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We review the multitude of definitions of energy security. They can be characterized according to the sources of risk, the scope of the impacts, and the severity filters in the form of the speed, size, sustention, spread, singularity and sureness of impacts. Using a stylized case study for three European countries, we illustrate how the selection of conceptual boundaries along these dimensions determines the outcome. This can be avoided by more clearly separating between security of supply and other policy objectives. This leads us to the definition of energy security as the continuity of energy supplies relative to demand. If security is defined from the perspective of private utilities, end consumers or public servants, the concept could further be reduced to the continuity of specific commodity or service supplies, or the impact of supply discontinuities on the continuity of the economy.

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Conceptualizing Energy Security

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August 2011

1 Abstract

Energy security[2] is one of the main targets of energy policy. However, the term has not been clearly defined, which makes it hard to measure and difficult to balance against other policy objectives.
We review the multitude of definitions of energy security. They can be characterized according to the sources of risk, the scope of the impacts, and the severity filters in the form of the speed, size, sustention, spread, singularity and sureness of impacts. Using a stylized case study for three European countries, we illustrate how the selection of conceptual boundaries along these dimensions determines the outcome. This can be avoided by more clearly separating between security of supply and other policy objectives. This leads us to the definition of energy security as the continuity of energy supplies relative to demand. If security is defined from the perspective of private utilities, end consumers or public servants, the concept could further be reduced to the continuity of specific commodity or service supplies, or the impact of supply discontinuities on the continuity of the economy.

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[2] Energy Security, the Security of Energy Supplies or more shortly Security of Supply are used as synonyms both in this article and in other parts of literature.

2 Introduction

Security of supply is an important goal of energy policy in many countries around the world. The three pillars of the European Union's energy policy are efficiency, sustainability and security of energy supplies (European Commission (EC) 2008; European Commission (EC) 2006) and a few years before his election as President, Barack Obama said: *"We need a national commitment to energy security, and to emphasize that commitment, we should install a Director of Energy Security to oversee all of our efforts." (Senator Barack Obama, February 28, 2006; Governor's Ethanol Coalition Washington, DC)*

Despite the high importance of energy security in policy, several authors have pointed out that the term is not clearly defined. In the words of Löschel et al. (2008): *"The concept of 'security of energy supply', or in short form 'energy security', seems to be rather blurred."* This is echoed by others who claim that *"there is no common interpretation"* (Checchi, Behrens, and Egenhofer 2009) of energy security, or that the concept is *"elusive"* (Kruyt et al. 2009; Mitchell 2002), *"slippery"* or *"difficult"* to define (Chester).

The confusion about energy security is also reflected in political actions. In the U.S. the focus of energy security has traditionally been on the reduction of vulnerability to political extortion, which has lead politicians to call for energy independence and rising shares of renewable energy. In Brazil on the other hand, where the vision of energy independence has already become a reality, there were periods when politicians advocated an increasing share of fossil fuel imports and decreasing shares of renewable energy to promote energy security. For some the goal of energy security is the protection of the poor against commodity price volatility. Others highlight the importance of protecting the economy against disruptions of energy service supplies, by allowing the prices of commodities to rise during periods of scarcity. For some people the goal of energy security is the reliable provision of fuels and the role of nuclear energy is one of enhancing security. For others, energy security is concerned with a reduction of hazards from accidents and proliferation and the expansion of the nuclear industry is a potential threat to energy security.

In the absence of a clear definition, energy security has thus become an umbrella term for many different policy goals. *"There is one thing that has not changed since the early 1970s. If you cannot think of a reasoned rationale for some policy based on standard economic reasoning then argue that the policy is necessary to promote 'energy security'" (Joskow 2009).*

The aim of this paper is twofold. *Firstly,* we want to provide a descriptive overview of the conceptual landscape. Such an overview can be used in order to locate different studies in the wider context. This can facilitate the communication between authors from different fields. It can also help to ensure that there are no unintentional gaps in any particular analysis. And *secondly,* we want to suggest a set of conceptual boundaries that reduce the overlap between the policy goals of energy security, sustainability and economic efficiency. Our intention for these boundaries is to make sure the concept of energy security remains operational so that it can be measured and traded-off against the other policy targets.

We will begin this paper with a literature review of explicit energy security definitions in section 3 and different implicit concepts in section 4 . In section 5 we give an overview of the big picture and summarize the dimensions along which the concepts can be distinguished. In section and 6 we explain dependencies between these dimensions. We conduct a case study focusing on the security of electricity supplies in section 7 to show that the choice of conceptual boundaries has an important impact on the results. The impact of the framing on results is likely to persist if other energy markets are included in the analysis. Based on the previous sections we finally propose conceptual boundaries to distinguish between the policy objectives of energy security, efficiency and sustainability in section 8. Section 9 describes additional limitations of the concept that could be caused by individual perspectives of private utilities, end consumers or public servants. We summarize our observations and draw conclusions in section 10.

