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SECURE – SECURITY OF ENERGY CONSIDERING ITS UNCERTAINTY,
RISK AND ECONOMIC IMPLICATIONS
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# Risk analysis based measures of energy security

Andrea Bigano (FEEM), Peter Burgherr & Stefan Hirschberg (PSI)

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# 1. Energy security risks: introduction and overview

In recent years, energy security has become a major issue on the international agenda (Scheepers et al., 2006; WEF, 2006; WEF, 2008; WEC, 2008). This is also reflected in the growing number of peer-reviewed, scientific publications in the ISI Web of Knowledge that increased from 46 in 2005 to 152 in 2008, when only the term "energy security" is searched for. It is important to note that the functioning of the energy infrastructures is likewise strongly dependent on supporting infrastructures ranging from telecommunication systems to fuel and water supply and financial services to name a few (IRGC Policy Brief, 2007; Jones, 2007; Rinaldi et al., 2001). Within the broader context of critical infrastructure protection (CIP) energy security plays a major role (Jones, 2007; Moteff and Parfomak, 2004; The White House, 2007).

Defining energy security is controversial due to the variety of stakeholders and views of what assets are risk. In the 1970s the focus was on oil supply disruptions, whereas in the past decade issues such as the terrorist threat, political disputes on trans-boundary oil and gas transportation, price shocks and potential global warming effects have gained substantial interest both in the political arena and public perception (e.g., Monaghan, 2005; WEF, 2006). For example the World Economic Forum considers energy security as an umbrella term that covers many concerns linking energy, economic growth and political power (WEF, 2006). The International Energy Agency (IEA) describes energy security as "the uninterrupted physical availability at a price which is affordable, while respecting environment concerns"[1]. Others look at it as a multidimensional concept, including external as well as internal action (Baumann, 2008).

Furthermore, there is no consensus among economists, energy experts and politicians on the correct hierarchy of energy challenges for Europe in the near to long-term future. However, in line with the current debate on energy security of supply in Europe a variety of risks and potential consequences can be identified (Table 1).

Table 1: Overview of energy security risks and their potential consequences.

| Type of risk | Potential consequences |
|---|---|
| Availability risks | Geopolitical, short- and/or long-term limitations |
| Import dependency | No/little diversity, transit countries |
| Rising and volatile prices | Domestic social/political issues |
| Overall stability and reliability of the supply system | Resilience |
| Uncertainty over liberalization | Slow down of investments |
| Regulatory risks | Flawed regulations |
| Climate change risks | Environmental and health risks |
| Severe accident risks | Damage to installations, human health, environment, property, economic loss |
| Terrorist threat (incl. sabotage, vandalism, theft) | Wide range of effects to human health, environment, property, economic activities, etc |

The following paragraphs provide more details on some of the topics listed above.

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[1] http://www.iea.org/Textbase/subjectqueries/keyresult.asp?KEYWORD_ID=4103

Technical risks are inherent to all energy systems, independent of their condition or exposure to internal and external factors. The impacts and consequences of severe accident risks have been subject to extensive analysis (Burgherr and Hirschberg, 2007; Burgherr and Hirschberg, 2008a; Burgherr and Hirschberg, 2008b; Burgherr et al., 2004; Hirschberg et al., 1998). Natural disasters such as earthquakes or wind storm can also trigger technical failures (Cruz and Krausmann, 2008; Cruz and Steinberg, 2005). Examples with a high media impact in Europe include the exceptionally long lasting electric blackout[2], which occurred in Italy on September 2003 and the power interruptions of November 2006, which originated in Germany by the tripping of several high-voltage lines and affected 15 million European households (UCTE, 2004; UCTE, 2007). Additionally, recent studies indicate that a changing climate is likely to affect current infrastructure (Doyle et al., 2008; Kintisch, 2008) and to alter resource potentials such as hydropower (Lehner et al., 2005).

A particular subcategory of technical risk has to do with the possible exhaustion of an energy source and it is sometimes referred to as “geological risk”. Oil and gas reserves in the European Union (EU) decreasing (BP, 2007) and over 90% of world hydrocarbon reserves are controlled by state-owned companies in the Middle East and Eurasia. The source of risk here is not in the very unlikely sudden and unforeseen depletion of a given resource, as much as in the fact there is a persistent uncertainty about the real amount of key primary sources in the ground, often for political reasons. Oil and gas are not only difficult to access for European companies, but total hydrocarbon reserves remain unknown. To some, oil production will peak in the next 20 years or so. Others believe that we are far from reaching the peak since only one third of the world reserves have been exploited so far (Yergin, 2000; Yergin, 2006).

Economic risks mainly cover erratic fluctuations in the price of energy products on markets. Price variations can be due to supply/demand actual or anticipated imbalances, but they can also result from speculative movements and market power abuse. Even when not anticipated, the market may be able to absorb the resulting stress with reasonably limited consequences. However, in the short run, pronounced price hikes may cause serious concern. On the one hand, the rise in fuel prices creates monetary and trade imbalances between energy producing and consuming countries especially harming the economy of the latter. Yet, high prices tend to slow down global economic prosperity eventually damaging producing countries economies. On the other hand, decreasing prices of energy sources tend to diminish capacity enhancing investment in energy producing countries creating new bottlenecks to oil and gas supply.

Regulatory risks have to do with government-regulated policies in energy-producing countries that may underplay the level of future investments causing related effects on production and prices. In the past, many suppliers have indeed proven unable to increase production, adding to the pressure on market prices (Riley, 2006; Riley, 2008). It may also have to do with the downright elimination of a energy supply option in response to political decisions, such as for instance the phasing out of nuclear power generation due to social acceptance concern.

Geopolitical risks concern potential government decisions to suspend deliveries because of deliberate policies, war, civil strife and terrorism. Energy industries in supplier

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[2] The duration of the blackout varied across regions, from a few hours in the North to 24 hours in Sicily.

countries are subject to extensive government interference, and do not function in a competitive market framework. This adds to the fears that energy will increasingly be used as a political weapon. In addition, security of supply is threatened by political instability of exporting regions where civil wars, local conflicts and terrorism have often been cause of temporary damage of energy facilities and infrastructures.

Environmental risks mainly describe the potential damage from accidents (oil spills or nuclear accidents, or dam ruptures) While for these kind of catastrophic event the threat to the energy system is self evident, a similar pattern can be envisaged also for operational damages resulting from the normal operation of the energy sector. In both cases in fact the consequence in terms of energy supply is that it may be more difficult (if not prevented) for the energy source involved supplying energy, due to the policy response to the environmental risks attached to that energy vector. Consider for instance as the case of greenhouse gas emissions. Climate policy views are increasingly supporting the idea that industrial countries will need to reduce emissions by at least 60-80% by 2050. Given that within the EU 80% of all emissions are related to fossil fuel burning in the energy, transport, household and industrial sectors, energy policy will increasingly be constrained by climate change objectives. While near zero carbon energy or possibly geo-engineering or nuclear fusion energy will ultimately be essential to meet the climate change challenge, the present focus is on how to reduce GHG emissions from fossil fuels which continues to dominate the EU's energy mix. The principal obstacle facing the EU is the absence of a comprehensive global climate-change agreement that would provide the necessary certainties for investors (Behrens and Egenhofer, 2008).

