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Månsson, André; Johansson, Bengt; Nilsson, Lars J

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LUND UNIVERSITY

PO Box 117
221 00 Lund
+46 46-222 00 00



Review

Assessing energy security: An overview of commonly used methodologies



André Månsson ^{a,*}, Bengt Johansson ^{a,b}, Lars J. Nilsson ^a

^a Environmental and Energy Systems Studies, Lund University, P.O. Box 118, SE-221 00 Lund, Sweden

^b Swedish Defence Research Agency, SE-164 90 Stockholm, Sweden

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ABSTRACT

This paper provides an overview of methodologies used for quantitative evaluations of security of supply. The studied material is mainly based on peer-reviewed articles and the methodologies are classified according to which stage in the supply chain their main focus is directed to, as well as their scientific background. Our overview shows that a broad variety of approaches is used, but that there are still some important gaps, especially if the aim is to study energy security in a future-oriented way.

First, there is a need to better understand how sources of insecurity can develop over time and how they are affected by the development of the energy system. Second, the current tendency to study the security of supply for each energy carrier separately needs to be complemented by comparisons of different energy carrier's supply chains. Finally, the mainly static perspective on system structure should be complemented with perspectives that to a greater extent take the systems' adaptive capacity and transformability into account, as factors with a potential to reduce the systems' vulnerabilities. Furthermore, it may be beneficial to use methodological combinations, conduct more thorough sensitivity analysis and alter the mind-set from securing energy flows to securing energy services.

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1. Introduction

In recent years the concept of 'Energy Security' has experienced a revival, with a resurging interest from academia as well as policy makers. The meaning and focus of the concept have varied over time and between different disciplines, although some issues have remained firmly on the agenda. For example, the perceived threats to national security due to dependence on a few oil producing regions and supply routes have been a concern and an issue for politicians and scholars since the early twentieth century [1]. However, some security scholars have tried to broaden the analysis by including new threats and actors in the analysis and deepening the perspective by approaching it through the lens of human security¹ [2], a concept originally put forward by UNDP [3]. From a situation when energy security used to be almost synonymous with

'security of oil supply', analyses now also often focus on other energy carriers such as natural gas, as well as renewable energy [4].

In order to curb greenhouse gas emissions and mitigate climate change, renewable energy is expected to increase its share in the global energy mix, see e.g. Ref. [5]. However, there are fundamental differences between renewables and fossil fuels and therefore the security features of low-carbon systems are likely to differ from those of current systems. For example, a move from tapping stocks to managing flows from variable production may require new methods to evaluate the ability to manage demand. Furthermore, a new energy mix may motivate methods to compare different energy carriers and/or supply chains. Also, changed trade patterns and altered or new dependencies between different parts of the system may require methods to study dynamic and structural changes within the system.

Although the term 'energy security' is widely used, the interest in methodology development for evaluating energy security has been less pronounced. This may partly be a result of the sometimes multiple, vague and often diverging meanings of the concept. Strengthening the methodological understanding would be helpful for improving energy security analyses. A first step is to develop a better understanding of the strengths and weaknesses of existing methodologies for evaluating energy security and assess if there are

* Corresponding author. Tel.: +46 46 222 4130.

E-mail address: Andre.Mansson@miljo.lth.se (A. Månsson).

¹ The human security paradigm questions the traditional notion of the state as the referent object that is to be secured. Instead the focus is on the level of security of individuals, emphasising humans' access to basic necessities and their well-being. In this mind-set an important policy goal is to reduce energy poverty by guaranteeing the entire population access to basic energy services.

important aspects that current methods do not capture, thus motivating further methodological development. In such a broad field as energy security, several methods are needed in order to study different aspects and different temporal scales.

To investigate this, we carried out a review of existing quantitative methodologies used to assess the level of energy security in society. Previous reviews of this area have mainly addressed the use of indicators to measure different dimensions of energy security, see e.g. Refs. [6–8]. Such reviews provide valuable information but only cover a subset of the techniques that have been used to date and only treat a limited set of aspects concerning the relationship between energy and security. Furthermore, reviews of indicators mainly address the issue of ‘what’ to measure, but ‘how’ and ‘why’ are as important to consider in order to understand what level of security that can be considered adequate as well as how different systems can be compared and how different policies and strategies impact on energy security, not least in relation to other societal objectives. For example, we may need to improve current methods to assess interactions between interrelated policy areas, for example in the water, energy and food security nexus. The concentration on quantitative methodologies in this paper is a way to limit the size of the study, but does not imply that we think that they are generally preferable to other methodologies and we recognise that quantitative parameters can only capture certain aspects of energy security.

2. Definitions of energy security

Chester [9] described the concept of energy security as ‘polysemic’ and ‘slippery’, referring to its tendency to symbolise multiple dimensions at the same time. One underlying cause may be the variation in different stakeholders’ perception of what security means and how to reach a desirable level. Some of this variation can probably be explained by differences in how stakeholders value the importance of different parameters, such as decentralisation of supply and energy intensity [10], and national differences, such as whether the country of the stakeholder is resource-rich or a net importer [11] and whether the emphasis in the country is on market solutions or state involvement. There can also be different priorities and opportunities in industrialised and developing countries. In the latter case, energy security tend to be more closely connected to provision of energy access to the poorest in rural areas and, in urban areas, access for the rapidly expanding industry and service sectors [12]. Another explanation for variation is the scientific background of researchers with, for example, political scientists, engineers and complex system analysts often approaching energy security as an issue of sovereignty, robustness and resilience, respectively [13].

Energy security itself is also dynamic, since the perspective may depend on the timeframe analysed. For example, those analysts studying longer timeframes tend to value stability over cost-effectiveness [14]. Overall, the differences in perspectives and priorities have contributed to a debate among scholars on how energy security will change over time and how best to respond to this change [15]. Johansson [16] proposed that a distinction can be made between: i) when the energy system is analysed as an object that is exposed to threats, commonly referred to as ‘security of supply’ or ‘security of demand’, and ii) when the energy system works as an agent that generates or enhances (in)security, for example caused by a perceived political or economic value. Thus, the focus of energy security studies and the weights assigned to different factors affecting security will depend on the purpose of the specific analysis. It is therefore improbable, and perhaps undesirable, for researchers to agree upon one single definition and interpretation of energy security.

Winzer [17] reviewed 36 definitions of energy security and he argued that it should be separated from other policy goals, e.g. goals related to economic efficiency and sustainability, by defining it as “the continuity of energy supplies relative to demand”, thus narrowing the concept to security of supply. Using this definition, a secure supply chain is a vital requirement in order to deliver the required energy services. The chain can be complex and involve many steps, such as extraction, transportation, conversion, distribution and final use. The chain can also stretch over long distances and across national borders. As an example, crude oil can be extracted in a remote country, transported by oil tanker to a refinery and then distributed by truck to a petrol station. The end user only experiences the final steps, filling up and driving the car. However, researchers and policy makers may be interested in exploring different parts of the upstream supply chain to identify root causes of insecurity, bottlenecks and interactions with other policy domains.

A variety of factors can be considered possible threats or risks that can either deliberately or accidentally lead to disturbances in the flow of energy. However, two interrelated dimensions that consumers are interested in securing can be distinguished [18]: a physical dimension, sometimes referred to as available, reliable and/or accessible energy supply, and an economic dimension that incorporates aspects such as price volatility and affordability.² These dimensions are connected, since physically unreliable supply or resource scarcity may affect prices. Low or volatile prices may also reduce investments in infrastructure and production facilities and thus affect the physical dimension, sometimes referred to as supply destruction. Markets should thus be designed so that prices can act as a mediator between producers and consumers and indicate a situation of future scarcity or oversupply.

Although physical and economic dimensions of energy security are frequently emphasised in the definitions it is not common to specify, for example, when high prices should be considered a threat to security. That is, most definitions highlight dimensions and perspectives but do not define thresholds. For the purposes of this overview we do not attempt to formulate a new definition of security of supply. We are interested in the broader research field and not further elaborations of certain security features. Instead we merely note that a variety of definitions exist, but common denominators are generally related to physical and/or economic characteristics.

3. Method and analytical framework

The overview is based on material collected in 2011–2013, searching scholarly databases for peer-reviewed articles using keywords such as ‘energy security’ and ‘security of supply’. Criteria for inclusion were studies of methodological interest, such as generic, state-of-the-art and/or novel methodologies used to evaluate security of supply. We also used snowballing (i.e. pursuing references within references) and, for comprehensiveness, included a few non peer-reviewed reports in this study. Thus, there may be methodologies that have been used to assess security of supply that are not included as authors may use another nomenclature, or if they have not been cited. Furthermore, as the focus of this article is to review methodologies and not individual articles only a limited amount of studies that use the same methodology has been included. Articles in which energy security is mainly discussed, described or studied qualitatively were not included.

² Some researchers distinguish between several dimensions, for example by using the 4-A classification, i.e. availability, accessibility, affordability and acceptability, see e.g. Refs. [7,19].

In order to make it easier to understand which part of the supply chain that is mainly analysed, the method/s used and how these two are related, we classified the methodologies in a framework that mirrors the flow of energy in the supply chain. We started with: Supply of primary energy (4.1), upstream markets and imports (4.2) and domestic markets and infrastructure (4.3). We also studied broader evaluations of economic vulnerability to disturbances in the energy system (4.4). These studies were analysed separately, as economic vulnerability may arise from failure in any one of the previous supply stages. Finally, we examined some frequently used methods that integrate several different perspectives, as well as different parts of the supply chain (4.5), see Fig. 1. It should be noted that some methods have been used in several of the clusters, e.g. diversity indices. In section four, these are analysed in one of the clusters but, for comprehensiveness, examples of other uses are provided in the summary in Section 5.

Each section below takes as its starting point a short overview of the field, after which methodologies and evaluated factors are analysed. Here, we noted how the assessment is approached. For example, different methods may be used to study threats and hazards that may affect the security of supply (e.g. an extreme weather event or internal war), the impact a disturbance would have on an energy system (e.g. supply shortage or price spike) or consequences arising for the society when the system is impacted by a strain (e.g. welfare effects of disturbances), see Fig. 2.

We also note system boundaries, timeframes, assumptions made (e.g. rational actors, type of uncertainty) and the type of data analysed (e.g. historical price movements or data from a simulation model). Key conclusions are presented in Section 5. See also Table 1 for a summary of aspects evaluated.

4. Evaluating security of supply

4.1. Supply of primary energy

A prerequisite for future supply security is an adequate available amount of primary energy to satisfy demand. In this section we analyse common perspectives and methods to study how much primary energy that can be supplied at a certain time and cost. Historical production figures, future demand forecasts and possible physical supply constraints are often used by different analysts to assess how much can be supplied by various sources of primary energy and at what cost. The resulting forecasts, or scenarios, of oil, coal, gas and renewables production can be used to assess and predict trends, e.g. changes in geographical concentration of reserves over time, market size and possible future scarcity.