3 Overview of Explicit Definitions

There are several competing definitions of supply security. They all include the idea of avoiding sudden changes in the availability of energy relative to demand. However, the definitions show strong differences in the impact measure that is used for the benefits of increased continuity and the level of discontinuity that is defined as insecure. We will discuss the authors in three groups. The first group consist of authors who focus on the concept of commodity supply continuity. The second group consist of authors who introduce additional severity filters. And the third group consists of those authors that extend the scope of the impact measure beyond the continuity of commodity supplies to the continuity of services, the continuity of the economy and impacts on sustainability and safety. We summarize our findings at the end of this section.

A first group of authors defines security as the continuity of energy commodity supplies. As we will see later, this concept is also central to all other definitions of energy security. Examples of definitions that focus on this central concept can be found in publications of the Department of Energy & Climate Change (2009): *"Secure energy means that the risks of interruption to energy supply, are low" (Department of Energy & Climate Change (DECC) 2009).* Other examples include (Scheepers et al. 2007; Lieb-Dóczy, Börner, and MacKerron 2003; Ölz, Sims, and Kirchner 2007; Wright 2005; Hoogeveen and Perlot 2007). The same concept is also used in technical analyses, however, with a different wording that can easily lead to confusion. Technical studies describe the general concept of low interruption risks as "reliability". Reliability is composed of two sub-concepts: system adequacy, which describes the ability of the system to meet the aggregate power and energy requirement of consumers at all times and system security, which describes the ability of a system to withstand disturbances (Makarov, Member, and Moharari 1999; Roy Billinton and Allan 1996). By contrast to the definitions used in (Department of Energy & Climate Change (DECC) 2009) and in the political context, security in the technical context does not refer to the general concept of low interruption risk, but to the sub-concept of system flexibility to adapt to fast changes. In this article the term security refers to the broader concept which is similar to the concept of 'reliability'. The common characteristic of the first group of definitions is the notion, that increases of the relative scarcity level of energy are a sign of insecurity. Whether or not price volatility is a sign of insecurity is disputed. In either case, a big advantage of these concepts is that they can be measured with established indicators of continuity such as the price volatility or the Loss of Load Probability (LOLP) and Expected Energy Unserved (EEU). If security is defined in this way it is obvious that not any level of security is desirable because increased stability usually comes at a price. But there are good frameworks for assessing the trade-off between decreasing volatility and increasing cost in order to determine efficient security levels (Roy Billinton and Allan 1996; Bagen and R. Billinton 2008).

A second group of authors introduce subjective severity filters to distinguish between secure and insecure levels of continuity. The most prominent of these definitions is the one given by the International Energy Agency: *"Energy security is defined in terms of the physical availability of supplies to satisfy demand at a given price" (International Energy Agency (IEA) 2001).* The concept behind this definition seems to imply, that apart from supply interruptions security is only impaired if the scarcity of energy leads to prices above a certain threshold, while the price volatility below that threshold is not relevant. The same or similar definitions have been used in (Vicini et al. 2005; Luciani 2004; Fondazione Eni Enrico Mattei (FEEM) 2008; Yergins 1988; Andrews 2005; Le Coq and Paltseva 2009; Jun, Kim, and Chang 2008).Other examples of subjective severity filters can be found in definitions such as: *„Security is impaired when supplies are reduced or interrupted in some places to an extent that causes a sudden, significant and sustained increase in prevailing prices" (Mabro 2008).* In this example an increasing scarcity or disruption of supplies is only relevant for security if the speed, size and sustention of the price increases are beyond a certain level. Other filter criteria that have been used include the sureness of events which can be foreseeable (Spanjer 2007) or unexpected (Rutherford, Scharpf, and Carrington 2007; McCarthy, Ogden, and Sperling 2007; Department of Trade and Industry (DTI) 2002). An advantage of this type of definition can be seen in the fact that the additional criteria filter out smaller discontinuities that are not important for the security of a country. But the use of subjective severity filters makes the concept of security very imprecise and difficult to measure. Continuity and price levels that are considered as insecure by one country could be completely sufficient for another country and the same is also true for different authors, which is illustrated by the divergence of opinions about suitable scarcity thresholds.