It is important to note that the time scale of different risks differs considerably from fractions of a second to hundreds of years (IEA, 1995; Mandil, 2008; Stern, 2006). In the short term, the concern is with the disruptive impacts of a price shock or an unanticipated cut in supply. The latter is generally associated with supply shortages due to accidents, extreme weather conditions, terrorist attacks or technical failures of grids. Such risks are sometimes referred to in the context of 'operational security' or 'systems security'. In the long term, the concern is more with the availability of sufficient energy supply that allows stable and sustainable economic development. Here the emphasis is on geological depletion, adequacy of investments in generation capacity, transport infrastructure and grids, the cut-off of regional supplies due to long term regional crises, as well as the quality of systems' management, including pricing mechanisms and mitigating market power.

The time dimension is also relevant for the technical characteristics of the energy systems, as technology changes across time. Thus some threats may be significantly reduced by technological progress that increases the reliability of transport infrastructures; on the other hand, new technologies, in their early stages may bring about unforeseen risks that were not accounted for in the designing stage. For instance, in 1944 a gas leak at the Liquefied Natural Gas (LNG) peak-shaving facility in Cleveland (Ohio) led to explosions and fires, killing 130 people and destroying a one square mile area on Cleveland, Ohio's east side. This catastrophic event also had a significant impact on the natural gas industry in the USA, i.e. any LNG activities were suspended until the 1960s. At that time a number of new developments allowed LNG facilities to operate much safer, including large-scale fire and vapour cloud dispersion, extensive cryogenic material compatibility studies, and experience from the construction and operation of liquefaction plants in Algeria and receiving terminals in France and England.

EU is confronted with both external and internal energy security risks. All the elements linked to energy imports dependence belong to external risks, including geopolitical issues, international transit, upstream technical issues in non EU countries, etc. While uncertainties related to European energy demand, infrastructure, as well as energy policy orientations and institutional developments refer to internal energy insecurity. Accordingly, market risks in the framework of liberalisation, either due to bottlenecks, market power or regulation, have to be addressed, as well as their potential impact on import development. The distinctions between internal and external insecurity are fundamental as far as tools available to the EC and to European governments are concerned. Dealing with external issues involves developing diplomacy and relying on European energy companies present in international markets.

The rest of this report is organised as follows. The following chapters address (1) risk and uncertainty, (2) comparative risk assessment to quantify potential consequences and damages, (3) the treatment of risk aversion, (4) energy security in the context of Multi-Criteria Analysis (MCA), and (5) a presentation of selected, chain-specific risks in the energy sector.

## 2. Risk and Uncertainty

According to the Society for Risk Analysis[3], Risk is the potential for realization of unwanted, adverse consequences to human life, health, property, or the environment. Within the context of risk and uncertainty, Cool (1999) provides independent definitions for the two terms, avoiding conceptual problems and inconsistencies. Risk then denotes the absolute value of probable loss, whereas uncertainty is defined in the following way:

- There is a distinction between certainty and uncertainty;
- Uncertainty forks into known (assumed) and unknown probabilities;
- Ignorance, or unknown probabilities forks into known and unknown categories;
- Known categories forks into including the uncertainties in the probabilities or neglecting (or using other non-probabilistic techniques).

In engineering and natural sciences risk is frequently defined in a quantitative way:

$$Risk\ (R) = Probability\ (p) \times Consequence\ (C)\ . \qquad (1)$$

Quantitative risk assessment is of critical importance in several risk-sensitive industries. Concerning the energy sector a comprehensive and objective risk evaluation is essential (Burgherr et al., 2004) because its complex and interdependent technical systems and facilities comprise critical infrastructure elements to the functioning of the economy and the accomplishment of societal needs. In the context of security, risk is often defined as a function of the three variables threat ($T$), vulnerability ($V$) and consequence ($C$):

$$R = T \times V \times C. \qquad (2)$$

Threat is the measure that a specific accidental or intentional event will take place. Vulnerability is the measure of likelihood that various types of safeguards fail. Consequence is the magnitude of negative effects in case of an accident or successful attack. This approach allows the identification of areas where high threat levels, extreme vulnerabilities and high consequences overlap. It is this intersection that causes security concerns.

In the literature a number of approaches on the concepts of risk and uncertainty can be found, which differ in definition, scope, assessment methods and management strategies.

Following Stirling (1994), three basic states of incertitude can be identified:

- *Risk*, as a quantifiable incertitude.
- . *Uncertainty*, as an acknowledgeable but not quantifiable incertitude.
- *Ignorance*, as a not knowledgeable hence not quantifiable incertitude.

Jansen et al. (2004) note that different methods should be used to tackle these different forms of incertitude.

- *Risks* allow for the application of traditional statistical methods.
- *Uncertainty* can be addressed by Bayesian and scenario-based approaches, or Delphi-like methods based on expert opinions.

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[3] http://www.sra.org/

- When *ignorance* is present, diversity can provide resilience to systems exposed to incertitude. Yet the creation of diversity implies foregoing certain cost reductions could such as those resulting from economies-of-scale or standardisation. A precise definition of diversity is needed to design optimum diversity strategies against of conditions of ignorance.

Whether we are dealing with quantifiable risks, uncertain situations or whether we are working under a veil of ignorance depends on the specific SoS and the time horizon considered.

A more formalised, but analogous taxonomy of uncertainties is the following:

- *Natural Variability*: the case in which possible outcomes and their probability distribution are both known. The typical example is a roulette game (assuming that the roulette has not been tampered with). Risks allow for the application of traditional statistical methods.
- *Parameter Uncertainty* (or. Statistical Inference Uncertainty): the uncertainty deriving from the inadequacy of the available data to extrapolate statistically valid properties (e.g. probability distributions).
- *Statistical Model Uncertainty*, the uncertainty resulting from the selection of a particular statistical model to explain the data.
- *Process Model Uncertainty*: the uncertainty related to using a process model based on incomplete process knowledge, or data, to represent reality.

Klinke and Renn (2001) propose six main categories of risks, named after characters from Greek mythology:

- *Damocles*: high catastrophic potential, probabilities (widely) known.
- *Cyclops*: no reliable estimate on probabilities, high catastrophic potential at stake.
- *Pythia*: causal connection confirmed, damage potential and probabilities unknown or indeterminable.
- *Pandora*: causal connection unclear or challenged, high persistency and ubiquity (bio-accumulation).
- *Cassandra*: intolerable risk of high probability and great damage but long delay between causal stimulus and negative effect.
- *Medusa*: perception of high risk among individuals and large potential for social mobilization without clear scientific evidence for serious harm.