Due to its importance in the global energy system, oil production and the future outlook of extraction is a frequently recurring topic in research. Sorrell et al. [20] proposed that two parameters are needed to describe forecasts of oil production, the total stock

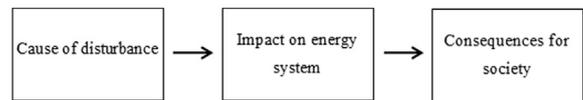


Fig. 2. Simplified illustration of the causal chain from cause of disturbance to consequences for society.

(i.e. amount of recoverable resources) and the production rate (i.e. the shape of the future production profile) and concluded that only evaluating the stock is insufficient. A case in point is that despite price increases, several countries have seen their rate of extraction decline at the same time as stock levels have remained at the same level or even increased [20]. One commonly used indicator of resource availability, the reserves-to-production ratio, may thus be deceptive as it does not account for aboveground problems or the future production profile. Another noteworthy aspect is that some researchers argue that commonly used figures on fossil fuel stocks and/or forecast extraction rates are overestimated. For a critique of oil production forecasts see Ref. [21] and for coal stocks see Ref. [22]. A related issue is the decline in energy balance or EROEI ('Energy Return on Energy Invested') for fossil fuels, decreasing the net production available to society as a larger share of gross production is used for extraction. According to Heun and de Wit [23], declining EROEI may cause sudden price movements that are not reflected in the current market price signals, due to a non-linear relationship between resource scarcity and production cost.

4.1.1. Resource availability

Long-term assessments of resource availability have been conducted both for the global energy supply mix and for certain resources. The global mix of future supply sources have been evaluated using models of the global energy system [24–26]. This approach makes it possible to analyse interactions between technology, demand and supply of different resources. They are usually based on specific analyses for single energy sources and include physical, economic and political aspects of resource supply. The physical aspects include estimates of fossil fuel stocks, geological restrictions on extraction rates, flows of renewable energy etc. Economic and political aspects include factors such as political stability and investments in exploration and extraction activities [27].

Models of the global energy system can originate from different scientific backgrounds such as top-down macroeconomic models [26], technical bottom-up models [24] or a combination of these [25]. Criqui and Mima [26] used the POLES-model, a partial equilibrium model which takes economic and demographic development as input parameters, to assess future demand and supply of energy up until 2050. A drawback with this method is that it does not consider feedback between, for example, changes in the energy system and the overall macroeconomy. Turton and Barreto [24] adopted a longer term perspective and studied global trends in supply up until 2100 using ERIS, a multi-regional bottom-up optimisation model with technology learning. Both models can be used to study consequences for the energy system of implementing various policies at regional or global scale, for example stringent climate change mitigation policies. Both also divide the global energy system into regions, thus making it possible to study changes in international markets and energy trade, assuming economically efficient allocation of energy resources.

Hallock Jr. et al. [28] studied the availability and diversity of conventional oil export, assuming that oil producing states first serve domestic demand and then export the surplus regardless the price difference. This economically irrational behaviour of exporters results in an inefficient world oil market. Based on these

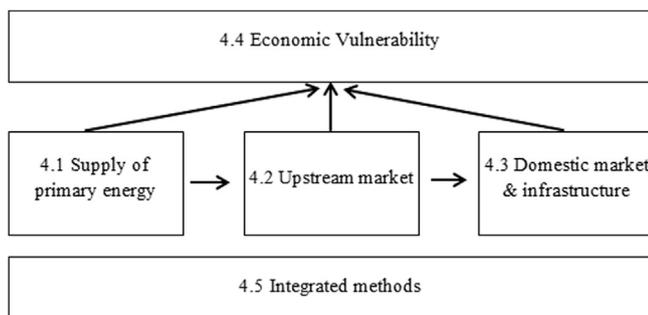


Fig. 1. Structure of the paper.

Table 1
Summary of categories and examples of aspects evaluated in the material.

| Category | Supply of primary energy | Upstream markets and imports | Domestic markets and infrastructure | Economic vulnerability | Integrated methods |
|-------------------------------|--|--|---|---|---|
| Examples of aspects evaluated | Availability of primary resources Geographical concentration of resources Forecasts or scenarios of energy export Average production cost and cost fluctuations | Systematic and specific risk Reliability of suppliers and supply routes Dependence, independence or interdependence among states | Reliability, resilience, and robustness of infrastructure | Welfare loss from high or volatile prices Economic consequences of resource scarcity Outage cost from power disruptions | Holistic supply chain security/security of energy services Spatial and/or temporal comparisons of security |

assumptions, to assess oil available for importers, they studied the difference between global extraction of oil and the fraction exported and hence available to importers, up until 2060. Estimates of EUR (extractable ultimate resource) and maximum depletion rate were used to construct several static scenarios of oil producing countries future extraction. These scenarios were combined with scenarios of exponentially increasing domestic demand in oil producing countries, a result of political, economic and demographic factors. The combination of constraints on extraction and distribution resulted in rapidly declining oil exports accessible for importers. A similar methodology has also been used to forecast the discrepancy between Russia's production and export of natural gas, see Söderbergh et al. [29].

Costantini et al. [30] compared global scenarios of extraction of both conventional and unconventional oil and gas resources up until the year 2100 and concluded that the geographical concentration of resources would increase over time. This insight was then used to qualitatively discuss the political consequences of increased resource concentration in a few producer countries. An example of the opposite perspective of political interaction can be found in Erb et al. [27], who constructed both optimistic and pessimistic scenarios of bioenergy potentials in the year 2050 using a 'thermodynamic biophysical balance model' in which the world was divided into 11 regions. One parameter that differed was political stability and the investment climate in producer countries. Including this factor reduced the available supply. Historically, aboveground factors, such as investment climate, have in some countries significantly constrained the growth in production capacity of oil [31].

Framing energy security as a problem of scarce supply and/or high cost has resulted in policy recommendations such as promoting alternative sources of energy or increasing end-use efficiency. However, long-term forecasts are inherently uncertain and it should be noted that overestimating the potential of different primary fuels may result in lock-in effects, while underestimating their potential may motivate investments in expensive and, at least in the short-term, uncompetitive alternatives. Furthermore, scarcity depends not only on supply but also on access, demand and the ability to pay, factors that are variable over time and differ between energy users. Complementary sensitivity analyses to study how constraints impact on these factors may be an option to evaluate the vulnerability of systems in a future scenario, reduce uncertainty and thus strengthen the analysis; examples can be found in Erb et al. [27] and Hallock Jr. et al. [28].

4.1.2. Average production cost and cost fluctuations

High production costs in itself are generally not framed as a security concern. However, the cost can be a factor to consider in technological assessments and comparisons if it is varying rapidly and/or unpredictably. For example, renewable energy sources have been evaluated and compared against conventional fossil fuels in

terms of fluctuation of production output [32] and, expected average cost [33].

Fluctuations of production output have been studied by analysing historical data on variations in inflow and production output to assess seasonal patterns, weather-sensitivity and how variable different production methods are [32]. Non-dispatchable output may increase price volatility but to what extent depends on, for example, the availability of energy storage, alternative production facilities and demand response. In these evaluations, domestic renewables are framed as a substitute for imported fossil fuels and the option with the lowest cost and/or variability is regarded as favourable. It is important to note here, that price volatility for consumers is not only a consequence of the development in primary energy supply but depend on disturbances (or expectancies of disturbances) in later stages of the energy chain.

Forecasting variability in production output may be difficult, as it can increase or decrease in the longer term, for example due to technical progress and exogenous factors such as climate change. Furthermore, in a longer timeframe policy makers and individual energy users may have the option to respond to stress by adapting or diversifying to alternatives that are less variable or integrate complementary options in a system, see e.g. Denault et al. [34]. For long-term evaluations it may therefore be interesting to assess the ability to respond to stress and short-term strain and how production output is affected by irregular short-term shocks.

4.2. Upstream markets and imports

Importing energy is commonly valued as negative for security of supply, as importing exposes a country to risks that are outside its jurisdiction. In the following section we review methods used to analyse dependence on upstream energy markets and the reliability of suppliers and supply routes. Typically, nations are framed as referent objects that import energy from suppliers or a global market and energy trade is sometimes characterised as of strategic importance since there are interactions with foreign policy objectives. For example, there is a risk of exporting or transit countries deliberately cutting off, or threatening to cut off, supply by using the 'energy weapon'. Thus, independence of imports in general and less reliance on individual exporters in particular are usually regarded as something to strive for. The assumption that imports pose a greater risk than indigenous supply may in some cases be misleading, since the ability to import energy can be used to compensate for domestic production losses. For example, following hurricane Katrina a large share of U.S. oil production and refining capacity was either damaged or 'shut-in', but the effects on consumers were contained through increased imports [35] and strategic petroleum reserves drawdown [36]. Thus, the ability to import energy may in some cases be an asset, as it can make the energy system more flexible and resilient. However, a prerequisite is access to a reliable and liquid upstream market.

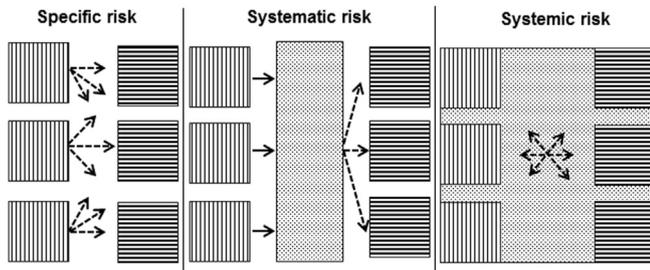


Fig. 3. Simplified illustration of specific risk (i.e. diversifiable risk), systematic risk (i.e. market risk), and systemic risk (i.e. the risk of market collapse). Boxes with vertical lines represent exporters, horizontal lines are importers, the dotted area symbolises the market and dashed line are the different categories of risk.

In this category of studies, energy markets and imports are commonly analysed for two broad groups of interrelated risks. The first is the specific risk, i.e. the diversifiable risk that is unique to every exporter or supply route. The second is the systematic risk that affects all agents on the market regardless of whom they trade with on that market, i.e. the market risk that it is not possible to diversify away from.³ A third category is systemic risk, i.e. the risk of market collapse, originating from interdependencies that enable cascading of events within systems that are instable or metastable, see Fig. 3.