A third group of authors extends the scope of the impact measure. Instead of measuring the continuity of prices and quantities on the commodity market, they extend the impact measure to the price and continuity of services, the impacts on the economy and in some cases the environment.

An extension of the concept to the continuity of services can be found in the study on gas supply security by Noel and Findlater (2010): *"security of gas supply (or gas supply security) refers to the ability of a country's energy supply system to meet final contracted energy demand in the event of a gas supply disruption" (Noel and Findlater 2010).* In their article the 'final contracted energy demand' refers to the demand for heating and cooking, and thus to energy services. This is an interesting alternative to commodity-focused definitions. By defining security in terms of service availability it introduces a weighting of potential commodity supply disruptions according to their impact on the continuity of energy services. Depending on the resilience of the 'end consumer devices' such as cars, heat pumps, light-bulbs and computers which are used to convert commodities into services, a disruption of commodity supplies may or may not lead to disruptions of service supplies. For example a computer that is connected via a UPS[3] device will continue to provide services during short black-outs and a hybrid car with a dual charging unit can continue to provide transportation services even when the supply of one of the fuels is interrupted. Further examples defining security in terms of service availability can be found in (Xianguo Li 2005; Patterson 2008).

The standard definition for the extension of the impact measure to the economy is the one given by Bohi et al. (1996): *"Energy insecurity can be defined as the loss*

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[3] Uninterrupted Power Supply (UPS) devices contain batteries that provide a near-instantaneous backup supply in case of power interruptions

of welfare that may occur as a result of a change in the price or availability of energy" (Bohi, Toman, and Walls 1996). The weighting of impacts by their monetary value is a useful way of aggregating different impact measures for economic decisions. Although the authors deliberately focus on a small set of externalities, this list could be widened if desired. Depending on the context, however, measures about the continuity of commodity or service supplies might still be needed, because they allow stakeholders to perform their own subjective valuation of continuity levels. Further examples for this type of definition can be found in (Lefèvre 2009; Grubb, Butler, and Twomey 2006; Joode et al. 2004).

Some authors such as the Asia Pacific Energy Research Centre propose a further extension of the impact measure to aspects of environmental sustainability: *"This study defines energy security as the ability of an economy to guarantee the availability of energy resource supply in a sustainable and timely manner with the energy price being at a level that will not adversely affect the economic performance of the economy" (Intharak et al. 2007).* Similar definitions are used in (Kruyt et al. 2009; Verrastro and Ladislaw 2007; European Commission (EC) 2000). By including sustainability as a component of supply security the concept is significantly broadened. Although a wider concept is more inclusive it is also increasingly difficult to measure and might render the concept un-operational.

To summarize, we can see that all energy security definitions include the idea of avoiding risks which affect the continuity of the energy commodity supply relative to demand. But some authors suggest different severity filters and a different scope of impact measures to distinguish between secure and insecure changes. The severity filters which have been suggested include the speed, size, sustention, spread, singularity and sureness of impacts. The scope of the impact measure that has been suggested includes the continuity of service supplies, the continuity of the economy and further impacts on the environment or the society. While the severity filters have mostly been defined in terms of the impacts on commodity supply continuity, the same filters can easily be applied to any other impact measure. An example where a severity filter is applied to another impact measure can be seen in the definition by (Grubb, Butler, and Twomey 2006), which includes only sufficiently fast (i.e. disruptive) impacts on the economy: *"security of supply … can be defined as a system's ability to provide a flow of energy to meet demand in an economy in a manner and price that does not disrupt the course of the economy".* As we will see later in our case study, the impact measure to which a filter is applied can make a big difference. For example some threats that can cause phase changes in the continuity of commodity supplies may not disrupt the continuity of services such as heating and transportation.

4 Overview of Implicit Definitions

In many articles, security of supply is not defined explicitly. Nevertheless, based on the topics and indicators that are mentioned by different authors we can draw conclusions about the implicit definitions of supply security underlying their work. We find that risk sources are often analysed separately. We will group the discussion according to the level of separation between different risk sources. The first level of separation is the treatment of risk sources as separate categories within a composite indicator. The second level of separation is the usage of different indicators for each risk source. The third and strongest level of separation is the discussion of different risk sources in separate debates with conflicting vocabulary. We will discuss each of these levels of separation with examples below and summarize our findings at the end of this section.

A first level of separation between human, natural and technical risk sources is their treatment as separate categories within a composite indicator. Examples for this can be seen in the distinction between different technologies (i.e. technical risk sources), geographical regions (i.e. natural risk sources) and countries (i.e. human risk sources) that underlies the widespread calculation of concentration measures or in the principal component analysis of simple indicators that represent different risk sources (Gupta 2008).