Finally, the International Risk Governance Council (IRGC, 2008) distinguishes within its risk governance framework between:

- *Complexity* refers to difficulties in identifying and quantifying causal links between a multitude of potential causal agents and specific observed effects.
- *Uncertainty* refers to a lack of clarity or quality of the scientific or technical data.
- *Ambiguity* results from divergent or contested perspectives on the justification, severity or wider meanings associated with a given threat.

According to the kind of risk and uncertainty as well as the scope and specific objectives a variety of analytical methodologies are available, each of which has its specific strengths and weaknesses. For an overview of quantitative risk measures see for example Jonkman et al. (2003).

Within the SECURE project the following approaches are of interest:

- *Comparative risk assessment* is based on historical experience and/or Probabilistic Safety Assessment (PSA) and aims to assign in a quantitative manner probabilities and potential consequences to hazardous activities.
- *Expected utility approach* (with or without risk aversion) and portfolio theory methods for quantifiable risks allow for the application of traditional statistical methods.
- *Bayesian and scenario-based approaches*, or Delphi-like methods based on expert opinions for uncertainty assessment.
- *Multi-criteria analysis* (MCA) allows combining in a structured way stakeholder preferences with specific technology characteristics related to energy security, considering the environmental, economic and social aspects of sustainability.

# 3. Comparative risk assessment

Reporting of industrial accidents is often regulated by national and supra-national frameworks. For example, companies are obliged to report accidental events from industrial activities falling under the SEVESO II Directive of the European Union allowing in-depth analysis of accident frequencies and consequences (Nivolianitou et al., 2006; Papadakis, 2000). Although accidents in the energy sector have been shown to form the second largest group of man-made accidents (after transportation), their level of coverage and completeness was not satisfactory because they were commonly not surveyed and analyzed separately, but just as a part of technological accidents (Burgherr et al., 2004; Hirschberg et al., 1998). The Paul Scherrer Institut (PSI) started a long-term research activity in the 1990s to close this gap and to enable a factual and appropriate treatment of accident risks in the energy sector. Severe accidents are most controversial in public perception and energy politics. Therefore they are the main focus of investigations, even when the total sum of the many small accidents with minor consequences is substantial.

A comprehensive and undistorted comparative assessment requires the objective expression of accidents and risks on the basis of extensive data collection and evaluation (Burgherr and Hirschberg, 2008a). In cases when historical experience is not representative (e.g. for nuclear) the application of Probabilistic Safety Assessment (PSA) is required to address probabilities and consequences of hypothetical accidents (Hirschberg et al., 2004a).

For this purpose, the database ENSAD (Energy-related Severe Accident Database) was first established in 1998 (Hirschberg et al., 1998) by the Paul Scherrer Institut (PSI). ENSAD uses a multitude of primary information sources whose contents are verified, harmonized and merged, thus a substantially higher degree of completeness and a much broader coverage can be achieved. A detailed description of the approach has been given earlier (Burgherr and Hirschberg, 2008a; Burgherr et al., 2004; Hirschberg et al., 2004a; Hirschberg et al., 1998). ENSAD provides a comprehensive coverage of severe, energy-related accidents and their technical aspects, allowing the users to make coherent analyses tailored to their specific needs.

Since its first establishment, the ENSAD database has been continuously updated, improved and extended, both in scope and content to provide solutions to upcoming problems and to meet the specific needs of new users. Specific advancements were achieved in the course of recent projects, including (1) the “China Energy Technology Program” (CETP) (Burgherr and Hirschberg, 2007; Hirschberg et al., 2003a; Hirschberg et al., 2003b); (2) the project “New elements for the assessment of external costs from energy technologies” (NewExt) within the EU 5th Framework Programme (Burgherr et al., 2004); (3) a study of natural gas accident risks (Burgherr and Hirschberg, 2005); and (4) the Integrated Project “New Energy Externalities Developments for Sustainability” (NEEDS) within the EU 6th Framework Programme (Burgherr et al., 2008a).

Within SECURE comparative risk assessment of energy technologies with regard to severe accidents and terrorist threat are assigned to Work Package 5.7, necessary exchanges with WPs 5.1-5.6 dealing with individual technologies are being established. Furthermore, results of WP 5.7 will included technology-specific risk indicators that provide inputs for MCA in WP 6, Task 2.

The actual methodological description of planned activities in WP 5.7 will be reported in the respective deliverable D5.7.1. Therefore, only a concise summary of the most essential topics and issues is given here:

- Consolidation of current version and content of ENSAD database.
- Update of ENSAD database within SECURE.
- Specific improvements in database architecture and interface.
- Simplified PSA for the assessment of consequences from hypothetical severe accidents in nuclear power plants.
- Establishment and application of a methodology to evaluate the threat of terrorist attacks to energy infrastructure.
- Analyses will use a full-chain approach for the various energy chains under consideration.
- Comparative results will be calculated using generic assumptions as well as for specific technology characteristics as defined within SECURE. On the one hand, data will be analyzed using well-established techniques (e.g. aggregated indicators, Frequency-Consequence curves) to ensure comparison with earlier studies. On the other hand, new developments need to be tested and implemented to comply with the overall goals of SECURE.
- Quantitative evaluations will be complemented by a qualitative analysis of indirect impacts of accidents on the energy sector, in view of their potential effects on the security of supply.
- Clearly defined and measurable risk indicators will be calculated, serving as input for MCA.

# 4. Risk aversion and the costs of an uncertain threat

When probabilities and outcomes are known with reasonable confidence, and when a monetary value can be realistically attached to the outcomes, the related monetary impacts can be quantified using standard procedures. The typical case in which this approach can be applied is the one of technical accidents along the energy chain (nuclear reactor failure, marine transportation accident, pipeline breakage, etc.).

In most analyses of accidents related to the supply of energy, damages and benefits are estimated by simply monetising expected consequences, relying on expert judgements about both the probability of consequences and their magnitude. This approach, termed Expert Expected Damage (EED), relies upon the fundamental implicit assumptions that individuals are indifferent to risk and that they share the same information about the accident under scrutiny as the experts in the field. It basically consists of multiplying the monetised expected consequences by the probability assessed by the experts[4].The implication of this approach is that if the per capita share of the value thus computed was offered to each of the individuals affected by the threat, for accepting the related risk, they would be fully compensated for the cost component of that risk actually taken into account in the assessment. Markandya and Taylor (1999) note that there are some obvious and not so obvious problems with this reasoning, the most obvious one being that there may be many more effects of an accident than the analyst can track and quantify. To the extent that some of these effects are missing, the money value derived will be too low. A partial response to this problem is to take higher probabilities; in general, however, the probability used refers to design requirements and is usually very small, and this in turn results in very low external costs.

Markandya and Taylor (1999) suggest as the strategy most likely to resolve these issues, to *allow more systematically for risk aversion and to use perceived probabilities in the evaluation*.