Assumptions and framing of relationships between states differ. Liberals assume that states value absolute gains, whereas realists assume that they value relative gains, i.e. seek position advantage [39]. Furthermore, realists view the international arena as an anarchic environment of power struggles between states. The liberal standpoint, on the other hand, is that cooperation between states will or can emerge if mutual benefits are achieved. When the capability or incentive of states to control and deliberately restrict the flow of energy is analysed, it is important to consider assumptions of international relations as well as the conditions (e.g. infrastructure, institutions and market structure) that must apply if flows of energy are to be used as leverage, see Mercille [40] and Smith Stegen [41]. Hooegeveen and Perlot [42] propose internal instability as another important interaction with politics that may cause supply disruptions. However, other researchers argue that even if instability results in a conflict, the extraction of energy is often unaffected [43].

4.2.1. Reducing the risks through diversity

Diversity, often assumed to be a factor reducing energy systems risks, can be with regard to energy sources, suppliers and infrastructure. Stirling [44] argued that if knowledge is lacking on the likelihood of an event occurring and on the possible outcome, then ignorance prevails and the best hedge option is to diversify in order to spread the risk as much as possible. The vulnerability can then decrease and resilience can increase, provided that the importance of each option's functionality decreases. Measures of the diversity level of energy systems have been developed to assess all three dimensions of diversity, i.e. variety, balance and disparity [45]. Variety and balance can be measured by dual diversity indices, whereas

³ To assess the importance of supplier diversity, Vivoda [37] proposed two different types of import indicators, those that analyse the specific situation of importing countries and those that analyse the entire market. Some markets have a significant systematic risk that may be important to consider when comparing markets or security policies. As an example, SAFE [38] concluded that in a tight oil market (i.e. low spare capacity), even small reductions in supply increase the price significantly for all importers, due to oil being a fungible commodity that is traded on a liquid market.

disparity is more subjective as it is the difference between the variants. Another method for measuring and valuing the level of diversity is to use financial portfolio theory (see 4.2.2). However, none of these methods can be used to assess the consequences if disturbances do occur, only the level of 'risk spreading', partly because the capacity to take advantage of diversity during a strain is not assessed.

A common method of valuing diversity of imports is to use a modified dual diversity index, e.g. modifications of the Herfindahl–Hirschman index or the Shannon–Wiener index, see e.g. Refs. [46–51]. A country's import portfolio is mainly evaluated on the basis of the composition of exporting countries, i.e. variety of suppliers and balance in the volume from each supplier. These factors are typically also complemented with weight factors to account for, for example, a supplier's political stability and transport distance. A generic import diversity index, based on a modified Herfindahl–Hirschman, can be formulated as:

$$\sum_i (S_i^2 * w_i)$$

where S_i is the share of supplier i in the portfolio, w_i is a weight factor (e.g. political stability of country i).

Depending on the timeframe considered, some authors also include the ability of importers to switch to a supplier with spare capacity to compensate for another supplier's shortfall in production [46], how liquid and fungible the market is, and the importer's net import dependence, see e.g. Ref. [49]. The import indices reviewed here measure diversifiable risk and only value exposure to market risk by measuring the imported volume. Thus, neither systematic risk, nor systemic risk is quantified.

A drawback with some import indices is that the supplier's political risk is only measured with a general risk indicator such as ICRG (International Country Risk Guide) (see e.g. Refs. [46,48]) or the World Bank governance indicators (see e.g. Ref. [52]). These risk measures do not take bilateral relationships between countries into account, nor do they consider specific political issues that might cause supply disruptions, as they only assess the general political stability. Furthermore, indicators of political risk tend to be too static to be useful for forecasting, as they only capture the recent or contemporary situation, not future political developments.

4.2.2. Reducing risks through financial portfolios

An approach that is sometimes used to identify energy systems that are less risky from an economic point view is to use financial portfolio theory. It also takes its starting point in a view that diversity is a way to reduce risks but base the analysis on the historic price volatility of assets (i.e. exporters) and their co-variance in order to construct 'optimal' portfolios and hedge fuel price risk, see e.g. Refs. [53–55]. According to Awerbuch and Berger [56], Mean Variance portfolios can be used if the average portfolio cost is minimised (instead of maximising profit as is typically the objective):

$$E(C_p) = \sum_i \omega_i E(C_i)$$

where C_p is the average cost of the portfolio, ω_i is the share of asset i in the mix and C_i is the average cost of asset i .

To find an optimal portfolio, the composition of assets that holds the lowest risk, measured by portfolio variance, for a given cost and vice versa, can be found through:

$$E(\sigma_p) = \sqrt{\sum_i \omega_i^2 \sigma_i^2 + \sum_i \sum_{j \neq i} \omega_i \omega_j \sigma_i \sigma_j \rho_{ij}}$$

where ω_i is the share of asset i in the mix, σ_i is the standard deviation of asset i , ρ_{ij} is the correlation between asset i and j .

Unlike other diversity measures, financial portfolios make it easy to separate the specific risk from the systematic risk. However, a prerequisite is that the historic volatility is a valid indicator of contemporary or future risk. Four different techniques have been used in the literature to value portfolio variance: mean variance, semi variance, VaR (value at risk) and CVaR (conditional value at risk) [57]. Mean variance uses the entire variance to calculate the risk, whilst the other methods only consider price increases as a risk. However, events that occur infrequently, and those that have so far not occurred, are poorly reflected in historical data material and such risks may therefore be underestimated. Skouloudis et al. [58] proposed a model which also simulates risks that have not occurred previously by using ‘catastrophe derivatives’. This method not only includes a deterministic and stochastic term, but also a jump component to calculate individual risk premiums for each import route. However, to be applicable all risk parameters need to be known and quantifiable, i.e. frequency of occurrence and the magnitude of price spike that an event might cause.

4.2.3. Reliable supply and transit routes

The aggregated risks from entire supply routes are evaluated in Refs. [59–61]. Le Coq and Paltseva [60] assessed the risk of different gas pipelines with an index, constructed in a similar way to the previously discussed import indices but also including factors such as political stability in the transit countries and the bargaining power between the gas exporter, transit country and importer. Doukas et al. [59] proposed a ‘graph-theory’ based method to assess the aggregated risk from different supply routes for oil or natural gas. The first step is to calculate the risk in each supply corridor using the average socioeconomic risk of each transit country or chokepoint.⁴ In the second step an algorithm is used to minimise the total import risk and simultaneously maximise the flow of energy through the preferred corridors. A portfolio of how existing import routes should be prioritised and managed is then created. A similar perspective, to calculate the risk of each supply corridor and manage the aggregated risk, is also found in Kanudia et al. [61]. Kanudia et al. integrate this method with TIMES, an energy system model, to study how the import and transit risk develops in different scenarios up until 2040 and the trade-off between system cost and import risk. In contrast to [59,60], in which the import volume is considered to be predefined, this enables the analysis of how changing levels of imports could impact the import risk. However, it may be too simplified to assume that domestic supply is risk free. Another room for improvement in assessments of transit risk [59–61] is in the variables used as proxy of threat since neither the choice of variable nor how the variable could be causally connected to the likelihood of disruption is explained. Most of the variables are also only useful to a short to medium timeframe, since static values are used to analyse threats that are dynamic over time (e.g. estimates of the current level of political stability).

4.2.4. Asymmetrical (inter)dependence and the ‘energy weapon’

The risk of suppliers deliberately restricting the flow of energy for political reasons has been analysed by attempting to quantify the incentive for the respective actors to sustain or break an arrangement. By applying a liberal perspective to international relations, in which nations behave as rational profit-maximising agents, Lilliestam and Ellenbeck [62] assessed the asymmetrical

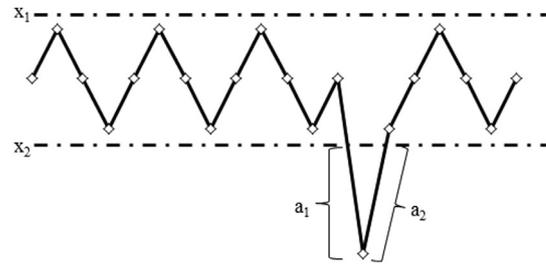


Fig. 4. Schematic illustration of how system state changes during a time period. Reliability is the probability of the system state staying between the upper (x_1) and lower (x_2) boundaries of desired system states. The deviation from a desired system state (a_1), arising when the system is exposed to a disturbance, depends on the system's vulnerability, the ability of the system to speedily respond and/or recover from a disturbance (following trajectory a_2) depend on the system's resilience.

interdependence between exporters and importers in order to estimate the bargaining power symmetry in a future scenario with regional electricity trade. Thus, the mutual dependences between importers and exporters were valued simultaneously to assess incentives to deliberately restrict the flow of energy in a game theory model. The method chosen was to calculate the economic interdependence as the difference in alternative cost in the event of a supply disruption by comparing the revenue loss of the exporter with the outage cost of the importer. It is thus mainly applicable for evaluating continuous flows of energy, since discrete flows enable storage or redirection of supply to other users.

4.3. Domestic markets and infrastructure

In this section we analyse methodologies used to evaluate whether the infrastructure and market design is sufficient to provide an adequate level of energy security. Although methods vary, energy infrastructure, such as the electricity or gas grid, is commonly analysed from the perspective of: i) reliability, i.e. probability of satisfactory operation over the long-term [63], ii) vulnerability, i.e. the consequences that arise when the system is exposed to a strain [64], and/or iii) resilience, i.e. the ability of the system to speedily respond to and/or recover from a disturbance [65], see Fig. 4. These different perspectives have also been analysed at different points in time, mainly in terms of the technical performance of current systems (e.g. Ref. [66]), and of future changes in system characteristics under different regulations and market designs, see e.g. Refs. [65,67–69]. Examples of the aspects studied are how an increased amount of intermittent renewables affects the reliability of the system [69] or volatility of the electricity price [67]. These aspects can be studied using agent-based modelling in which system components (e.g. a technical system) and actors (e.g. individuals or organisations) are represented as autonomous agents and their respective interactions and response to a disturbance are simulated. The method can be used to model complex socio-technical systems such as a decentralised electricity market and assess how policies will affect different business models, e.g. incentives to invest in back up capacity and implications for the system's reliability, see Kröger and Zio [68].

4.3.1. Infrastructure reliability

Reliability analyses are commonly conducted to assess the reliability of power systems using probabilistic or deterministic methodologies [70]. Probabilistic methods use the historical failure and repair rate of components to assess the reliability of the entire system, or parts of it, using indicators such as LOLP (Loss of Load Probability) [71] or SAIDI (System Average Interruption Duration Index) [66]. Low reliability can result in costly outages for energy

⁴ The web tool from EC FP7 project ‘REACCESS: Risk of energy availability – common corridors for Europe supply security’ was used to assess the risk of different chokepoints (e.g. Strait of Hormuz).

users, while high reliability can involve expensive investment in power infrastructure. Using a probabilistic method makes it possible to optimise the level of reliability using CBA (cost-benefit analysis). On the other hand, a deterministic method can assist in specifying requirements of system reliability in a defined situation, for example, the minimum reserve margin or the functionality of the system if one or several components are out of operation. The latter is sometimes referred to as the N-1 criterion, which stipulates that the system must continue to operate even though any component fails. Reliability evaluations of power systems can analyse one or several of the system's parts, including generation, transmission and distribution, see e.g. Refs. [71–73]. The evaluations can also target two different aspects of power reliability, namely system adequacy and system security [63]. System adequacy describes the system's ability to meet consumer requirements at all times and has been analysed as 'steady state', i.e. a static condition where the system is in equilibrium. The opposite, system security, is a valuation of the system's ability to 'withstand disturbances', a dynamic state. However, these perspectives have also been combined, see e.g. Refs. [71,73].

