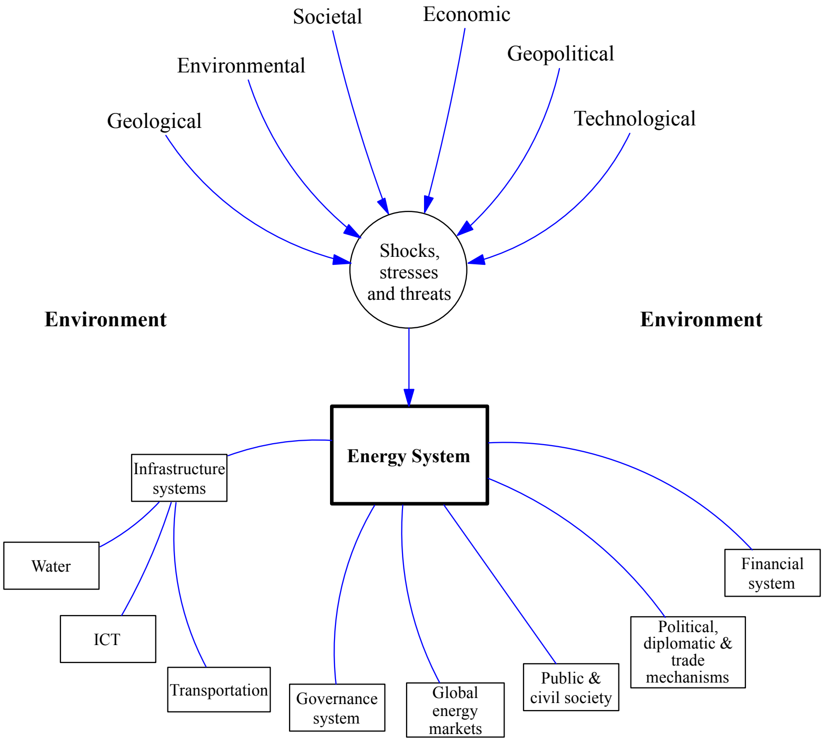

Fig. 1. The energy system as a system of systems

At the macro level, the energy system can be viewed as a complex adaptive "system of systems" (SoS) interacting with other complex systems in its environment. Complex adaptive SoS are extremely complex socio-technical systems with multiple interdependencies and as a result are vulnerable to a variety of threats, risks and systemic failures[15,16]. Related complex systems include the governance system, infrastructure systems, financial markets, information and telecommunications systems, global energy markets, international institutions (e.g.: IEA, UN, etc.) and other systems (See Figure 1).

3.2. Risk and the energy system

3.2.1. Defining risk and uncertainties

The energy system has multiple potential vulnerabilities because it is a dynamic system with complex internal interactions and multiple interdependencies with other complex systems in its environment. Where vulnerabilities are exploited by shocks, stresses and threats there is risk. Risk reflects the potential inability of the energy system to deliver on its essential function, which we define as *the reliable, stable and sustainable supply of energy at affordable prices and social costs*[31].

There is general agreement that energy security is concerned with risks[2,7]. Furthermore, energy security is about assessing various types of risk in the energy system[17] and developing strategies and policies to manage those risks[6].

It is important to distinguish between risk and other uncertainties.Stirling[18] has pointed out four fundamental categories of "incertitude", each corresponding to different evaluation and response strategies. These categories are derived from two factors: knowledge of the likelihood (or probability) of an event occurring and knowledge about the nature of the outcome[18] (see Table 1).

Strictly speaking, the use of the term “risk” should only be applied to situations where both the outcome and the probability are well understood. For example electricity transformers in electricity grids have a well-known failure rate and the impact of a failure on the grid is also well understood. Risk can therefore be measured with a high degree of reliability and steps taken to manage this risk using well-known risk management methods. Other forms of incertitude do not lend themselves to traditional risk assessment and treating them as if they are risk raises serious reliability and validity concerns[19]. Various methods exist, including diversification and other techniques, to hedge against the outcome of incertitude.