Three issues, from an economics perspective, arise in the expert expected damage (EED) approach:

Ignoring risk aversion. The EED approach assumes that money and satisfaction are proportionally related. The evidence in study after study, however, is that people need more money to compensate them for taking risks than the actuarial value of these risks. The reason is simply that people are averse to taking risks, particularly of the type we are considering here.

Ignoring the ex ante perspective in individual decision making. A distinction is made here between an ex ante approach and an ex post approach to making decisions when outcomes are uncertain. The ex post approach, which is part of the EED approach, assumes that individuals maximise the expected value of their welfare realised in alternative states. However, economists have found more empirical support for individuals' maximising expected utilities, which we term the ex ante approach, following Hammond (1981). The term "expected utility" is used because individuals are assumed to maximise the expected value of their utility over a state with, and a state without, the accident while accounting for the probability of each state occurring. This may be distinguished from the EED approach where one estimates the loss in

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[4] See Markandya and Taylor (1999) where Oak Ridge National Laboratories and RFF (1995) is mentioned as an application of this approach to the case of the evacuation costs for a nuclear accident.

satisfaction from the consequences of an accident if it occurred with certainty and then multiplies this amount by the probability that the accident will occur.

In theory, unless these issues are addressed, the sum of money estimated as the damage will not match the amount needed to make whole those potentially harmed. Accordingly, an alternative paradigm is suggested here, termed expected utility (EU) approach, that incorporates risk aversion, the ex ante perspective (that is, expected utility maximisation), and lay perceptions of risks. The EU model is then used to simulate the consequences for damage estimates of substituting the EU model for the EED model using the "state-dependent utility function approach" alluded to above.

## 4.1 Functional form of the utility function

The degree of risk aversion depends on the concavity of the utility function. There are two main measures of this concavity: the coefficient of absolute risk aversion and the coefficient of relative risk aversion. The terms "absolute risk aversion" and "relative risk aversion" are tied to the nature of the lottery. Absolute risk aversion applies to additive lotteries that are expressed in monetary units while relative risk aversion applies to multiplicative lotteries in rates or fraction[5].

From the theoretical point of view, various functional forms of utility functions have been studied which reflect different attitudes towards risk. Many experimental studies have also been developed to estimate the risk aversion coefficient of individual decision-makers by presenting them lotteries (that is, a set of probabilities associated with different loss of wealth) and by letting them rank these lotteries[6]. These studies usually show that the absolute risk aversion decreases with wealth. As far as relative risk aversion is concerned, they seem to support the idea of a rather constant coefficient of relative risk aversion. As a consequence, the most general way to express suitable potential functional forms of the utility function is a power function (Xie, 2000) defined by:

$$U(W)=\frac{1}{\gamma}\left[1-\exp\left(-\gamma\left(\frac{W^{1-\sigma}-1}{1-\sigma}\right)\right)\right], \sigma\geq 0, \gamma\geq 0. \qquad (3))$$

When $\gamma = 0$ this function boils down to

$$U(W)=\frac{W^{1-\sigma}-1}{1-\sigma} \qquad (4)$$

and exhibits positive and decreasing absolute risk aversion, while the coefficient of relative risk aversion is constant and amounts to $\sigma$. The logarithmic specification U(W) = lnW (implying that the coefficient of relative risk aversion is equal to unity) can also be derived as a special case of the power function (1) by choosing $\sigma = 1, \gamma = 0$.

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[5] If the individual is risk neutral, the relative risk aversion coefficient is zero and the utility function is: *U(W) = W*. When lotteries are additive the outcome can be expressed in absolute terms as an increase or decrease of current wealth (for instance the outcomes of a simple additive lottery can be $W-A$ with probability *p* and *W* with probability *1-p*). When lotteries are multiplicative the outcome can be expressed in relative terms as a percentage increase or decrease of current wealth (for instance the outcomes of a simple multiplicative lottery can be $aW$ with probability *p* and *W* with probability *1-p*).

[6] See ExternE (1995), Friend and Blume (1975), Hansen and Singleton (1982), Szpiro (1986), Mehra and Prescott, (1995).

## 4.2 Risk premium computation

The Willingness to Pay (WTP) of a risk averse individual for avoiding a risky situation can be computed by comparing what would be the welfare change of a risk neutral individual and the correspondent of a risk averse one. We label these welfare losses respectively, cost of accident without risk aversion and cost of accident with risk aversion.

To fix ideas, suppose that a risk averse individual faces the following lottery. During a given year, with probability $p_1$ its place of residence will be affected by a moderate energy supply disruption. With probability $p_2$ ( $p_1 > p_2$ ), its place of residence will be affected by a much large energy supply disruption. If a moderate disruption takes place, the per capita damage for the inhabitants of the affected region is $X_1$. In case of a more substantial disruption, the per capita damage for the inhabitants of the affected area is $X_2$ (with $X_1 < X_2$ ). With probability $p_0 = 1 - p_1 - p_2$, no disruption will affect his place of residence and hence no damage would occur. If $W_0$ is the wealth of the individual under scrutiny, her situation in the three possible state of the world is summarized in Table 2:

Table 2: States of the world for a simple energy disruption lottery.

| State of the world | Probability | Wealth |
|---|---|---|
| No Disruption | $p_0 = 1 - p_1 - p_2$ | $W_0$ |
| Moderate Disruption | $P_1$ | $W_0 - X_1$ |
| Very Large Disruption | $P_2$ | $W_0 - X_2$ |

Now, for a risk neutral individual, the **cost of accident without risk aversion** is simply

$$CA_{RN} = W_0 - E(W) = W_0 - \left[(1 - p_1 - p_2)W_0 + p_1(W_0 - X_1) + p_2(W_0 - X_2)\right] \qquad (5)$$

where $E(W)$ is the expected value of the individual's wealth. On the other hand, for a risk averse individual, the **cost of accident with risk aversion** is

$$CA_{RA} = W_0 - U^{-1}\left[E\left(U^*\right)\right] \qquad (6))$$

where $U^{-1}\left[E\left(U^*\right)\right]$ is the so- called *"certainty equivalent"*, that is that value of wealth that yields the same level of "satisfaction" to the (risk averse) individual as being exposed to the lottery.

In terms of the power function (1), the certainty equivalent is

$$U^{-1}\left[E\left(U^*\right)\right] = \left[1 + (1-\sigma) * E\left(U^*\right)\right]^{\frac{1}{1-\sigma}} \qquad (7)$$

where

$$E\left(U^*\right) = \left[(1 - p_1 - p_2)U\left(W\right)_0 + p_1 U\left[\left(W_0 - X_1\right)\right] + p_2 U\left[\left(W_0 - X_2\right)\right]\right]. \qquad (8)$$

This is the step where concavity plays a crucial role. Note in fact that, for a risk neutral agent, the certainty equivalent is *E(W),* since is utility function is simply *U(W)* = *W*.