A second level of separation between risk sources is the usage of indicators that address different individual risk sources. For example there are separate indicators for some human risk sources such as geopolitical risk and political instability (Net Energy Import Dependency, Political Stability Rankings), indicators for natural risk sources such as resource depletion (Resource Estimates and the Reserve/Production Ratio) and indicators for technical risk sources such as mechanical and thermal failure (Forced Outage Rates) and emissions (Non-Carbon Share). A description of these and other indicators can be found in (Kruyt et al. 2009).

A third level of separation between risk sources is their analysis in completely separate debates. For example infrequent events such natural disasters are usually analyzed as topics of their own. One of the main reasons for this is probably that the effect on the energy supply chain represents only a small portion of the total impacts. But even risks with an impact closely centred on the energy supply chain are often discussed in separate debates. The most striking example of this is the isolated discussion of technical risk sources, which is not only treated in separate publications but also uses a different terminology (Makarov, Member, and Moharari 1999; Roy Billinton and Allan 1996; Wenyuan Li 2005; Guo et al. 2009). As mentioned earlier, instead of talking about 'energy security', articles focusing on technical risk sources talk about the 'reliability' of supply. Another example can be seen in the analysis of threats arising because of the links between the energy infrastructure and other infrastructure systems. Instead of talking about 'energy security', these articles talk about 'critical infrastructure protection'. In a similar way, although less pronounced, articles that focus on the measurement of different natural risk sources often talk about 'variability or 'intermittency' risk (Kooten 2009; Skea et al. 2008)or the 'depletion' of reserves. Further topics which are often treated on their own are the measurement of human risk sources such as strategic withholding (Holz, von

Hirschhausen, and Kemfert 2008; Boots and Rijkers 2000), capacity underinvestment (Ikonnikova 2006) and sabotage and terrorism (Salmerón and Baldick 2004; Baldick and Salmerón 2009). The term security itself is most frequently used by articles that focus on geopolitical risks.

An overview of the risk sources that are distinguished in literature is given in the upper part of Figure 1. By combining the indicators for different risk sources, the composite indicators and other broad studies suggest that the different risk sources are all important for the security of supplies. The separate discussions on each risk are therefore still part of the same larger debate on supply security (Fondazione Eni Enrico Mattei (FEEM) 2008; Joode et al. 2004; Mabro 2008; Department of Trade and Industry (DTI) 2006; Mitchell 2002). This also makes sense from the perspective of end consumers, because it doesn't make a difference whether discontinuities of supplies are a result of human, natural or technical risks.

5 Proposed Dimensions of Supply Security

Despite the confusion about the concept of energy security, there seems to be an agreement that security is concerned with risks. Some authors mention this explicitly (Rutherford, Scharpf, and Carrington 2007; Ölz, Sims, and Kirchner 2007; Wright 2005; Keppler 2007; Lieb-Dóczy, Börner, and MacKerron 2003), but as we have seen the idea is also implicit in the other articles on the topic. This is in line with the general definition of *"security"* according to the Oxford English Dictionary, which defines security as *"the condition of being protected from or not exposed to danger".*

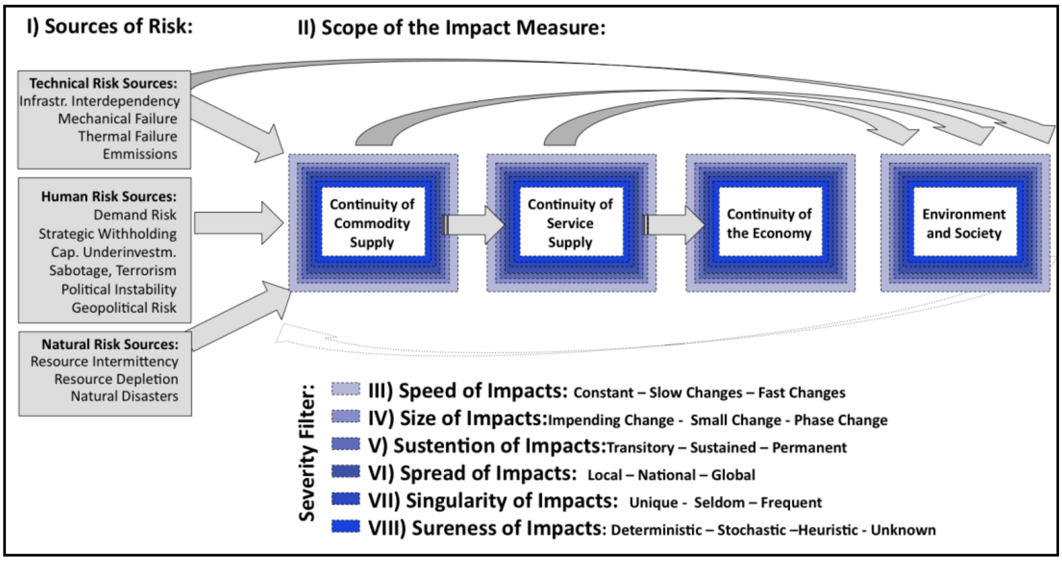
In the case of energy security these threats are related to, i.e. caused by having an impact on the energy supply chain. The common idea behind all the different definitions of energy security can thus be described as "*the absence of, protection from or adaptability to threats that are caused by or have an impact on the energy supply chain".*