Table 1. Stirling’s categories of incertitude

Knowledge about Likelihoods	**Knowledge about Outcomes**	
	Well-defined outcomes	*Poorly defined outcomes*
Some basis for probabilities	Risk (apply: probabilistic techniques such as Monte Carlo analysis, portfolio theory, cost-benefit analysis, other risk assessment methods)	Ambiguity (apply: fuzzy logic, expert groups, Delphi methods, multiple perspectives, etc.)
No basis for probabilities	Uncertainty (apply: demand margins, scenario analysis, sensitivity analysis, enhance adaptability)	Ignorance (apply: diversification, redundancy, enhance resilience and adaptability)

“Uncertainty” applies to situations where there is good information to characterize the outcome of a threat but little basis for determining the probability of the threat occurring. An example is an earthquake where models exist that can reliably estimate the damage that would be incurred at a given magnitude, but the earthquake itself cannot be predicted with any degree of confidence.

“Ambiguity” on the other hand is where an event is predictable but once it has occurred the understanding of what happened or the implications are poorly understood. For example, therewas some basis for predicting insurgent warfare would breakout in Iraq in 2014 but an unexpected outcome was that a hydro dam came under the control of the insurgents with consequences that were poorly understood at the time.[†]

Under conditions of “ignorance” the outcome of a threat is poorly understood or not understood at all and there is no basis to determine the probability of the threat occurring. For example, anthropogenic climate change was not recognized as a threat until its effects began to be felt and research began to study the problem.

3.2.2. Types, sources and temporality of risk

Threats and risks to the energy system can be categorized by the following characteristics:

- *Source* - where the threats or risks originate, either internal or external to the energy system
- *Controllability* - the extent to which risks and threats can be managed or controlled
- *Temporality* - in terms of the difference between short-term shocks and long-term stresses

Source and Controllability

The source of risks and threats can be either internal or external. Internal risk sources are endogenous to the energy system (i.e. originate within energy subsystems and the energy supply chain). External risks or threats are exogenous, originating in related systems that interact with the energy system, or elsewhere in the energy system’s external environment.

[†] “ISIS battling to seize Iraq’s largest dam — which can unleash ‘a 15-foot wall of water’ on Baghdad”, National Post, August 5, 2014. http://news.nationalpost.com/2014/08/05/isis-battling-to-seize-iraqs-largest-dam-which-can-unleash-a-15-foot-wall-of-water-on-baghdad/

Risks and uncertainties can also be classified based on their degree of controllability[20]. Controllability refers to the ability to influence or manage risk. Energy systems face different types of risk and these risks should be managed using the appropriate risk management approaches and strategies.

We can categorize threats and risks into two types based on source and controllability:

Internal risks: These risks are generated from within the energy system and are controllable. Internal risks include both technical and human risk sources[2]. Technical risk sources such as from equipment breakdowns or the risk to human health from a refinery leak can be managed through regulation and the use of well-established risk management approaches such as HRE, ISO31000, probabilistic techniques, cost-benefit analysis and other methods. Human risk sources including those generated from employee errors, poor management decisions or unauthorized actions can be addressed through prevention methods such as TQM, and rules-based compliance approaches.

External threats (also referred to as uncertainties): These are threats or events originated in the external environment and are usually uncontrollable. Uncertainties and external threats can be further categorized along several dimensions[21,22]:

- *Economic threats* can arise from volatility in the price of energy products and services, spikes in energy commodity prices including oil price shocks, and the failure of energy infrastructure that can disrupt the supply of energy in the economy.
- *Environmental threats* to the energy system can have both anthropogenic and natural causes. Such threats can be caused by greenhouse gas induced climate change including severe weather events (floods, storms, fires), natural disasters (earthquakes, tsunami’s) water shortages affecting dams and power plants, and damage to energy infrastructure such as pipelines, ports and railways from climate variability.
- *Societal threats* can arise from a lack of public acceptance of energy activities (e.g. resistance to nuclear power, “fracking”, oil pipelines, high voltage overhead transmission wires, NIMBYism), energy poverty and social inequities.
- *Geological threats* arise from the possible depletion or exhaustion of energy sources. Economically recoverable reserves are decreasing in some regions, including in the EU and China, which are also regions with increasing levels of import dependency.
- *Technological threats* can be generated from cyber crimes (“hacking”) that attack energy subsystems and control systems as well as information and telecommunications networks on which energy systems increasingly depend resulting in infrastructure disruptions, data loss and system failures. Also, lack of investment in maintaining and upgrading technology systems and infrastructure that supports energy activities. Nuclear accidents can also threaten other related energy systems.
- *Geopolitical threats* can arise from energy being used as a political “weapon” posing a serious economic threat to other countries. As a result there are significant geopolitical and military dimensions to energy security. Other potential threats to the energy system include embargoes, wars, terrorism, disruptions to sea lanes and the exercise of market power in countries where energy is subject to political control.

Temporality

A distinction can be made between very short-term (very close to real time), short-term (minutes to weeks) and medium to long-term energy security (months to beyond the investment cycle)[23]. There are different response strategies for dealing with disturbances to the energy system and these strategies depend upon the type of risk and threat as described above, as well as the location in the supply chain and the time frame in which they occur. We now expand our discussion on strategies for responding to external threats.

3.2.3. Response strategies

Given the nature of complex systems and the inherent uncertainty of many of the threats facing energy systems, the approach presented in this paper is built around notions of diversification, impact reduction and responsiveness rather than attempting to predict threats or model possible impacts on the energy system. We propose strengthening the response characteristics of the system as a whole – including the attributes of stability,resilience and adaptability – rather than putting an excessive focus on any single subsystem or trying to manage risks over which we have little or no control.

It has been argued that diversity is an appropriate "system level" response strategy for dealing with uncertainties[19]. This is especially the case under conditions of "ignorance". Diversification therefore allows for hedging under conditions where we are uncertain about the threats or events we are trying to hedge against. In such cases, diversification allows the impacts of a threat to be spread amongst a number of components in the system, reducing the impact on any one component.

For importing countries, diversification can be implemented along several dimensions including primary energy sources (e.g. coal, oil, electricity, natural gas), geographic region, transit routes in order to avoid choke points (e.g. Strait of Hormuz, Suez Canal, Malacca Strait) and transportation modes (e.g. pipeline, rail, ship, grid interconnects). For exporting countries, diversification can be implemented for types of energy resources, export markets, and transportation modes. However, diversification aloneis insufficient to reduce uncertainty. In some cases, it can actually contribute to poor system performance and create inefficiencies if alternatives are implemented without sufficient regard to costs or compatibility with existing systems. Diversity may also come into conflict with other policy goals, including energy security strategies, competitiveness initiatives, or other priorities[19].

In addition to diversification, response strategies can be related to three properties or attributes of energy systems that describe their behavior in response to disturbance or change.

Stability refers to the capacity of systems to with stand sudden shocks or disturbances and maintain their operating function within narrowly defined tolerances[23]. In electricity grids, stability of grid frequency and voltage is a priority in the very short-term (milliseconds to real-time). Supply and demand for power must be balanced in real-time throughout the grid.

Resilience refers to the capacity of a system to absorb disturbance and retain its essential function and structure[24]. The system can be pushed far from its usual stable state, but as long as it returns to its normal function and structure, it is resilient. In the short to medium term, energy security concerns focus on the disruptive impacts of price shocks or unanticipated disruptions in energy supply. This is of particular concern in electricity markets where energy import dependency is often high. Market mechanisms help send price signals that act to adjust supply and demand, mitigating the effects of short-term shocks to the energy system. Other response strategies include diversifying energy import sources and shifting to more trusted suppliers. Also, the development of domestic renewable energy sources and energy conservation can reduce risks by reducing the dependence on imported fossil fuels in the first place, and thus help protect countries from supply shortages and price shocks[25].

Emergency stockpiles can be effective for the short-term mitigation of supply disruptions. For energy exporting jurisdictions, the diversification of export markets can reduce the risk of restrictive trade policies in importing countries.