The risk premium is then computed by looking at the difference between the two welfare changes:

$$RP = CA_{RA} - CA_{RN}. \qquad (9)$$

# 5. Multi-Criteria Analysis for energy security aspects

Multi-Criteria Analysis (MCA) provides a complementary approach to monetization measures because multiple indicator values are not condensed into one aggregated indicator but rather combined with stakeholder preferences. Within the EU-project NEEDS (New Energy Externalities Developments for Sustainability) MCA has been used to evaluate sustainability performance of a set of future electricity generation technologies, based on preference profiles from a wide range of stakeholders.

For the NEEDS sustainability assessment of individual technologies a hierarchical set of criteria and indicators was proposed that covered environmental, economic and social dimensions of sustainable development. The acceptance of this set was examined by an online stakeholder survey that revealed no major disagreement in the structure and composition (Burgherr et al., 2008b). Therefore, only minor adjustments to the criteria and indicator set were necessary (Hirschberg et al., 2008). Afterwards the actual MCA for the NEEDS technology set was organized, developed, implemented, analyzed and the major findings and conclusions presented in a detailed report (Schenler et al., 2009).

In the remaining part of this chapter, risk-relevant indicators assessed in NEEDS are presented. This is considered a valuable starting point for discussion to identify suitable indicators, necessary modifications and potential new developments to establish a criteria and indicator set that meets the scope and objectives of SECURE, while at the same time benefiting from the detailed experience accumulated within NEEDS.

Table 3 shows the NEEDS criteria and indicator set, with shaded cells indicating risk-relevant indicators. Undertaking a full sustainability assessment allows taking into account indicators from all three sustainability dimensions that related to different aspects of energy security, although some areas are only partially or not at all covered by the NEEDS MCA. Nevertheless, the indicators quantified within the NEEDS project provide a valuable starting point to develop and establish a comprehensive set of criteria and indicators for energy security within SECURE. This requires a multi-step approach:

- Identification of energy security risks relevant within the scope of SECURE.
- Establishment of a criteria and indicator system for these different risks that incorporates a sustainable development perspective.
- Definition of understandable, accurate and measurable indicators that can be assessed for the set of technologies under consideration.
- Evaluation of available methods as well as development of new ones where necessary, to calculate technology-specific indicator values.
- Assessment of energy security using a MCA of policy options.

In practical terms, MCA should be an integrative activity of SECURE, i.e. indicator inputs should mostly come from WPs 5.1-5.6 for the various energy chains, with some likely complements regarding economic aspects of energy security from WP 2. Interfaces to WP 2, WP 3 and WP 4 also need to be established to ensure consistency in basic assumptions of long-term strategies and scenarios used by the different analytical frameworks in SECURE. Finally, MCA requires a strong link with WP7 because its success is strongly dependent on stakeholder integration and feedback in all phases from its development and establishment to the actual execution and dissemination of results, conclusions and recommendations.

Table 3: Criteria and indicator set as used within the NEEDS project. Cells shaded in orange denote indicators concerning severe accident risks and the terrorist threat, whereas cells in gold refer to other aspects of energy security.

| | **Criterion** - Indicator(s) |
|---|---|
| ENVIRIONMENTAL DIMENSION | RESOURCES |
| | **Energy** - Fossil fuels, Uranium |
| | **Minerals** - Metal ore |
| | CLIMATE - Carbon dioxide emissions |
| | ECOSYSTEMS |
| | **Normal operation** – Biodiversity, Ecotoxicity, Air pollution |
| | **Severe accidents** – Hydrocarbons, Land contamination |
| | WASTE - Chemical waste, Radioactive waste |
| ECONOMIC DIMENSION | CUSTOMERS - Generation cost, |
| | SOCIETY - Direct jobs, Fuel autonomy |
| | UTILITY |
| | **Financial** - Financing risk, Fuel sensitivity, Construction time |
| | **Operation** - Marginal cost, Flexibility, Availability |
| SOCIAL DIMENSION | SECURITY |
| | **Political continuity** - Secure supply, Waste repository |
| | POLITICAL LEGITIMACY – Conflict, Participation |
| | RISK |
| | **Normal risk** – Mortality, Morbidity |
| | **Severe accidents** -Accident mortality, Maximum fatalities |
| | **Perceived risk** - Normal operation, Perceived accidents |
| | **Terrorism** - Terror-Potential, Terror-Effects, Proliferation |
| | RESIDENTIAL ENVIRONMENT – Landscape, Noise |

# 6. Security risks and their chain-specific implications

This section provides an overview of the major threats to security of energy supply for oil, natural gas, coal, nuclear, new renewable energy sources and electricity. We have no pretence of exhaustiveness: the aim here is to provide examples of different threats that require different approaches in order to clarify why we need different approaches and why there are different degrees of limitation.

The main risks faced by the various energy sectors in Europe are described in detail in Deliverable 3.1 (Checchi et al., 2008), on which this section draws heavily for the characterisation of sector-specific threats. Here we briefly summarise the most relevant ones for the convenience of the reader, and we integrate them with additional considerations on related threats.

## *6.1 Oil*

**Oil transport risks**

The vast majority of oil supplies to the EU (over 85%) is transported by sea; only 14% come by pipelines from Russia through the Druzhba North and South pipelines, and from Norway through Norpipe (to the UK). Pipeline oil imports from the Former Soviet Union (FSU) region will increase, and this may increase risks: For one thing, the Druzhba pipeline is already working at full transport capacity, and further expansion will be necessary to meet European demand. Second, Russia may be tempted to cut supply to the states of the Former Soviet Union. However existing IEA and EU stockpiling policies can minimize possible geopolitical threats coming from Russia.

As to oil transportation by tanker, shipping increases flexibility for both exporters and importers by allowing rerouting of their oil exports/imports. The sources of vulnerability are the “chokepoints”, (the narrow sea-lanes through which the oil tankers have to transit). For instance from Middle East to Europe, oil must pass through the Bosphorus (linking the Black Sea to the Mediterranean Sea), the Bab el-Mandab Strait (from the Arabian Sea to the Red Sea), and the Suez Canal (from the Read Sea to the Mediterranean Sea). Shipping accidents, and some pirate attacks, could cause serious impediments to transport on these routes, with significant impact on oil supply and prices (Willenborg et al., 2004).

Accidents at chokepoints can be treated as events whose probability of occurrence can be inferred from previous accident statistics from the characteristics of the type of accident and from the specificities of the chokepoint. The impacts of the accidents can be assessed by various consequence indicators and other damage estimation techniques.

In contrast, fathoming the probabilities of occurrence and the possible consequences of a geopolitical crisis involving oil producing or transit countries is a much more uncertain exercise.

## *6.2 Natural gas*

Energy security risks related to gas have an external and an internal dimension (IEA, 2004). External risks have to do with increasing import dependence from external suppliers, in terms of transit risk: investment risks, the reliability of exporting countries. On the other hand, the internal dimension has to do with the development and liberalisation of the internal EU gas market and the related with under-investment in the internal gas market.