It is immediately obvious that the number of threats that could be considered under this definition is huge (Gnansounou 2008). Studies therefore usually limit the analysis to a subset from the list of possible threats. These limitations are the main cause of conceptual differences between the authors. They differ along one or several of the following eight dimensions

- **i. sources of risk**
- **ii. scope of the impact measure**
- **iii. speed of threat impacts**
- **iv. size of threat impacts**
- **v. sustention of threat impacts**
- **vi. spread of threat impacts**
- **vii. singularity of threat impacts**
- **viii. sureness of threats**

Dimensions i. and ii. describe the boundaries of an observation system and the remaining six dimensions iii. to viii. describe severity filters that are used to determine which threats are relevant for the analysis. The list of filter criteria is not exhaustive. It includes dimensions that have not been mentioned in the previous sections and could be extended further if required. The severity of a threat increases with the speed, size, sustention and spread as well as with decreasing singularity and sureness of the impacts. Different values along these dimensions are associated with different concepts of energy security. This is true not only for the size of severity thresholds but also for their location, i.e. the impact measure to which they apply. Figure 1 gives an overview of the dimensions. We discuss each of the dimensions with examples below.

Figure 1: Dimensions of Energy Security.



The ***sources of risk*** describe which types of risk are considered by a study. We can distinguish between three broad categories. Examples for supply chain endogenous *technical risk sources* are the failure of infrastructure components such as transmission lines, power plants or transformers due to a failure of interdependent infrastructure such as communication networks, or due to mechanical or thermal failure. Examples for *human risk sources* are events such as demand fluctuations, strategic withholding of supplies, capacity underinvestment, sabotage and terrorism, political instability and geopolitical risks like wars and export embargos. Examples for *natural risk sources* are events such as stochastic intermissions of renewable energy supplies, the depletion of fossil fuel stocks and natural disasters. For each of these categories further examples can be found and the categorisation can be re-fined. In literature *natural* and *human* risk sources have been pointed out as different aspects of supply security in (Kruyt et al. 2009; Intharak et al. 2007), where they are referred to as 'availability' and 'accessibility'. As discussed in the previous section, many studies focus on a subset of these risk sources source or at least don't treat all of the risks with the same level of detail.

The ***scope of the impact measure*** describes how energy security is measured. We can distinguish between four broad categories. The majority of risks that have an impact on the supply chain affect the *continuity of the commodity supplies* by changing the availability or the price of energy commodities such as oil, gas, coal or electricity. Depending on the resilience of the end-consumer devices to interruptions of input commodities, changes in the availability and price of different commodities affect the *continuity of service supplies* by changing the availability or the price of energy services such as heating, lighting, communication or transport. Depending on the disutility of service disruptions and repercussions throughout the economy, changes in the availability and price of energy services eventually have an impact on the *economic continuity* of a country. Apart from influencing the economy, the provision and consumption of energy commodities will also have an impact *on human safety and environmental* *sustainability*, for example in the form nuclear proliferation and water pollution. In literature the impacts of energy supplies on welfare or the environment and society have been pointed out as aspects of supply security in (Kruyt et al. 2009; Intharak et al. 2007), where they are referred to as 'affordability' and 'acceptability'.

The ***speed of threat impacts*** refers to the time-scale on which the impacts of risk materialize. We can distinguish between three different speeds. Examples for a *constant scarcity* can be seen in the renewable energy potential of a country. Examples for *slow stresses* would be the depletion of fossil fuels, the accumulation of greenhouse gases or growing demand. Examples for *fast shocks* would be political disruptions, technical failure or intermittency. The difference between shocks and stresses has been explored in (Stern 2002) where they are described as 'short-term' and 'long-term' impacts. Most studies focus on a single time scale.