In the long-term, a number of secular stresses and slowly changing factors impact on the energy system including energy demand shifts, changing infrastructure requirements, geological reserves depletion, technology evolution, and climate change. These types of factors call for a systemic approach rather than one that is focused on any one subsystem or component. A system must be adaptable so that it can alter itsstructure, function and interactions with other systems allowing it to evolve and change over time. *Adaptability* is an inherent capability of complex adaptive systems, is applicable at various spatial/system scales and has both reactive and proactive characteristics[26]. While resilience remains important in the short-term, adaptability is particularly relevant to long-term energy security because it is the attribute of the system that is proactive, allowing the system to adjust to long-term stresses while co-evolving with changes in the environment for energy[13].

Response strategies that enhance adaptability include liberalized market mechanisms which help stimulate timely investments in energy infrastructure and services, and diversifying transportation modes including rail, pipeline and port infrastructure which provides flexibility should one or more transportation modes be disrupted. Also, investment in innovation and technology development including "intelligent systems" such as smart grids, unbundling of energy services to enhance market responsiveness, improving regulatory quality, transition management, instituting participative stakeholder processes, scenario planning, and utilizing expert groups.

A summary of external threats with appropriate response strategies matched to the location in the energy supply chain is summarized in Table 2.

3.2.4. Systemic risk

Systemic risk is another type of uncontrollable risk that can affect the energy system broadly. Systemic risk has been defined as “a phenomenon in which, through contagion and cascading, failure of a system component leads to the dysfunction of the entire system or large parts of it” [27]. Systemic risk can arise from unpredictable events that can affect large parts of the energy system and include:

- Disruptions to transportation infrastructure (e.g.: terrorist acts and natural disasters affecting pipelines, railways, and other energy infrastructure)
- Technology disruptions (e.g., cyber crime – computer viruses in the electricity grid, internet attacks on pipeline control systems, etc.)
- Disruptions affecting interdependent energy subsystems. The “Ice Storm of 1998” that caused widespread power outages for millions of people in the northeastern United States and Canada is an example of a systemic risk and highlighted serious vulnerabilities in the integrated North American electricity grid[28].

As we have already noted, the energy system is a “system of systems” that interacts with a wide range of other systems simultaneously and on an ongoing basis. With the increasingly complex and integrated nature of energy systems within, between and among countries and regions, vulnerabilities to systemic risk are likely to increase. The development of “intelligent” and “smart” system algorithms and controls may increase the ability of theenergy system to sense risks and “self-heal” in response to threats, failures and disturbances[29]. This may result in improved system adaptability in dealing with systemic risk.

3.2.5. A summary of responses to risk

We have demonstrated that there are various types of risk and uncertainty, with consequences for energy security. A comprehensive assessment should consider the type, source and temporality of threats and risks as well as the

Table 2. Risks, threats and response strategies

Supply Chain Subsystem	**Primary Energy Procurement**	**Transformation**	**Demand for Energy Services**
Temporality/ Response Strategy			
Very short-term (close to real time) Focus of response strategies:***Stability***		**Threats**: Shocks causing sudden disruptions in the electricity grid or pipeline systems, equipment or component failures, load imbalances from the intermittency of renewables generation. **Responses**: Real-time management/automated systems, regulation, redundancies.	
Short to Medium-term (hours to months) Focus of response strategies: ***Resilience***	**Threats**: Disruptions to energy supply arising from wars, terrorism, cyber crime, geopolitical disputes, natural disasters, accidents, social unrest, strikes, severe weather, increase in price volatility, short-term demand shifts, lack of stakeholder participation in policy development process and market failures. For energy exporters, geopolitical or policy related disruptions affecting energy export markets.		
	Responses: Diversification of supplier and fuel type, emergency stockpiles. For exporters, diversification of export markets, commodities and transportation modes.	**Responses**: Diversified electricity generation mix, flexible fuel power plants.	**Responses**: Energy efficiency measures, distributed generation, demand management, demand response, market mechanisms.
Long-term (months to years) Focus of response strategies: ***Adaptability***	**Threats:** Secular stresses and long-term pressures on the energy system including major shifts in demand preferences, depletion of primary energy reserves, exercise of geopolitical leverage in supplier countries/regions, ageing or inadequate infrastructure, poor regulatory quality, systemic risks from system complexity and interdependency, inadequate market structure, energy poverty and climate change pressures affecting energy production and use.		
	Responses: Diversified transportation modes and routes, liberalized market mechanisms, investments in energy innovation and technology, timely infrastructure investments, diversified energy infrastructures, investment in "smart" systems, improved regulatory quality, transition management, participative stakeholder processes, enhanced market liquidity for primary energy sources. Also, state-sponsored strategies designed to hedge against threats to energy security (e.g.: support for energy FDI, energy cooperation, energy diplomacy, energy clauses in FTA's).		