4.3.2. Infrastructure vulnerability and robustness

The vulnerabilities of a system can be analysed in order to understand its dynamic behaviour in response to a disturbance and to identify causes of system instability [74]. Such analysis commonly makes use of a deterministic approach, as the characteristic of the disturbance, e.g. magnitude, is predetermined and its likelihood of occurring is ignored, as it is only the severity of the consequences that are assessed. Strains can originate from different causes, e.g. an external attack on the system that causes component failures, a technical malfunction, accidents or natural disasters. Studies of vulnerabilities are sometimes framed as part of CIP (Critical Infrastructure Protection), see e.g. Ref. [74]. Some CIP approaches can be used to simulate energy systems and their interdependencies with other systems, such as a physical, cyber, geographical or logical relationship between infrastructures [75].

Frequently used methods include relational databases, network theory, rating matrices, system dynamics and multi-agent systems [74]. As an example, a network topology model can be used to represent an energy system as nodes (e.g. generators) and edges (e.g. transmission lines) [76]. The system is tested by disabling nodes and edges, either randomly or in a predefined pattern (e.g. a geographical area), and simulating how the system functionality is affected, see e.g. Ref. [64]. CIP simulations can reveal cascading effects and identify the components that are critical for a system's functionality. They can also be applicable for studying various aspects, for example how to prioritise where proactive measures should be implemented (e.g. redundancy, increased protection, etc.) and which components should be restored first after an outage. The system can be considered robust if it has a low vulnerability, i.e. it has the capacity to restrain disturbances.

4.3.3. Infrastructure resilience

Fuel flexibility of individual system components, such as power generators, has been used as a proxy of response capacity to disruptions [77,78]. In studies of system resilience the focus is the entire system's ability to respond and/or rapidly recover and the costs are analysed in addition to how the disturbance directly impacts on the system, see e.g. Refs. [65,79,80]. Another characteristic of system resilience studies is that they emphasise structure, relationships and interactions between different parts of the system rather than the performance of individual parts or components [81].

A characteristic of resilient systems is that they possess an adaptive capacity that enables adjustment to new conditions [82].

Thus, the surrounding environment and exogenous factors of the system are framed as being in a state of constant transition and hence the system needs to be agile. As the system recovers from disturbances it should reach a stable state, although this does not have to be the same as the original state. The disturbance is sometimes assumed to appear randomly, for which deterministic methodologies are used [65], and/or with a certain probability, for which probabilistic methods are used [80]. Deterministic methodologies make it difficult to conduct traditional CBA, as the likelihood of the disturbances studied is unknown. However, even if costs and benefits cannot be quantified, increasing system robustness or resilience can be considered a hedge against future uncertainty. As an example, UKERC [65] studied the development of the UK physical gas infrastructure using the MARKAL-MED, WASP and CGEN models sequentially to create four detailed scenarios. System shocks were simulated by testing the consequences of disconnecting major gas terminals for different lengths of time, i.e. the shock was caused by physically unavailable primary energy. The cause and probability of the disturbance were thus irrelevant for the analysis, as it was the system's resilience that was analysed. The studied system responded to the shocks by different means, for example by compensating through increased use of other fuels and gas interruptions to industrial customers, which resulted in welfare losses. The analyses were complemented with an insurance analogy in which the frequency point of breakeven was estimated, i.e. how often a shock must occur for an investment to increase resilience to be economically justifiable.

4.4. Economic vulnerability

Disturbance in all supply stages may result in price increases and/or disruptions in downstream stages that at the micro scale affect individual energy users and at the macro scale affect the national economy. In this section we analyse methodologies to study: i) economic vulnerability to price movements, and ii) the cost of supply interruptions.

During an unexpected and exogenously caused price shock, the economy may move out of equilibrium if it is not able to respond rapidly enough. This causes consumer countries to experience three different types of economic loss: i) loss of the potential to produce, ii) macroeconomic adjustment losses, and iii) excess wealth transfer to producer countries [83]. These losses affect the macroeconomy, reduce welfare and have a negative impact on the balance of trade. Indicators such as energy use by a nation or sector, spending on energy or the energy use per capita have been used in several studies to assess exposure to high energy prices, see e.g. Refs. [8,84–86]. These types of indicators can be useful for comparing countries or following trends and progressions over time if used as early warning indicators. However, these indicators only provide a 'static' view of economic vulnerability, as they measure the current situation and not what happens during, or after, a price increase. Thus, the indicators mentioned may be useful as a proxy for exposure to high prices, but not the sensitivity of the economy or the adaptive capacity of users.

4.4.1. Macroeconomic effects of high or volatile prices

The potential welfare loss that occurs due to high and volatile oil prices has been studied with top-down economic models, see e.g. Refs. [83,87–89]. Price shock characteristics (e.g. probability of occurring) are generally estimated from historical data on price movements [87] and/or a forecasts that are fairly similar to historical figures [83], while the resulting loss of wealth is estimated using a macroeconomic model that considers factors such as elasticity of demand. These studies thus presume that the price increase is temporary and that the price reverts back to the mean.

Lutz et al. [90] adopted a similar perspective, i.e. of estimating national welfare loss, but instead analysed the economic consequences for importing nations of a persistent decline in oil production. Thus, instead of mainly relying on data on historical price movements, an explorative scenario in which supply of energy is scarce was analysed.⁵ The reviewed studies of welfare loss are often combined with impact assessments examining which policies are cost efficient and reduce the dependence on oil imports, e.g. increased end-use energy efficiency or replacing oil with biofuels [83,87]. However, since the probability, occurrence, duration and magnitude of a price shock is predefined and the import risk is fixed for a given import volume (i.e. only systematic risk), security policies proposed in the studies are bound to be demand side options or fuel switching. If it is possible to reduce the risk of a price shock by switching suppliers, supply routes or similar means, a complementary analysis of the specific risk from different import sources would be valuable.

4.4.2. Cost of power interruptions

The economic aspect of energy insecurity has also been studied empirically to calculate the direct and/or indirect cost of a power supply interruption for end users, sometimes measured as the VoLL (*value of lost load*). As there is a trade-off between reliability and cost, some researchers have tried to determine the optimal level of reliability. De Nooij et al. [93] list four different methods for estimating this: i) surveys and interviews of stated preferences (e.g. willingness to pay to avoid an outage), ii) the production-function method (lost production or leisure time during an outage), iii) market behaviour (revealed preferences), and iv) case studies (e.g. monetising the negative effects from a real supply interruption). The different methods have their respective strengths and weaknesses, for example only a few larger participants deal with interruptible contracts, which limit the ability to draw general conclusions on market behaviour.⁶ However, it is worth noting that studies on outage cost demonstrate a great variety in results. For example, Praktijnjo et al. [95] conducted a literature review of private household outage cost and found 21 studies with estimates ranging from 0.48 to 68 €/kWh lost through outage.

4.5. Integrated perspectives

Integrating and comparing different aspects of security calls for prioritisation. Cost-benefit analysis, as discussed above, is one option for prioritising on monetary grounds, but it may only be used when the analyst has firm knowledge of the characteristics of the security threat (e.g. magnitude and probability), the outcome of the impact (e.g. severity) and options for a prevention policy. If this information is not available other methods may be used, such as complex indicators or methods to support decision making under uncertainty.

4.5.1. Complex indicators

Indices, sometimes referred to as complex indicators, are constructed by adding the results from several quantitative indicators into a single value, see Fig. 5. An index value can be interpreted as a proxy of a general level of 'insecurity'. To construct an index a scoring scheme is needed (i.e. the scale on each indicator) as well as

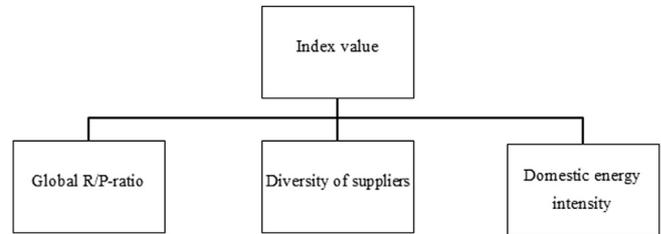


Fig. 5. Illustration of a complex indicator consisting of three indicators. To calculate these three indicators can, in its turn, require conducting evaluations of various parts of the supply chain (e.g. to assess diversity of suppliers).

a weighting scheme (i.e. the aggregation rule that determines how indicators should be added). Some indices rely on expert opinions to come up with weight factors [78,96], whereas others use the same weight factor for all indicators [97–99]. However, the selection of criteria (e.g. choice of different indicators) and weight factors is usually not transparent or well explained.

Although the above indices all have a broad coverage of research perspectives, they differ somewhat in focus. For example, the index developed by Molyneaux et al. [98] mainly focuses on contemporary perspectives of resilience of power system and is used for spatial (i.e. cross-national) comparisons. An index may be useful as a starting point to provide an overview and identify best practices within a group of countries, although the aggregation makes detailed assessments of strengths and weaknesses difficult. Furthermore, perceptions and preferences of what energy security is and how it should be valued may differ between countries [100]. It is therefore questionable whether the same index and criteria can be used to analyse heterogeneous countries without losing validity. Another purpose with the indices is to follow up developments, historical trends and progressions over time [101–103] and/or to compare and evaluate scenarios of systems development [78,104,105]. It can thus also serve as a tool in an early warning system.

4.5.2. Decision making and prioritisation under uncertainty

Another tool used to support decision making is multi-criteria analysis, see Refs. [45,106,107]. Karvetski et al. [106] proposed use of an analytical hierarchy process whereby experts make pairwise comparisons of various aspects, policies or scenarios and rank them individually based on their judgement and a set of predefined criteria. Multi-criteria analysis can be used to analyse both qualitative and quantitative aspects. If only quantitative data is evaluated, the ranking weights can be used to construct a complex indicator (see 4.5.1). To account for uncertainty in knowledge of the development of exogenous parameters, Stirling [45] combined the multi-criteria analyses with an assessment of diversity. This allows the importance of diversity to be weighted differently depending on the respondent's or policy maker's priorities. Lee et al. [107] also used multi-criteria analysis to prioritise technological options and formulate a robust development strategy, but combined it with fuzzy logic so that respondents could provide a range rather than a fixed value for the performance of different options. A drawback with fuzzy logic is that it does not consider second order probabilities, i.e. within the interval all values are assumed to be equally plausible.