The ***size of threat impacts*** describes the magnitude of changes in scarcity within the affected area. We can distinguish three different levels. Threats like reduced reserve margins can be seen as *impending changes*, because they indicate the increased likelihood of negative impacts without having themselves a direct impact on consumers. Threats like price volatility or marginal rises of global temperature can be seen as *small changes* in the sense that they have an impact on consumers but don't change the way the system works. And threats like delivery disruptions or global warming of more than 2°C can be seen as *phase changes*, because in addition to having a direct impact on consumers they also change the way in which the system works. The importance of size as a defining criterion can be seen in the fact that some authors include all levels of price (change) within their definition (Scheepers et al. 2007; Jamasb and Pollitt 2008; Spanjer 2007), others include only certain levels (or changes) of price (Rutherford, Scharpf, and Carrington 2007; Keppler 2007; Andrews 2005; Le Coq and Paltseva 2009; Mabro 2008; Grubb, Butler, and Twomey 2006; Department of Trade and Industry (DTI) 2002; Joskow 2005) and yet others don't include price risk at all but only mention interruptions (Wright 2005; Lieb-Dóczy, Börner, and MacKerron 2003; Noel and Findlater 2010; McCarthy, Ogden, and Sperling 2007; Nuttall and Manz 2008).

The ***sustention of threat impacts*** describes the duration during which the impacts of a threat persist. We can distinguish three different levels. Threats like small interruptions and short-term price volatility usually have a *transitory* impact. Both threats that occur at a slower speed and fast threats that exceed a certain size have a *sustained* impact that lasts for a considerable amount of time. In some cases, like the depletion of fossil fuels, the impact of threats could be *permanent* in the sense that it is impossible for the system to return to the state in which it was before the threat occurred. An explicit reference to the sustention of impacts as defining criterion can be found in (Mabro 2008).

The ***spread of threat impacts*** describes the size of the largest geographical unit that is simultaneously affected. We can distinguish three different levels. Threats like technical component failures usually have an impact on a *local level* that can range from individual households to whole regions within a country. Disruptions of exports due to political risk usually simultaneously affect an import country as a whole on a *national level*. Some environmental threats such as climate change or solar storms affect all countries simultaneously and therefore have impacts on a *global* level. Apart from the threat itself, the spread of threat impacts is also determined by the geographical size of political units (sea-level rises are a national threat for the Bangladesh but only a local threat for neighbouring India) and the existence of virtual or physical sub-markets as in the case of locational marginal pricing or physically disconnected parts of pipeline and transmission networks which reduce the spread of price risks. The spread of impacts has not been discussed widely in literature. However, we believe that it is an important dimension for determining the administrative level at which the provision of security should be coordinated.

The ***singularity of threat impacts*** describes their frequency of recurrence. We can distinguish three different levels. Threats like fuel depletion, anthropogenic climate change and nuclear wars are *unique* in the sense that they have not been experienced before. Threats like political disruptions and natural catastrophes have happened in the past but are rather *infrequent*. Threats such as alterations of wind-speeds or many types of technical faults on the other hand are relatively *frequent*. In literature, infrequent or unique events are often analysed separately from more frequent events. An example for a reference that includes the singularity of threats as a defining criterion is the article by (Stern 2002) which distinguishes between 'operational' (i.e. frequent) and strategic (i.e. infrequent) risks.

The ***sureness of threats*** describes the level of uncertainty about them. We can distinguish four different levels. Threats can be *predicted*, as in the case of fuel depletion, where the end of production from existing wells can be calculated based on assumptions about extraction rates. Threats can be *probabilistic*, as in the case of resource intermittency or technical failure, where the time of occurrence is usually not known but the probability can be calculated with reasonable precision based on past experience. Threats can be expected but so hard to predict, that it is debatable whether a probability of occurrence reflects more than a *heuristic*, as in the case of political disruptions or terrorist attacks. And finally threats can be *unknown*, as in the case of anthropogenic global warming, which was not discovered as a potential risk until its impacts started to be felt. More detailed characterizations of uncertainty can for instance be found in (Walker et al. 2003). References to the sureness of threats as defining criterion can be found in articles where the insecurity is limited to either unexpected interruptions and price increases(Rutherford, Scharpf, and Carrington 2007; McCarthy, Ogden, and Sperling 2007; Department of Trade and Industry (DTI) 2002) or foreseeable events (Spanjer 2007). Apart from that an implicit distinction can be seen in the fact that with the exception of approaches based on diversity (Stirling 2007) or the precautionary principle unexpected risks are not included in the analysis.