In the absence of new gas field discoveries in Europe, EU's import dependence is expected to rise. Over the period from 1990 to 2006, natural gas imports of EU-27 already doubled, exceeding 300 bcm. Europe's two main current suppliers, Russia and Algeria will keep providing most of the imports, although Middle East, the region holding the largest reserves, may experience a sharp increase.

Stern (2002) notes that there are three main risks associated with Europe's gas import dependence: investment and facility risks, exporters' reliability risks and transit risks. The first ones are generally technical or financial in nature, while the last two typically are political risks related to governmental policies in producing and transit countries.

### Investment and facility risks

In order to allow supply to meet international demand, as gas trade grows, substantial investments in new infrastructures or in refurbishing the existing ones are needed in production and transit countries[7]. The source of concern here is that often the energy sector in producing countries is not so keen in making these investments. Gazprom's production, for example, depends on aging and inefficient facilities built during the Cold War and its ability to manage and develop its gas reserves is limited[8].

From the point of view of gas suppliers new infrastructures for cross-border trade require substantial start-up and maintenance costs, which can only be recouped in the long-term. Thus there is a substantial risk of under-investment in interconnectors.

The reluctance to spend in maintenance and refurbishment of existing facilities implies that European gas supplies are vulnerable to potential accidents at key transmission and import facilities, some of which are remote from European territory and therefore far from its control. Europe's security of gas supply is thus likely to be temporarily damaged in case of a technical accident due to bad maintenance (Stern, 2002).

### Exporters' reliability risks

The recent clash between Russia and Ukraine over natural gas contracts and the resulting interruption to exports to Europe clearly highlights the main source of concern and debate for the EU in terms of natural gas security, that is the to the political reliability of producing (and transit) countries. Nationalistic policies and possible internal instability are seen as major energy security threats. Because of resource nationalism following the increase in fossil fuels prices after 2003, OECD governments and international companies and have experienced increased requests by host governments for larger shares of rents from joint activities and reduced access to resources (Stern, 2006). The main fear is the temptation to use Europe's dependence as a tool of political pressure. Natural gas is likely to be the preferential tool of producers: because of is larger potential for consumer lock-in, due to the more extensive use of pipelines than oil, it allows deliveries to be suspended to target countries pushing them towards a specific political behaviour.

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[7] See deliverable 3.1 (Checchi et al., 2008) for more details on projected investment needs.

[8] It may be argued that foreign investment could help; however there are important factors at play that may seriously limit their attractiveness or their feasibility. On one hand in fact, a fair and clear ground rules should be enforced, but in non-OECD countries it might be difficult to bring the sovereign risks of investment down to an acceptable level. More important, gas producing countries may be opposing foreign influence in their gas industry. However there are signs of increasing openness in this sense (Noël, 2007).

An additional source of concern for Europe related to exporters' reliability is the unpredictability of supplies interruption caused by internal political turmoil, entailing a non negligible risk of terrorism, riots and political downturn in countries governed by undemocratic regimes.

## Transit risks

The bulk (89%) of Europe's natural gas imports travels by pipelines across at least, one transit country, thus increasing import risks. Checchi et al (2008) note on this regard that trade negotiations among several countries are complex and costly, especially if politically unstable countries are on the route or if their relationships with the exporter are tense and that, when one of these conditions is fulfilled, the risk of supply interruption increases.

Again, as highlighted by the recent crisis in Ukraine, the main concern for transit is related to Russia's gas export. Around 90% of Russian gas exports to Europe pass through Ukraine or Belarus before reaching the EU border. As Russia's relationships with other Former Soviet Republics remain tense this situation clearly represents a threat for European security of supply.

The transit risk is reduced by the enlargement of the EU, but being at the end of a transnational pipeline will always entail a certain extent of uncertainty for European importers.

LNG has the potential to reduce at least partially these transit risks; however it is not immune from drawbacks and uncertainties. First, it still accounts for barely 11% of Europe's gas supply. Second, LNG facilities are highly capital intensive. As a consequence, exporters are not able to keep up with increasing facilities in importing countries; as a consequence some re-gasification terminals are underexploited. Third, LNG is sensible to physical threats as much as pipelines.

## Internal security of supply

Checchi et al. (2008) point out that, also the liberalisation process and the completion of the internal market add some internal concerns, in addition to those deriving from Europe's increasing import dependence from non-OECD regions.

They also argue that the main rationale for the creation of the EU single market for natural gas is that higher competition should foster economic efficiency; moreover, allowing customers to choose their supplier, it should push operators to reduce costs and improve the quality of their services. However, they note, moving from centralised to de-centralised decision-making and from volume-signals to price-signals, unless the market is "perfect", could in reality lead to less efficiency in the allocation of gas in the system. Competition may result in a race to the bottom in terms of quality of the system management. .The main concern in terms of the ability of the system to guarantee the security of supply regards the delivery of timely signals and competitive incentives for investment to guarantee secure and reliable gas supply all the way to the final consumer.

## Short-term security: coping with low-probability events

A secure gas supply should be able to meet the demand also in case of a supply disruption or an unexpected event – such as extreme weather conditions or a technical accident. Unless there is the possibility to switch to other sources, a failure to deliver gas on a cold winter day would have serious consequences for most households and, to a lesser extent, for industry. Some instruments have been envisaged to ensure a high degree of supply reliability in case of low-probability events,. The relevant are storage facilities, long-term contracts, flexibility instruments (supply flexibility, interruptible contract, etc), the interconnection of national grids,, and the diversification of supply sources and routes (IEA, 2004). Checchi et al. (2008) note that while in the past, the gas industry has had a very good record in covering low-probability/high-impact events by providing the aforementioned instruments and passing them to customers, the liberalisation of the European gas market might undermine some of these instruments contributing to the insecurity of supply. The source of concern are two: the structure of the contract that will became predominant in liberalised market (whose balance will probably shift towards short term contracts), and the reduced incentive to invest in storage facilities and spare capacity under liberalised market conditions.[9]

## 6.3 Coal

Coal is by far a lesser source of concern in terms of security of supply for the EU than oil and gas. It is more abundant in terms of resources, regionally more diversified, and although experiencing a rising demand globally, less relevant for the EU, where primary coal demand has decreased considerably since the 1980s, largely due to the switch from coal- to gas-fired power production in Western Europe and economic transition in the East, and is projected to stay constant for the next decades. On the negative side, domestic coal will continue to decrease within the EU27, resulting in increasing dependence on imports. Dependence is less an issue compared with gas and oil because coal market is a truly global, open and well-functioning one, not dominated by a single supplier such as OPEC. Finally, coal is relatively safe to transport and store. All these factors contribute to the assessment that European import dependency does not pose an elevated risk to its uninterrupted supply of coal in the long-run. However, there may be some risks in the short-run.