Real options theory has been used to optimise investments when the future is uncertain, see Ref. [108]. Originating in financial theory, real options theory takes account of managerial flexibility as the timing of the decision is a central part, i.e. agents can decide to either invest now or wait one or several time periods and see how the future unfolds. Blyth [108] proposed that policy makers use the method to analyse how energy companies may respond in various uncertain situations, e.g. due to incomplete knowledge on future prices of fuels or legislation.

⁵ Other researchers who assume that upstream markets will operate, remain liquid and allocate available resources efficiently have studied how scarcity affects GDP at regional and global level, see e.g. Refs. [91,92].

⁶ Some authors propose mandatory security markets, with tradable security agreements, as they argue that this would enhance security and benefit the long-term interests of both producers and users [94].

5. Discussion

5.1. Aspects studied

Generally, upstream supply stages are primarily analysed on long-term trends. These evaluations tend to focus on technical or below ground issues, such as resource scarcity, that may result in increased geographical concentration of resources and future disturbances. Trends in production costs are also evaluated.

Imports are assessed on the basis of risk spreading among exporters, exposure to unreliable suppliers, supply routes and/or upstream markets. Most methods, and previous studies, make use of a portfolio approach to measure the level of diversity in the import mix. When import dependence is analysed, the domestic production is commonly assumed to be risk free.

Downstream stages are analysed on reliability, vulnerabilities and/or resilience to disturbances (known and/or partially unknown). The disturbance can have its origin internally within the system (e.g. component failure) or externally (e.g. severe weather or terrorist attack) resulting in a physical strain. Others analyse economic vulnerability, e.g. the macroeconomic effects of volatile prices, using equilibrium models. Finally, some researchers evaluate and compare several of the above aspects and integrate different perspectives, using complex indicators and/or multi-criteria analysis.

There are a variety of sources that can cause disturbances that have been analysed but, some methods do not enable connecting a potential threat to the likelihood of it causing a disruption or the consequences that can arise. Also, threats are commonly seen as exogenous factors that are constant over time and can be projected into the future. For example, the historic level of political instability in producer countries is sometimes used in assessments of these countries future reliability as suppliers without assessing how the level of stability can develop over time or the likelihood of instability affecting supply.

Only analysing disturbances, and neither its cause nor impact, has mainly been done for price volatility, for example using financial portfolios. In these evaluations, the strain is framed as occurring in the energy market and the aim is to protect the economy.

Methods that analyse how a disturbance could impact an energy system can either use models that are representations of energy systems in which vulnerability can be tested (e.g. "what would happen if component X would fail") or indicators that can be used as proxies of the systems vulnerabilities or capabilities, such as capacity to switch between fuels.

The outcome for society, when the energy system is exposed to a strain, is generally assessed for disturbances of short duration. This is probably because the historical experience of disturbances is mainly of this character. One exception is found in Lutz et al. [90], who estimate the national welfare loss caused by declining availability of oil. A lack of this longer perspective is mainly a problem with the occurrence of major trend shifts in energy supply disturbances, causing persisting physical strain and high prices, something which has not happened historically.⁷ However, this is not to say that it will not happen in the future.

5.2. Scientific origin, strength and weaknesses of the methodologies

There is a great variety in terms of methodologies being used partly due to the researcher's background in different scientific

fields (e.g. economics, engineering, political science and natural Science; see Table 2), but also to enable valuation of different aspects of energy security. Since the methods complement each other, having different strengths and weaknesses, there is not one which is always the best option. The suitability depends on the research question.

Energy security researchers have adopted several methods from the field of economics. Here, there is an aspiration to monetize effects (e.g. macroeconomic welfare effects from price volatility or cost of power outages); it is assumed that rules describing the behaviour of the current energy system can be used to predict the future (e.g. financial portfolios use historic data on prices and volatility to hedge volatility), and threats to market efficiency are seen as relevant energy security factors to study (e.g. concentration of producers). Often, these methods are used to value and compare different options to increase security of supply and find cost efficient solutions. However, these methods are less suitable to study radical system changes and longer timeframes if this alters the structure and feedbacks within the system. If these aspects are analysed, an opportunity for improvement could be to conduct more thorough sensitivity analysis. Concerning dual diversity indices, these methods are easy to use and provide results of how to hedge insecurity through increasing the number and balance of options. However, a limitation is that risks that correlate, such as systemic and systematic risk, is overlooked. Also, these methods can only be used to value risk spreading and not to find an optimal level.

Methods from the field of engineering have been adapted to value reliability of energy systems, particularly power systems, and the subfield of operations research has contributed with methods to support decisions in uncertain environments, such as multi-criteria analysis. Analysis of reliability depart from a probabilistic view of threats and use historical failure rates, which is observable, to estimate reliability of systems or deterministically the reliability if a certain component is malfunctioning. This knowledge can then be used and combined with insights of outage cost to find cost efficient investments to increase systems reliability. One strength of this methodology is that it is based on actual observations. However, since this requires the distribution of threats to be known the method is mainly applicable to analyse frequently occurring technical failures. Methods originating from operations research have been used to analyse and weigh different threats to security of supply to compare the level of security of different energy systems. These methods can be used to evaluate factors that are hard or sometimes impossible to monetize. The results from these evaluations depend to a large extent on subjective judgement and expertise of those who contribute to the analysis. Increasing the transparency of the decision process would improve the ability to interpret the validity and generalizability of the results.

Political science provides different perspectives of how international relations and energy security interacts. Concerning quantitative methods, researchers have developed methods to analyse degree of interdependence, distribution of power and incentive to use the energy weapon. These evaluations use game theory and are sensitive to assumptions of states rationale and ability to have perfect foresight of their action's consequences. It could be useful to compare the result with how states have acted in the past and use their historic or doctrinal behaviour as basis for assumptions of their behaviour.

In system studies there are methods that in some way depart from more than one scientific tradition, such as combining engineering and economics, in order to analyse energy systems in a broader sense. Energy system models, such as MARKAL – an optimization partial equilibrium bottom-up model that generates scenarios of technologies that minimises total system cost, have

⁷ A summary of major historical disruptions of gas and electricity can be found in Ref. [65] and of oil in Ref. [5].

Table 2
Overview of methodologies indicating strengths and weaknesses, disciplinary origin and examples of publications.

| Disciplinary origin | Economics | | | Engineering | | |
|--|---|---|---|--|--|---|
| Sub-discipline | Macro-economics | Micro-economics | Industrial Organization | Financial Theory | Power & Robustness Engineering | Operations Research |
| Examples of method | Partial equilibrium models, impact assessment, cost-benefit analysis | Surveys, production-function approach, market behaviour, case studies | Dual diversity indices (e.g. Herfindahl –Hirschman index, Shannon Wiener Index) | Financial portfolios, real options theory | Power system reliability assessments | Multi-criteria analyses, analytic hierarchy process, fuzzy logic |
| Examples of aspects evaluated | Welfare loss from high or volatile prices | Cost of power outage | Exposure to market risk or specific risk | Exposure to market risk and specific risk, uncertainty/timing of investment decisions | Technical reliability (probability of system operating during a specified time) | “Holistic” supply chain security |
| Strengths | Possibility to compare, and identify cost efficient, strategies to increase security | Can be combined with power reliability assessments to identify cost efficient infrastructural investments | Required data is often easily accessible and publicly available | Enables analysis of trade-offs between diversity and portfolio cost | Useful to mitigate frequently occurring failures | Useful to compare factors that are difficult to quantify with a single digit, fosters dialogue and illuminates priorities |
| Weaknesses and opportunities for further development | Require quantifiable data on strains (distribution and outcome) and mitigation options, sectorial and distributional effects are often overlooked | Macroeconomic cost of outage and long-term effects are not evaluated | Correlation between risks are overlooked (e.g. market risk) | Mainly applicable to short timeframes and easily quantifiable parameters, underestimates tail events | Requires a firm knowledge of system and the distribution of threats/failure rate | Result can have low transparency, making it difficult to draw generalizable conclusions |
| Example of papers, reports, studies | [83,87–90] | [93,95,109] | [46–51,60] | [53–55,57,58,108,110,111] | [63,66,69,71–73] | [45,106,107] |

^a System studies integrate methods from several disciplines, e.g. economics and engineering.

been used to generate forecasts or scenarios of how energy systems could develop. Sometimes energy security parameters have been incorporated as a constraint the model has to satisfy (e.g. a certain level of installed back up capacity), in other studies some aspect of energy security is analysed after the model has constructed a scenario using single indicators (e.g. import dependence) or one of the other methods mention in this overview (e.g. diversity of energy carriers). These models can be useful to analyse trends and development over time. However, depending on the granularity and iteration steps, short-term threats (e.g. fluctuations in production) and problems related to interregional trade are sometimes disguised. Security issues related to price volatility is commonly overlooked. Also, some models do not capture macroeconomic feedbacks from high energy prices, an exception can be found in Ref. [86] that hard-link a bottom-up with a top-down model.

A system perspective has also been adapted to construct complex indicators in which data is aggregated to enable comparisons over time and/or space. The aggregation can disguise the vulnerability of certain sectors (e.g. transportation), users (e.g. energy poverty in heterogeneous societies) and since aggregation rules are predefined it is assumed that priorities and threats are static. Furthermore, implications for security are difficult to derive from a certain value.

In complex system studies it is assumed that systems are dynamic, adaptive and system parts interact through feedback mechanisms. Methods from this field have been used to analyse interdependencies between infrastructures and to identify components that are critical for the functionality of the energy system. Generally, these methods require a detailed description of system properties and, consequently, have primarily been used to analyse energy systems similar to existing systems and not profound changes over longer timeframes. Properties of the energy system

are seen as affecting the severity and consequences a disturbance would have while threats and hazards are exogenous.

From the field of natural science, methods have been adapted to estimate resource potentials and diversity. In estimates of resource potentials and flow rates researchers make assumptions of how much energy can be produced or extracted from a resource during a defined period of time taking into account the boundary conditions and restrictions that needs to be met at all times, such as laws of thermodynamic, assumed maximum conversion efficiency and geological depletion rates. The results can be used to estimate physical aspects of availability and trends over time. Economic aspects, such as effects on energy prices or volatility, are usually not valued. Also, feedbacks between scarcity, prices and technological progress are rarely studied.

From ecology, diversity metrics have been adapted that value the three dimensions of diversity; balance, variety and disparity. In an uncertain environment, diversity is seen a hedge that can reduce exposure to unforeseen events. However, if disturbances do occur the consequences arising depends on the energy system’s capability to take advantage of the various options at hand, i.e. a diversified system is not equivalent with a resilient system. A future research direction could be to develop metrics to analyse these aspects, for example by placing greater emphasis on adaptive capacity and flexibility.