6 Interdependencies between the Dimensions

So far we have been treating the conceptual dimensions in isolation. However, there are several interdependencies, in particular between the dimensions describing the severity filter. Some of these dependencies will be discussed below. If the value along one of the dimensions was completely determined by the value along another dimension, it would not make sense to consider these dimensions as separate criteria. Rather they should be seen as different forms of describing the same concept. For each of the interdependencies, we therefore also give a counterexample, which shows, that it makes sense to distinguish the conceptual dimensions and treat them as separate criteria.

Threats that are faster often cause a larger impact size because the system has less time to adapt. This is one of the reasons why many authors are focused on supply disruptions and worry less about gradual depletion. But if adaptation is not possible, for example because society is not able to find substitutes for depleting resources, a gradual stress would eventually also lead to disruptions.

There is a tendency to be less sure about more singular threats, because there is less measurement data available for predictions. For example events such as anthropogenic climate change, which have not been experienced in the past, are very hard to predict. Events that occur with a high frequency, on the other hand are very unlikely to be completely unknown. But there are also counterexamples in the form of very infrequent events that can be predicted with high precision, such as solar storms and eclipses, and highly frequent events that are still hard to predict such as intermittent generation from renewable sources.

In a similar way there is a connection between the singularity and the speed of a threat. Constant scarcity can either be seen as unique in the sense that it cannot recur because it never goes away, or as highly frequent, in the sense that it recurs at every step of the time-resolution. Threats which occur at a slow speed cannot occur with a high frequency simply because it takes too much time for them to repeat. But the reverse is not true as fast events can both be frequent, as in the case of diurnal variations of solar irradiation, and infrequent such as floods that can build up at a similar speed.

And finally the geographic spread of impacts usually increases their scope. While the cumulated damage from commodity price increases for a small number of consumers will not have a tangible impact on the economic output of a country, simultaneous commodity price increases for all consumers can strongly influence the continuity of the economy. But the reverse is not true, as the scope of impacts can be equally wide if the smaller spread of threats is compensated by a larger impact size at the local level. For example blackouts that affect only parts of a country or catastrophic accidents with severe impacts at the regional level will also affect the continuity of a country's economy as a whole.

7 Case Study: Result of Using Different Concepts

Measuring the security of energy supplies from all fuels requires a very broad analysis. In practice, quantitative studies therefore often focus on a particular energy form and indicate this by talking about the security of gas, oil or electricity supplies instead of energy security. This reduces the data requirements and the complexity of the analysis. The concepts that were derived in the previous sections describe the security of energy supplies in general but can also be applied to the specific case of a single commodity.

In this section we illustrate the practical importance of the conceptual framing for the results of an analysis by comparing the security of electricity supplies in the UK, Austria and Italy for different energy security concepts. In order to keep it simple, the measures that we use as representatives for the different concepts are very rough approximations. More detailed assessments will change the numerical values of individual countries, but should on average not lead to a convergence or divergence of the rankings across different concepts. An overview of the measures and the corresponding energy security concepts is shown in Table 1. We will discuss each of these measures in a separate paragraph below and present the results of using these measures at the end of this section.

Table 1: Overview of measures used to quantify energy security and description of associated energy security concept along conceptual dimensions.

ID	Measure for Energy Security	Sources of Risk	Scope of Impacts	Speed of Impacts	Size of Impacts	Sustention of Impacts	Spread of Impacts	Singularity of Impacts	Sureness of Impacts
0)	Electricity SAIDI Including All Events	-Natural -Technical -Human	-Electricity Commodity Continuity	-Fast	-Phase Changes	-Transient -Sustained	-Local -National -Global	-Unique -Infrequent -Frequent	-Deterministic -Stochastic -Heuristic -Unknown
1)	Electricity SAIDI Excl. Except. Events	-Technical -Unexcept. Natural	'-Electricity Commodity Continuity	-Fast	-Phase Changes	-Transient -Sustained	-Local -National -Global	-Frequent	-Deterministic -Stochastic
2)	Heat SAIDI	-Natural -Technical -Human	-Heating Service Continuity	-Fast	-Phase Changes	-Transient -Sustained	-Local -National -Global	-Unique -Infrequent -Frequent	-Deterministic -Stochastic -Heuristic -Unknown
3)	GDP Loss Caused by Ele.SAIDI	-Natural -Technical -Human	-Electricity Economic Continuity	-Fast	-Phase Changes	-Transient -Sustained	-Local -National -Global	-Unique -Infrequent -Frequent	-Deterministic -Stochastic -Heuristic -Unknown
4)	CO2 per Capita	-Natural -Technical -Human	-Electricity Environmental Sustainability	-Fast	-Gradual Change -Phase	-Sustained -Permanent	-Global	-Unique	-Deterministic -Stochastic -Heuristic
5)	Renewable Energy Potential	-Natural -Technical -Human	'-Electricity Commodity Continuity	-Constant	-Phase Changes	-Permanent	-Local -National -Global	-Unique	-Deterministic -Stochastic -Heuristic -Unknown
6)	Electricity SAIFI Trend	-Natural -Technical -Human	'-Electricity Commodity Continuity	-Slow	-Phase Changes	-Sustained -Permanent	-Local -National -Global	-Unique -Infrequent	-Deterministic -Stochastic -Heuristic -Unknown
7)	Electricity Price Trend	-Natural -Technical -Human	'-Electricity Commodity Continuity	-Slow	-Gradual Change	-Sustained -Permanent	-Local -National -Global	-Unique -Infrequent	-Deterministic -Stochastic -Heuristic -Unknown
8)	Electricity Price Volatility	-Natural -Technical -Human	'-Electricity Commodity Continuity	-Fast	-Gradual Change	-transient -Sustained	-Local -National -Global	-Unique -Infrequent -Frequent	-Deterministic -Stochastic -Heuristic -Unknown