Temporary supply disruptions may occur although its just-in-time supply chains are able to respond quickly to demand. More worrying is the risk potentially stemming from changing global demand structures, such as those implied in the fast increase in Chinese demand for coal that resulted recently into China turning into a net coal importer.

Long term security risks are linked to the environmental impacts of the coal chain. Local impacts may reduce the acceptability of mining sites and coal fuelled power plants, while global impacts like those related to green house emissions may reduce the appeal of investing in coal fuelled plants, or introduce the additional requirement (and financial burden) of investing in emission abatement (and eventually of finding viable solutions for CCS). In view of Europe's ambitious energy and climate change targets, clean coal technologies must be developed quickly, otherwise coal cannot continue to play a major role in Europe's energy mix.

## 6.4 Nuclear

Nuclear energy mostly exhibits high reliability and has substantial potential to contribute to climate change mitigation. At the same time it faces acceptance problems due to concerns in terms of risk of catastrophic events, nuclear proliferation issues and uncertainties related to the implementation of waste disposal facilities. For this reason EU member states are deeply divided about nuclear energy, although recent events such

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[9] Deliverable 3.1 (Checchi et al., 2008) analyses these issues in closer detail

as rising oil prices, increasing energy demand and the increasing concern about carbon emissions is slowing eroding the adamant opposition of some governments. Therefore, nuclear energy should be addressed in the broader context of comprehensive sustainability assessment for both current (Hirschberg, 2008; Hirschberg et al., 2004b) and future systems (Schenler et al., 2008). Within SECURE, the pros and cons of nuclear energy are presented in Deliverable 3.1 (Checchi et al., 2008). In this chapter we focus briefly on those characteristics of this energy vector that imply potential threats to energy security.

In particular, fuel import dependency is not considered to be a critical issue for nuclear energy at present. Known conventional Uranium resources are sufficient for several decades, depending if a price of up to 40, 80 or 130 USD per kg U is assumed. When unknown conventional resources are included the cumulated range of Uranium is already more than 200 years, based on current consumption. Consideration of unconventional resources (i.e. Uranium in phosphates and sea water) expands the range to about 600 and 80'000 years. Use of the large potential of lower grade and unconventional resources is probably affordable since the price of raw Uranium is a small contributor to overall nuclear electricity cost. Furthermore, the use of breeder reactors is a real technological option that may be pursued in the future, which in turn would further increase the lifetime of the Uranium resource. For more detailed information see OECD/NEA and IAEA (2007) and Hirschberg et al. (2005).

The main reasons why the use of nuclear energy can undermine energy security are due to the physical characteristics of the process that if not duly controlled, have the potential to release high amount of radiation, as a consequence of unlikely but not impossible events. This results in particular concerns about the safety of the whole process and on the potential for nuclear proliferation, These concerns beside underlining the need of taking high care in the design and operation of the nuclear energy chain, can also be manifested by the hostile attitude of parts of the general public to the installation of this technology on the territory, and can thus reduce the potential of this energy option.

Finally, public opinion and perception of nuclear power is fundamental to the future developments of European nuclear policy because public opposition further increases the risks of undertaking a nuclear project. The 2007 Eurobarometer reported indeed that 53% of European citizens still consider nuclear energy as a problem rather than a solution for their security of supply.

## 6.5 Renewable energy sources

Notwithstanding their increasing penetration in European energy markets, renewable energy still plays a limited role in the EU (about 8.5% of EU total primary energy supply). The promotion of renewable sources has always been a priority of EU energy policy in the last decade. The last significant step in this direction is the approval by the European Parliament (on December 17, 2008) of a Directive on the promotion of the use of energy from renewable sources which will be the legislative act to implement the 20% renewables target.

The attention given by the Commission to renewable energy sources follows the three pillars approach of the Green Paper Energy that combines sustainability, competitiveness and security of supply. On this regard, indeed small hydro and wind for self-production tend, to be dispersed and not to involve major security risk in terms of exposure to sabotage (IEA, 2007). Also, electricity supply in rural and isolated regions might be improved cost-effectively by on-grid and distributed generation options that may rely on renewable sources for electricity generation.

On the other hand, renewable sources are not immune from drawbacks from the point of view of short term and long term energy security[10]. "Wind is intermittent because turbines do not operate when wind speed is either low or too high since there are risks of damage for the turbines. Solar photovoltaic is subject to seasonal variation from winter to summer as well as to daily variation from diurnal to night time. In addition, PV is not dispatchable, meaning its output cannot be controlled and scheduled to respond to the variable consumer demand for electricity (IEA, 2007). The possible lack of continuity in electricity generation from wind and solar energy requires a backup capacity from more flexible sources. This could ideally be provided by other renewables such as large hydro but, more realistically, the difference would be met by fossil fuels such as natural gas or coal. Natural gas however increases import dependency further while coal has high $CO_2$ emissions. Back-up capacity increases costs of renewable energy.

Moreover, in the long-run, some renewable inputs may become tradable across countries raising import dependence risks. In this regard, biomass is the most eligible source. Its physical characteristics, namely storability and transportability, allow a parallel between security of supply risks of biomass and traditional energy sources, both in terms of physical availability and prices. For biomass, competition risks are worsened by the fact that biomass is used not only for energy uses – such as electricity, heat and transport – but also for food, fibre and chemical production. In turn, this leads to price volatility of biomass inputs. Another import dependency concern is related to solar energy and the on-going discussion to build a large-scale grid to import solar electricity (by concentrating solar power) produced in North Africa and the Middle East. On the one hand, the project would allow Europe to diversify its energy portfolio augmenting the share of a clean energy sources but, on the other hand, imports of solar power from these regions would further increase Europe's dependence from unstable regions. On balance, how much Europe would gain, or possibly lose, in terms of energy security is a matter of discussion".

## 6.6 Electricity

The EU electricity sector is characterised by a remarkable increase of cross-border trades determined by economic trade reasons. The increased utilization of the grid, compared to a relatively slow development (particularly concerning cross-border transfer capacities), could represent one of the major risk for electricity security of supply. It must however be observed that electricity supply is traditionally evaluated in terms of reliability: it is recognized that low levels of investments normally result in unreliable supplies, while excessive investments can result in unnecessarily high security levels and consequently unnecessary expenses with an increase of electricity transmission and distribution tariffs to consumers.

On the technical side two main issues are to be considered. For one thing, electricity is a secondary form of energy; therefore electricity security of supply remarkably depends on fuel security of supply. It is widely recognized that the role of gas in power generation in EU Member States is growing today and will significantly increase in the future, determining risk of insecure supply in case of gas shortages. One of the possible

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[10] See Deliverable 3.1 (Checchi et al., 2008)

solutions for dealing with this risk is fuel substitution in power plants where this substitution is possible. In contrast with the case of electricity demand response, this substitution could have an important social cost, because the "constrained-in" generation is expected to be less competitive and less environmental-friendly than the "constrained-off" production.