6. Moving forward and concluding remarks

A great variety of methodologies exist to evaluate energy security. As a result of this overview, we suggest putting more effort into developing: i) methods that enable evaluation of sources of insecurity that are dynamic and change over time, ii) methods to compare energy carriers and supply chains in the medium

| Political science | System studies ^a | | Natural science | | |
|--|--|--|---|--|--|
| International Relations Theory | Complex System Analysis | General/Applied System Analysis | | Geology/Physical Resource Theory | Biology/Ecology |
| Estimates of bargaining power symmetry, distribution of political power | Network theoretical models, agent-based simulations, dynamic system models | Energy system scenarios or forecast derived from energy system model (e.g. MARKAL) | Complex indicators/Indexes | Geological depletion model/extraction rates, biophysical flow models | Triple diversity indices (i.e. balance, variety and disparity) |
| Dependence, independence or interdependence among states | Resilient/robust infrastructure, interdependencies between systems | Various (e.g. geographical concentration of energy production, size of international trade, import dependence) | “Holistic” supply chain security | Estimates of resource potentials, restrictions to energy production and export | Diversity (proxy for resilience) |
| Could be used to analyse how some antagonistic threats develop if systems are changed | Useful to analyse consequences of short-term shocks with low-probability but high impact (i.e. “tail events”) that are difficult to anticipate | Can provide internally consistent scenarios of how energy systems could develop over time. Capability to handle interactions between various energy carriers | Can be used to compare energy systems over time and/or space | Analysis of constraints and potentials can be used to identify and anticipate future bottlenecks | Useful in uncertain environments with limited knowledge about the future |
| Can be deceptive if states have different rationales or actors are unable to calculate the consequences of their actions | Low ability to evaluate stress occurring over long time | Low resolution and long iteration steps can disguise short-term imbalances, economic threats (e.g. price volatility) are often overlooked | Aggregation of data can disguise vulnerability of certain sectors and systematic risk, validity of indices are seldom justified | Economic consequences (e.g. prices) are not assessed, sensitive to assumptions of future technological progress and substitutability | Assumes that increased diversity is preferable but do neither assess if cost increases can be justified, nor capability to utilise the higher diversity (i.e. adaptive capacity) |
| [60,62] | [59,64,65,67,74] | [24–26,30,61,85,86] | [78,97–99,101–104] | [27–29,112] | [44,45] |

timeframe, and iii) approaches to assess adaptive capacity and transformability.⁸ Further, it may be beneficial to use interdisciplinary methods, conduct more thorough sensitivity analysis and approach security of supply from the perspective of securing energy services rather than supply flows.

Sources of insecurity can be dynamic and change over time, for better or worse, but insecurities are in most studies seen as static and independent of the development of the energy system; for example, historic levels of political stability in producer countries is used in assessments of these countries' future reliability. An option for improvements could be to conduct subsequent valuations with more extensive sensitivity and uncertainty analyses, particularly of factors that are important for security of supply and assumed to be exogenous (e.g. how international relations and upstream market structure will develop) in order to reveal which policies are robust (i.e. useful in situations where exogenous factors differ). Inspiration can be found from the field of scenario studies that sometimes use scenarios of exogenous factors to identify robust policies and analyse certain strategies sensitivity (see e.g. Refs. [114,115]). Concerning some sources of insecurity, it can also be fruitful to assess if and how these insecurities would be affected from the development of the energy system; for example, how the likelihood of antagonistic threats can be reduced if the resilience of the system is improved.

In many studies, each energy carrier is analysed separately when it comes to their level of security. This makes it difficult to compare novel end-use technologies and how they could impact security, e.g. comparing vehicles powered by electricity, hydrogen and biofuels. Researchers that compare energy carriers, e.g. Refs. [32,87,88,110,111], use the historical level and/or volatility of the market price for the comparison, which narrows the timeframe considered as the relative market price, and volatility, of commodities may change over longer timeframes. In order to compare

supply chains on longer timeframes, one could turn the analyses from the volatility itself to how parameters that affect volatility develop, e.g. comparing the supply chains on parameters such as flexibility of production, spare capacity, storage and demand side response.

The portfolio approaches (financial portfolios, dual or triple diversity indices) rely on data of the composition of options used historically or what is used in a particular scenario. Current approaches can disguise risks that correlate between options (such as systemic and systematic risk) and the vulnerability of individual sectors (such as transportation). Furthermore, the capability to use options not in the current portfolio, such as switch between fuels or suppliers, is underestimated or not valued. An alternative approach could be to move from analysing portfolio diversity to agility and flexibility of energy systems; for example, evaluating portfolios of options available to respond to disturbances and new conditions and how to develop current systems to increase those options. This would involve evaluating which options and capabilities that exist to enable change. A starting point can be found in Stirling [116] and Blum and Legey [117] who suggests placing more emphasis on evaluating resilience, adaptability and transformability. Evaluating these capabilities would also make it possible to reduce negative consequences from trend shifts and low-probability but high impact events that may be hard to anticipate in advance. It could also be useful to shift the referent object, from evaluating security of energy supply to security of energy services since this shift would illuminate that security can be achieved through different means. Focusing on delivering secure energy services, rather than securing flows, opens up the possibility to identify different opportunities throughout the supply chain; for example, overall increased energy efficiency, demand side management of electricity or modal shift of transportation.

Finally, several of the methodologies are usually used separately, so energy security is a multidisciplinary rather than interdisciplinary field. This is not a problem per se, but the different methodologies sometimes depart from conflicting assumptions and promote opposing solutions on how to increase the level of security (e.g. a diversified system vs. a cost efficiently optimised system,

⁸ Walker et al. [113] defined transformability as “the capacity to create a fundamentally new system when ecological, economic, or social structures makes the existing system untenable”.

reduce imports vs. increase interdependence, reduce threats vs. increase resilience). An option for bridging the gap between the various assumptions and scientific fields and simultaneously improving current valuations may be to combine different methodologies, for example, by testing a system's response to both volatile prices and physical disruptions.