location of vulnerabilities in the energy system. The final step is to match the assessment of risk or uncertainty to the appropriate response strategy.

When risks are within our ability to control, we can regulate them or manage them using well-established risk management approaches. When they are out of our direct control, we need to strengthen the resilience of energy subsystems as well as enhance the ability of the energy system as a whole to adapt.

3.3. Relevance to energy security assessment

While the concepts in this paper provide a starting point for energy security assessment, the application of appropriate energy security indicators is also required before an overall assessment can be completed. Indicators provide specific information about potential vulnerabilities. In a complex system of systems, there are multiple dynamic vulnerabilities making the assessment itself complex.

The use of indicators will necessarily depend on the way the energy system itself is conceptualized, how energy security is defined and what the specific characteristics of the system under study are. These variables will help determine the scope, depth and relevance of the assessment. In this paper, we have employed a broad definition of energy security, one that we feel is sufficiently comprehensive to account for the wide range of factors affecting modern energy systems. Furthermore, unlike many approaches to energy security in the literature, we have conceptualized the energy system as a complex “system of systems” rather than as an independent, linear, deterministic system. As a result of adopting these two approaches, an assessment framework would necessarily have to address the breadth and complexity of factors impacting on the energy system.

A comprehensive energy security assessment framework should utilize indicators to identify and measure vulnerabilities so that the appropriate response strategy can be applied in order to secure the energy system. Indicators can be related to the response characteristics (i.e. stability, resilience and adaptability) we wish to enhance in the energy system so as to ensure energy security over the short, medium and long-term.

Energy security assessment must also be sensitive to unique characteristics of the country or region under study so that it is relevant for policy development purposes. The assessment of risks and threats to energy security will necessarily vary depending on the characteristics, conditions and priorities in various jurisdictions.Energy security challenges also vary by country according to factors such as level of economic development, geographical size, resource endowments and market characteristics[30].

While it is beyond the scope of this paper to describe specific energy security indicators or develop a complete assessment framework, it is part of the author’s ongoing research.

4. Conclusion

Many energy security assessment frameworks exist in the literature but most define the energy system and energy security rather narrowly and do not clearly identify the broad range of risks, threats and uncertainties facing modern energy systems. This paper has attempted to address this issue by employing a complex systems perspective in conceptualizing the energy system and a more comprehensive approach to identifying risks, threats and vulnerabilities for energy security assessment purposes.We believe this policy-oriented approach is more policy-relevant than approaches focused only on energy subsystems or narrower definitions of security of energy supply.

In light of the increasing complexity and interdependence of energy systems, as well as the number and severity of threats facing the energy system in an increasingly uncertain environment, we suggest broader perspectives are needed for the enhancement of energy security. We recommend that more attention be given to a response-oriented, adaptive approach as suggested in this paper. Response strategies to reduce the impact of external shocks and stresses should include enhancing resilience in energy subsystems as well asstrengthening the adaptability of the energy system as a whole. It is intended that the policy-oriented approach to risk and uncertainty presented in this paper provide a foundational piece toward further research on the development of appropriate indicators and a general framework for the assessment of energy security in complex energy systems.

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