The second technical issue to be considered is that electricity security of supply strongly depends also on the investment decisions by transmission and distribution companies. It is widely recognized that low levels of investments normally result in unreliable supplies, while excessive investments can determine unnecessary expenses with a consequent increase of electricity transmission and distribution tariffs to consumers. In a liberalized industry where companies have to justify their expenses to a regulatory or governmental body on the basis of the benefits these expenses provide to consumers, the assessment of Value Of Lost Load (VOLL), jointly with calculations of the Expected Energy not Supplied, is one of the traditional approaches to investigate these benefits. As recent black outs have shown there are strong interdependencies across systems, where accidents "travel" across Europe creating wide interruption of service.

On the regulatory side, Transmission System Operators (TSOs) play a fundamental role in guaranteeing electricity Security of Supply, both at national and international level. Still, they have different missions and regulatory frameworks and also operate under different market rules.

Energy security of electric generation technologies can be evaluated using a Multi-Criteria Analysis framework (MCA) (compare chapter 5). Here we provide a simplified overview for fossil, nuclear and renewable technologies, using the NEEDS criteria and indicator set. Individual indicators are here represented according to a 5-step scale (--, -, 0, +, ++) and not in a fully quantitative manner; and thus should be seen as exemplary demonstration of the potential of this methodological approach. Indicators have been assigned to the three dimensions of sustainability (i.e. environment, economy and society), with those in red that are considered relevant for energy security. A full scope MCA addressing the various components of energy security could be based on the NEEDS indicator set as a starting point, but would have to be modified substantially to meet the specific objectives of the SECURE project. Furthermore, individual technologies need to be characterized and defined to establish specific indicator values, since categories such as renewable energy sources comprise a variety of technologies, which is why only ranges could be assigned for a number of indicators. Table 4 shows indicator results for the environmental, economic and social dimensions of sustainability, based on the NEEDS project, with indicators related to security of supply marked in red.

Table 4: Criteria and indicator set as used within the NEEDS project. Indicators marked in red are related to security of supply.

| Criterion / Indicator | Oil | Natural Gas | Coal | Nuclear | Renewables |
|---|---|---|---|---|---|
| ENVIRONMENT | | | | | |
| RESOURCES | | | | | |
| Energy | | | | | |
| Fossil fuels[11] | -- | - | -- | ++ | ++ |
| Uranium[12] | ++ | ++ | ++ | -- | ++ |
| Minerals | | | | | |
| Metal ore | ++ | ++ | ++ | ++ | -- to + |
| CLIMATE | | | | | |
| Carbon dioxide emissions | -- | - | -- | ++ | 0 to ++ |
| ECOSYSTEMS | | | | | |
| Normal operation | | | | | |
| Biodiversity | - | 0 | -- | ++ | - to ++ |
| Ecotoxicity | - | 0 | -- | ++ | -- to ++ |
| Air pollution | - | 0 | -- | ++ | -- to ++ |
| Severe accidents | | | | | |
| Hydrocarbons | -- | ++ | ++ | ++ | ++ |
| Land contamination | ++ | ++ | ++ | -- | ++ |
| WASTE | | | | | |
| Chemical waste | - | ++ | -- | + | -- to ++ |
| Radioactive waste | ++ | ++ | - to + | -- | ++ |
| ECONOMY | | | | | |
| CUSTOMERS | | | | | |
| Generation cost | 0 | 0 | + | ++ | -- to + |
| SOCIETY | | | | | |
| Direct jobs | - | - | 0 | - | 0 to ++ |
| Fuel autonomy | -- | -- | 0 | + | ++ |
| UTILITY | | | | | |
| Financial | | | | | |
| Financing risk | ++ | + | + | -- | -- to + |
| Fuel sensitivity | -- | -- | 0 | ++ | ++ |
| Construction time | ++ | ++ | + | -- | -- to ++ |

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[11] The evaluation employed in NEEDS only addressed consumption of **fossil fuels** in terms of primary energy. Extent of resources has not been taken into account. This would be more favorable to coal technologies.

[12] The evaluation employed in NEEDS only addressed consumption of **uranium** in terms of primary energy. Extent of resources has not been taken into account. This would be much more favorable to nuclear.

| Criterion / Indicator | Oil | Natural Gas | Coal | Nuclear | Renewables |
|---|---|---|---|---|---|
| Operation | | | | | |
| Marginal cost | -- | -- | - | ++ | ++ |
| Flexibility | ++ | ++ | + | ++ | -- to ++ |
| Availability | ++ | ++ | ++ | ++ | -- to ++ |
| SOCIAL | | | | | |
| SECURITY | | | | | |
| Political continuity | | | | | |
| Secure supply | -- | -- | + | + | ++ |
| Waste repository | 0 | 0 | - | - | 0 to ++ |
| Adaptability | 0 | + | 0 | -- | - to + |
| POLITICAL LEGITIMACY | | | | | |
| Conflict | 0 | 0 | - | -- | - to ++ |
| Participation | - | - | - | -- | - to ++ |
| RISK | | | | | |
| Normal risk | | | | | |
| Mortality | - | 0 | -- | ++ | - to ++ |
| Morbidity | - | 0 | -- | ++ | - to ++ |
| Severe accidents | | | | | |
| Accident mortality | -- | 0 | - | ++ | - to ++ |
| Maximum fatalities | - | 0 | 0 | -- | -- to ++ |
| Perceived risk | | | | | |
| Normal operation | -- | - | -- | - | ++ |
| Perceived accidents | - | - | - | -- | ++ |
| Terrorism | | | | | |
| Terror-Potential | -- | -- | 0 | 0 | - to ++ |
| Terror-Effects | - | - | 0 | -- | -- to ++ |
| Proliferation | ++ | ++ | ++ | -- | ++ |
| RESIDENTIAL ENVIRONMENT | | | | | |
| Landscape | - | - | -- | 0 | - to ++ |
| Noise | - | - | -- | + | - to ++ |

# 7. Conclusions

- This deliverable aimed to provide an overview of the different methods used to assess energy security risks from different viewpoints, and how they can be used to create valuable insights and potential recommendations within the SECURE project.
- A consistent and at the same time operational definition of energy security is needed as a necessary prerequisite that also is in line with the specific objectives of the SECURE projects.
- Comprehensive characterization of individual energy technologies provides another important step to generate adequate and comparable results.
- Energy security risks can be evaluated by a variety of methodological frameworks and analytical tools, which however should rather be seen as complementary than competing.
- Comparative risk assessment focuses on aspects that can be addressed in a (mostly) quantitative manner using an engineering or natural sciences perspective, whereas risk aversion includes assessment of subjective elements.
- Cost assessment of risk aversion can be achieved by application of econometric methods. While the methodology is well established in the literature, the resulting quantification, and its applicability to real world issues still are at risk of being disputed and not accepted by some stakeholders.
- Multi-Criteria Analysis (MCA) combines a set of technology specific indicator values and stakeholder preferences within an interactive framework, which is particularly useful to support the complex decision processes present in the formulation of energy policies.

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