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References

- [1] Yergin D. Ensuring energy security. *Foreign Aff* 2006;85(2):69–82.
- [2] Vivoda V. Evaluating energy security in the Asia-Pacific region: a novel methodological approach. *Energy Policy* 2010;38(9):5258–63. <http://dx.doi.org/10.1016/j.enpol.2010.05.028>.
- [3] UNDP. Human development report. Oxford/New York: Oxford University Press; 1994.
- [4] Bilgin M. New energy order and FAST principles: premises of equitable and sustainable energy security in the 21st century. *Int J Global Energy Issues* 2010;33:4–21.
- [5] IEA. World energy outlook. Paris: International Energy Agency; 2011.
- [6] Ecofys, Redpoint, ERAS. Analysis of impacts of climate change policies on energy security. European Commission DG Environment; 2009.
- [7] Kruyt B, van Vuuren DP, de Vries HJM, Groenenberg H. Indicators for energy security. *Energy Policy* 2009;37(6):2166–81. <http://dx.doi.org/10.1016/j.enpol.2009.02.006>.
- [8] Sovacool BK, Mukherjee I. Conceptualizing and measuring energy security: a synthesized approach. *Energy* 2011;36(8):5343–55. <http://dx.doi.org/10.1016/j.energy.2011.06.043>.
- [9] Chester L. Conceptualising energy security and making explicit its polysemic nature. *Energy Policy* 2010;38(2):887–95. <http://dx.doi.org/10.1016/j.enpol.2009.10.039>.
- [10] Bambawale MJ, Sovacool BK. China's energy security: the perspective of energy users. *Appl Energy* 2011;88(5):1949–56. <http://dx.doi.org/10.1016/j.apenergy.2010.12.016>.
- [11] Bradshaw MJ. Global energy dilemmas: a geographical perspective. *Geogr J* 2010;176(4):275–90. <http://dx.doi.org/10.1111/j.1475-4959.2010.00375.x>.
- [12] Kuik OJ, Lima MB, Gupta J. Energy security in a developing world. *Wiley Interdiscip Rev Clim Change* 2011;2(4):627–34. <http://dx.doi.org/10.1002/wcc.118>.
- [13] Cherp A, Jewell J. The three perspectives on energy security: intellectual history, disciplinary roots and the potential for integration. *Curr Opin Environ Sustain* 2011;3(4):202–12. <http://dx.doi.org/10.1016/j.cosust.2011.07.001>.
- [14] Hippel Dv, Suzuki T, Williams JH, Savage T, Hayes P. Energy security and sustainability in Northeast Asia. *Energy Policy* 2011;39(11):6719–30. <http://dx.doi.org/10.1016/j.enpol.2009.07.001>.
- [15] Ciută F. Conceptual notes on energy security: total or Banal security? *Secur Dialogue* 2010;41(2):123–44. <http://dx.doi.org/10.1177/0967010610361596>.
- [16] Johansson B. A broadened typology on energy and security. *Energy* 2013;53(0):199–205. <http://dx.doi.org/10.1016/j.energy.2013.03.012>.
- [17] Winzer C. Conceptualizing energy security. *Energy Policy* 2012;46:36–48. <http://dx.doi.org/10.1016/j.enpol.2012.02.067>.
- [18] Luft G, Korin A, Gupta E. Energy security and climate change: a tenuous link. In: Sovacool BK, editor. *The Routledge handbook of energy security*. New York: Routledge; 2011. pp. 43–55.
- [19] APERC. A quest for energy security in the 21st century. Japan: Asia Pacific Energy Research Centre; 2007.
- [20] Sorrell S, Speirs J, Bentley R, Brandt A, Miller R. Global oil depletion: an assessment of the evidence for a near-term peak in global oil production. UK Energy Research Centre; 2009.
- [21] Hallock Jr JL, Wu W, Hall CAS, Jefferson M. Forecasting the limits to the availability and diversity of global conventional oil supply: validation. *Energy* 2014;64(0):130–53. <http://dx.doi.org/10.1016/j.energy.2013.10.075>.
- [22] Heinberg R, Fridley D. The end of cheap coal. *Nature* 2010;468:367–9.
- [23] Heun MK, de Wit M. Energy return on (energy) invested (EROI), oil prices, and energy transitions. *Energy Policy* 2012;40:147–58. <http://dx.doi.org/10.1016/j.enpol.2011.09.008>.
- [24] Turton H, Barreto L. Long-term security of energy supply and climate change. *Energy Policy* 2006;34(15):2232–50. <http://dx.doi.org/10.1016/j.enpol.2005.03.016>.
- [25] Bollen J, Hers S, van der Zwaan B. An integrated assessment of climate change, air pollution, and energy security policy. *Energy Policy* 2010;38(8):4021–30. <http://dx.doi.org/10.1016/j.enpol.2010.03.026>.
- [26] Criqui P, Mima S. European climate—energy security nexus: a model based scenario analysis. *Energy Policy* 2012;41(0):827–42. <http://dx.doi.org/10.1016/j.enpol.2011.11.061>.
- [27] Erb K-H, Haberl H, Plutzar C. Dependency of global primary bioenergy crop potentials in 2050 on food systems, yields, biodiversity conservation and political stability. *Energy Policy* 2012;47(0):260–9. <http://dx.doi.org/10.1016/j.enpol.2012.04.066>.
- [28] Hallock Jr JL, Tharakan PJ, Hall CAS, Jefferson M, Wu W. Forecasting the limits to the availability and diversity of global conventional oil supply. *Energy* 2004;29(11):1673–96. <http://dx.doi.org/10.1016/j.energy.2004.04.043>.
- [29] Söderbergh B, Jakobsson K, Aleklett K. European energy security: an analysis of future Russian natural gas production and exports. *Energy Policy* 2010;38(12):7827–43. <http://dx.doi.org/10.1016/j.enpol.2010.08.042>.
- [30] Costantini V, Gracceva F, Markandya A, Vicini G. Security of energy supply: comparing scenarios from a European perspective. *Energy Policy* 2006;35(1):210–26. <http://dx.doi.org/10.1016/j.enpol.2005.11.002>.
- [31] Toft P, Duero A. Reliable in the long run? Petroleum policy and long-term oil supplier reliability. *Energy Policy* 2011;39(10):6583–94. <http://dx.doi.org/10.1016/j.enpol.2011.08.001>.
- [32] Eaves J, Eaves S. Renewable corn-ethanol and energy security. *Energy Policy* 2007;35(11):5958–63. <http://dx.doi.org/10.1016/j.enpol.2007.06.026>.
- [33] Bauen A. Future energy sources and systems—acting on climate change and energy security. *J Power Sources* 2006;157(2):893–901. <http://dx.doi.org/10.1016/j.jpowsour.2006.03.034>.
- [34] Denault M, Dupuis D, Couture-Cardinal S. Complementarity of hydro and wind power: improving the risk profile of energy inflows. *Energy Policy* 2009;37(12):5376–84. <http://dx.doi.org/10.1016/j.enpol.2009.07.064>.
- [35] Goldwyn DL. Squaring the U.S.-Africa-China Energy Triangle: the path from competition to cooperation. In: Luft G, Korin A, editors. *Energy security challenges for the 21st Century: a reference handbook (Contemporary Military, strategic, and security issues)*. Santa Barbara: Praeger; 2009. pp. 233–49.
- [36] Chow E, Elkind J. Hurricane Katrina and US energy security. *Survival* 2005;47(4):145–60. <http://dx.doi.org/10.1080/00396330500433449>.
- [37] Vivoda V. Diversification of oil import sources and energy security: a key strategy or an elusive objective? *Energy Policy* 2009;37(11):4615–23. <http://dx.doi.org/10.1016/j.enpol.2009.06.007>.
- [38] SAFE. Oil shockwave 2005. Washington DC: Securing America's Future Energy; 2005. http://www.secureenergy.org/sites/default/files/151_Oil_Shockwave_Report_2005.pdf.
- [39] Cohen BJ. The political economy of international trade. *Int Organ* 1990;44(2):261–81.
- [40] Mercille J. The radical geopolitics of US foreign policy: the 2003 Iraq War. *Geographical* 2010;75(4):327–37. <http://dx.doi.org/10.1007/s10708-008-9253-6>.
- [41] Smith Stegen K. Deconstructing the “energy weapon”: Russia's threat to Europe as case study. *Energy Policy* 2011;39(10):6505–13. <http://dx.doi.org/10.1016/j.enpol.2011.07.051>.
- [42] Hoogeveen F, Perlot W. The EU's policies of security of Energy Supply towards the Middle East and Caspian region: major power politics? *Perspect Global Dev Technol* 2007;6(1–3):485. <http://dx.doi.org/10.1163/156914907X207847>.
- [43] Toft P. Intra-state conflict in oil producing states: a threat to global oil supply? *Energy Policy* 2011;39(11):7265–74. <http://dx.doi.org/10.1016/j.enpol.2011.08.048>.
- [44] Stirling A. On the economics and analysis of diversity stirring. SPRU Paper no. 281998.
- [45] Stirling A. Multicriteria diversity analysis: A novel heuristic framework for appraising energy portfolios. *Energy Policy* 2010;38(4):1622–34. <http://dx.doi.org/10.1016/j.enpol.2009.02.023>.
- [46] Cohen G, Joutz F, Loungani P. Measuring energy security: trends in the diversification of oil and natural gas supplies. *Energy Policy* 2011;39(9):4860–9. <http://dx.doi.org/10.1016/j.enpol.2011.06.034>.
- [47] Fronzel M, Schmidt CM. Measuring energy security: a conceptual note. *Ruhr economic papers #52*. Ruhr-Universität Bochum (RUB), Department of Economics; 2008.
- [48] Gupta E. Oil vulnerability index of oil-importing countries. *Energy Policy* 2008;36(3):1195–211. <http://dx.doi.org/10.1016/j.enpol.2007.11.011>.
- [49] Le Coq C, Paltseva E. Measuring the security of external energy supply in the European Union. *Energy Policy* 2009;37(11):4474–81. <http://dx.doi.org/10.1016/j.enpol.2009.05.069>.
- [50] Löschel A, Moslener U, Rübhelke DTG. Indicators of energy security in industrialised countries. *Energy Policy* 2010;38(4):1665–71. <http://dx.doi.org/10.1016/j.enpol.2009.03.061>.
- [51] Ryu H, Dorjragchaa S, Kim Y, Kim K. Electricity-generation mix considering energy security and carbon emission mitigation: case of Korea and Mongolia. *Energy* 2014;64(0):1071–9. <http://dx.doi.org/10.1016/j.energy.2013.10.089>.
- [52] Lefèvre N. Measuring the energy security implications of fossil fuel resource concentration. *Energy Policy* 2010;38(4):1635–44. <http://dx.doi.org/10.1016/j.enpol.2009.02.003>.
- [53] Lesbirel SH. Diversification and energy security risks: the Japanese case. *Jpn J Polit Sci* 2004;5(1):1–22. <http://dx.doi.org/10.1017/s146810990400129x>.
- [54] Wabiri N, Amusa H. Quantifying South Africa's crude oil import risk: a multi-criteria portfolio model. *Econ Model* 2010;27(1):445–53. <http://dx.doi.org/10.1016/j.econmod.2009.10.011>.

- [55] Wu G, Wei Y-M, Fan Y, Liu L-C. An empirical analysis of the risk of crude oil imports in China using improved portfolio approach. *Energy Policy* 2007;35(8):4190–9. <http://dx.doi.org/10.1016/j.enpol.2007.02.009>.
- [56] Awerbuch S, Berger M. Energy security and diversity in the EU: a mean-variance portfolio approach. IEA Report no. EET/2003/03. Paris: IEA; 2003.
- [57] Suzuki K, Uchiyama Y. Quantifying the risk of an increase in the prices of non-energy products by combining the portfolio and input–output approaches. *Energy Policy* 2010;38(10):5867–77. <http://dx.doi.org/10.1016/j.enpol.2010.05.041>.
- [58] Skouloudis A, Flamos A, Psarras J. Energy Supply risk premium: review and methodological framework. *Energy Sources Part B – Econ Plan Policy* 2012;7(1):71–80. <http://dx.doi.org/10.1080/15567240903047830>.
- [59] Doukas H, Karakosta C, Flamos A, Flouri M, Psarras J. Graph theory-based approach for energy corridors network to Greece. *Int J Energy Sect Manag* 2011;5(1):60–80. <http://dx.doi.org/10.1108/1750622111120901>.
- [60] Le Coq C, Paltseva E. Assessing gas transit risks: Russia vs. the EU. *Energy Policy* 2012;42:642–50. <http://dx.doi.org/10.1016/j.enpol.2011.12.037>.
- [61] Kanudia A, Gerboni R, Loulou R, Gargiulo M, Labriet M, Lavagno E, et al. Modelling EU-GCC energy systems and trade corridors: long term sustainable, clean and secure scenarios. *Int J Energy Sect Manag* 2013;7(2):243–68. <http://dx.doi.org/10.1108/ijesm-01-2012-0007>.
- [62] Lilliestam J, Ellenbeck S. Energy security and renewable electricity trade—will Desertec make Europe vulnerable to the “energy weapon”? *Energy Policy* 2011;39(6):3380–91. <http://dx.doi.org/10.1016/j.enpol.2011.03.035>.
- [63] Kundur P, Paserba J, Ajarapu V, Andersson G, Bose A, Canizares C, et al. Definition and classification of power system stability. *IEEE Transac Power Syst* 2004;19(2):1387–401.
- [64] Johansson J. Risk and vulnerability analysis of interdependent technical infrastructures: addressing socio-technical systems. Faculty of Engineering, LTH: Lund University; 2010.
- [65] UKERC. Building a resilient UK energy system. U.K. Energy Research Centre; 2011.
- [66] Fenrick SA, Getachew L. Formulating appropriate electric reliability targets and performance evaluations. *Electr J* 2012;25(2):44–53. <http://dx.doi.org/10.1016/j.tej.2012.01.019>.
- [67] Redpoint Energy, Trilemma UK, EPRG. Implementation of EU 2020 renewable target in the UK electricity sector: renewable support schemes, a report for the Department of Business, Enterprise and Regulatory Reform; 2008.
- [68] Kroger W, Zio E. *Vulnerable systems*. Dordrecht: Springer; 2011.
- [69] Grave K, Paulus M, Lindenberger D. A method for estimating security of electricity supply from intermittent sources: scenarios for Germany until 2030. *Energy Policy* 2012;46:193–202. <http://dx.doi.org/10.1016/j.enpol.2012.03.050>.
- [70] Elmakias D. Basic notions of power system reliability. In: Elmakias D, editor. *New computational methods in power system reliability*. Berlin Heidelberg: Springer-Verlag; 2008.
- [71] Leite da Silva AM, Enrenyi J, Wang L. Integrated treatment of adequacy and security in bulk power system reliability evaluations. *IEEE Transac Appl Supercond* 1993;3:275–85.
- [72] Farahat MA, Al-Shammari BM. Power system reliability evaluation and quality assessment by fuzzy logic technique. In: *Universities power engineering conference UPEC 2004*. Bristol, UK; 2004. pp. 478–83.
- [73] Porretta B, Kiguel DL, Hamoud GA, Neudorf EG. A comprehensive approach for adequacy and security evaluation of bulk power systems. *Conf Compr App Adequacy Secur Eval Bulk Power Syst*;6:433–441. 10.1109/59.76684.
- [74] Yusta JM, Correa GJ, Lacal-Arántegui R. Methodologies and applications for critical infrastructure protection: state-of-the-art. *Energy Policy* 2011;39(10):6100–19. <http://dx.doi.org/10.1016/j.enpol.2011.07.010>.
- [75] Rinaldi SM, Peerenboom JP, Kelly TK. Identifying, understanding, and analysing critical infrastructure interdependencies. *IEEE Control Syst Mag* 2001;21:11–25.
- [76] Bompard E, Napoli R, Xue F. Analysis of structural vulnerabilities in power transmission grids. *Int J Crit Infrastruct Prot* 2009;2(1–2):5–12. <http://dx.doi.org/10.1016/j.ijcip.2009.02.002>.
- [77] Söderholm P. Fuel flexibility in the West European power sector. *Resour Policy* 2000;26(3):157–70. [http://dx.doi.org/10.1016/S0301-4207\(00\)00025-8](http://dx.doi.org/10.1016/S0301-4207(00)00025-8).
- [78] Jansen JC, Seebregts AJ. Long-term energy services security: what is it and how can it be measured and valued? *Energy Policy* 2010;38(4):1654–64. <http://dx.doi.org/10.1016/j.enpol.2009.02.047>.
- [79] Afgan N, Veziroglu A. Sustainable resilience of hydrogen energy system. *Int J Hydrogen Energy* 2012;37(7):5461–7. <http://dx.doi.org/10.1016/j.ijhydene.2011.04.201>.
- [80] Ouyang M, Dueñas-Osorio L, Min X. A three-stage resilience analysis framework for urban infrastructure systems. *Struct Saf* 2012;36–37(0): 23–31. <http://dx.doi.org/10.1016/j.strusafe.2011.12.004>.
- [81] Halimes YY, Crowther K, Horowitz BM. Homeland security preparedness: balancing protection with resilience in emergent systems. *Syst Eng* 2008;11(4):287–308. <http://dx.doi.org/10.1002/sys.20101>.
- [82] O'Brien G, Hope A. Localism and energy: negotiating approaches to embedding resilience in energy systems. *Energy Policy* 2010;38(12):7550–8. <http://dx.doi.org/10.1016/j.enpol.2010.03.033>.
- [83] Greene DL. Measuring energy security: can the United States achieve oil independence? *Energy Policy* 2010;38(4):1614–21. <http://dx.doi.org/10.1016/j.enpol.2009.01.041>.
- [84] Xia XH, Huang GT, Chen GQ, Zhang B, Chen ZM, Yang Q. Energy security, efficiency and carbon emission of Chinese industry. *Energy Policy* 2011;39(6):3520–8. <http://dx.doi.org/10.1016/j.enpol.2011.03.051>.
- [85] Mondal MAH, Denich M, Vlek PLG. The future choice of technologies and co-benefits of CO₂ emission reduction in Bangladesh power sector. *Energy* 2010;35(12):4902–9. <http://dx.doi.org/10.1016/j.energy.2010.08.037>.
- [86] Sarica K, Tyner WE. Alternative policy impacts on US GHG emissions and energy security: a hybrid modeling approach. *Energy Econ* 2013;40(0): 40–50. <http://dx.doi.org/10.1016/j.eneco.2013.06.003>.
- [87] Hedenus F, Azar C, Johansson DJA. Energy security policies in EU-25—the expected cost of oil supply disruptions. *Energy Policy* 2010;38(3):1241–50. <http://dx.doi.org/10.1016/j.enpol.2009.01.030>.
- [88] Jun E, Kim W, Chang SH. The analysis of security cost for different energy sources. *Appl Energy* 2009;86(10):1894–901. <http://dx.doi.org/10.1016/j.apenergy.2008.11.028>.
- [89] Markandya A, Pemberton M. Energy security, energy modelling and uncertainty. *Energy Policy* 2010;38(4):1609–13. <http://dx.doi.org/10.1016/j.enpol.2009.01.046>.
- [90] Lutz C, Lehr U, Wiebe KS. Economic effects of peak oil. *Energy Policy* 2012;48(0):829–34. <http://dx.doi.org/10.1016/j.enpol.2012.05.017>.
- [91] Waisman H, Rozenberg J, Sassi O, Hourcade J-C. Peak oil profiles through the lens of a general equilibrium assessment. *Energy Policy* 2012;48(0):744–53. <http://dx.doi.org/10.1016/j.enpol.2012.06.005>.
- [92] Kumhof M, Muir D. Oil and the world economy: some possible futures. *Phil Trans R Soc* 2014;372(2006):20120327. <http://dx.doi.org/10.1098/rsta.2012.0327>.
- [93] de Nooij M, Koopmans C, Bijvoet C. The value of supply security. *Energy Econ* 2007;29(2):277–95. <http://dx.doi.org/10.1016/j.eneco.2006.05.022>.
- [94] Rutherford JP, Scharpf EW, Carrington CG. Linking consumer energy efficiency with security of supply. *Energy Policy* 2007;35(5):3025–35. <http://dx.doi.org/10.1016/j.enpol.2006.10.031>.
- [95] Praktikno AJ, Hähnel A, Erdmann G. Assessing energy supply security: outage costs in private households. *Energy Policy* 2011;39(12):7825–33. <http://dx.doi.org/10.1016/j.enpol.2011.09.028>.
- [96] McCarthy RW, Ogden JM, Sperling D. Assessing reliability in energy supply systems. *Energy Policy* 2007;35(4):2151–62. <http://dx.doi.org/10.1016/j.enpol.2006.06.016>.
- [97] Gnansounou E. Assessing the energy vulnerability: case of industrialised countries. *Energy Policy* 2008;36(10):3734–44. <http://dx.doi.org/10.1016/j.enpol.2008.07.004>.
- [98] Molyneux L, Wagner L, Froome C, Foster J. Resilience and electricity systems: a comparative analysis. *Energy Policy* 2012;47:188–201. <http://dx.doi.org/10.1016/j.enpol.2012.04.057>.
- [99] Sovacool BK, Mukherjee I, Drupady IM, D'Agostino AL. Evaluating energy security performance from 1990 to 2010 for eighteen countries. *Energy* 2011;36(10):5846–53. <http://dx.doi.org/10.1016/j.energy.2011.08.040>.
- [100] Bambawale MJ, Sovacool BK. Energy Security: Insights from a ten country comparison. *Energy Environ* 2012;23:559–86.
- [101] U.S. Chamber of Commerce. Index of U.S. energy security risk, assessing America's vulnerabilities in a global energy market. Washington DC: U.S. Chamber of Commerce; 2013. <http://www.energyxxi.org/sites/default/files/pdf/2013-esri.pdf>.
- [102] Wu G, Liu L-C, Han Z-Y, Wei Y-M. Climate protection and China's energy security: win–win or tradeoff. *Appl Energy* 2012;97:157–63. <http://dx.doi.org/10.1016/j.apenergy.2011.11.061>.
- [103] Geng J-B, Ji Q. Multi-perspective analysis of China's energy supply security. *Energy* 2014;64(0):541–50. <http://dx.doi.org/10.1016/j.energy.2013.11.036>.
- [104] Augutis J, Krikstolaitis R, Martisauskas L, Peculyte S. Energy security level assessment technology. *Appl Energy* 2012;97:143–9. <http://dx.doi.org/10.1016/j.apenergy.2011.11.032>.
- [105] He Y-x, Zhou Y, Wang B, Xiong W, He H-y. Early warning model for risks of energy prices and energy price ratios in China's energy engineering. *Syst Eng Procedia* 2012;3:22–9. <http://dx.doi.org/10.1016/j.sepro.2011.11.003>.
- [106] Karvetski CW, Lambert JH, Linkov I. Scenario and multiple criteria decision analysis for energy and environmental security of military and industrial installations. *Integr Environ Assess Manag* 2011;7(2):228–36. <http://dx.doi.org/10.1002/ieam.137>.
- [107] Lee SK, Mogi G, Kim JW. Decision support for prioritizing energy technologies against high oil prices: a fuzzy analytic hierarchy process approach. *J Loss Prev Process Ind* 2009;22(6):915–20. <http://dx.doi.org/10.1016/j.jlpp.2009.07.001>.
- [108] Blyth W. Use of real options as a policy-analysis tool. In: Bazilian M, Roques F, editors. *Analytical methods for energy diversity & security: portfolio optimization in the energy sector: a tribute to the work of Dr Shimon Awerbuch*. Oxford: Elsevier; 2008. pp. 69–83.
- [109] Reichl J, Schmidthaler M, Schneider F. The value of supply security: the costs of power outages to Austrian households, firms and the public sector. *Energy* 2013;36(0):256–61. <http://dx.doi.org/10.1016/j.eneco.2012.08.044>.
- [110] Awerbuch S. Portfolio-based electricity generation planning: policy implications for renewables and energy security. *Mitig Adapt Strategies Global Change* 2006;11(3):693–710. <http://dx.doi.org/10.1007/s11027-006-4754-4>.
- [111] Bolinger M, Wiser R, Golove W. Accounting for fuel price risk when comparing renewable to gas-fired generation: the role of forward natural gas

- prices. *Energy Policy* 2006;34(6):706–20. <http://dx.doi.org/10.1016/j.enpol.2004.07.008>.
- [112] Asif M, Muneer T. Energy supply, its demand and security issues for developed and emerging economies. *Renew Sustain Energy Rev* 2007;11(7): 1388–413. <http://dx.doi.org/10.1016/j.rser.2005.12.004>.
- [113] Walker B, Holling CS, Carpenter SR, Kinzig A. Resilience, adaptability and transformability in social–ecological systems. *Ecol Soc* 2004;9(2).
- [114] Börjeson L, Höjer M, Dreborg K-H, Ekvall T, Finnveden G. Scenario types and techniques: towards a user's guide. *Futures* 2006;38(7):723–39. <http://dx.doi.org/10.1016/j.futures.2005.12.002>.
- [115] Andrews-Speed P, van der Linde C, Keramidas K. Conflict and cooperation over access to energy: implications for a low-carbon future. *Futures* 2014;58(0):103–14. <http://dx.doi.org/10.1016/j.futures.2013.12.007>.
- [116] Stirling A. From sustainability to transformation: dynamics and diversity in reflexive governance of vulnerability. In: Hommels A, Mesman J, Bijker W, editors. *Vulnerability in technological cultures: new directions in research and governance*. Cambridge MA: MIT Press; 2014. pp. 305–32.
- [117] Blum H, Legey LFL. The challenging economics of energy security: ensuring energy benefits in support to sustainable development. *Energy Econ* 2012;34(6):1982–9. <http://dx.doi.org/10.1016/j.eneco.2012.08.013>.