As a base case we use the historical system average interruption duration index (SAIDI) of electricity supplies, which is the quotient between the cumulated number of minutes during which individual customers were disconnected from electricity supplies and the number of customers in the system. The data for this rating can be found in the appendix 12.2.1. Historically, the majority of outages recorded in these indices have been due to distribution network failures. However, if events such as natural disasters, an export embargo of primary energy sources or sabotage of the energy infrastructure had led to customer disconnections, they would also have shown up in the SAIDI. If the SAIDI is calculated on the basis of all interruptions, including those caused by such exceptional events, it therefore represents the concept of electricity commodity supply continuity taking into account risks from all sources. The focus of the SAIDI on forced, physical disconnection implies a limitation of the concept on fast, phase changing events. The sustention of impacts can be either transient or sustained, depending on the size of the outage. The geographical spread of the risks that are captured by the historical SAIDI can be anything from a local to a global event. While forecasts of expected outage times usually neglect highly uncertain and infrequent events, the historical realisations we use were drawn from a distribution that includes all levels of impact spread, singularity and sureness.

The first variation of the base-case concept consists in selecting a certain subset of risk sources. Instead of the historical values of the SAIDI of electricity including all events we now use the SAIDI excluding exceptional events. The data for this rating can be found in the appendix 12.2.2. Conceptually the SAIDI excluding exceptional events roughly corresponds to the base case but selecting only technical and some of the natural risk and filtering out human risk sources such as strikes and export embargos for fuels, sabotage and terrorism or other unique or highly infrequent as well as heuristic or unknown risks.

The second variation of the base-case concept consists in extending the scope of the impact measure to the continuity of service supplies. We calculated the SAIDI of heat supply by weighting the SAIDIs for gas and electricity based on the assumption that all heating demand in a country that is provided by gas is interrupted if either electricity or gas is interrupted, because without electricity the gas heating controllers and warm water pumps cease to work, electricity based heating is only interrupted if there is no electric power and all other heating technologies are perfectly available due to the possibility to store the fuels. The data for this rating can be found in appendix 12.2.3. A more refined estimation would have to make more detailed distinctions between the heating technologies and include an assessment of household specific vulnerability to commodity supply disruptions. Conceptually the SAIDI of heat corresponds to the base case, except that the scope of the impact measure is extended to the continuity of heating supply.

The third variation of the base-case concept is illustrated by extending the scope of the impact measure to the impact on the economy caused by discontinuities of commodity supplies. We use the continuity of GDP as a proxy for this concept. The percentage of the GDP that is lost due to electricity interruptions is calculated based on the customer average interruption duration index (CAIDI), the system average interruption frequency index (SAIFI), the sector specific damage functions of industry, services and households as well as their contribution to the total GDP of each country. The data and calculation steps can be found in appendix 12.2.4. A more refined estimation would have to measure the interruptions experienced by each sector rather than assuming that interruption durations are equally spread between the different sectors and the hours of a year. Conceptually the GDP loss caused by interruptions corresponds to the base case, except that the scope of the impacts is extended to the continuity of the economy.

The fourth variation of the base-case concept consists in extending the scope of the impact to impacts on the environment. We use the per capita CO_2 emissions as a proxy for this concept. The data for the different countries can be found in appendix 12.2.5. It is clearly an incomplete representation of the concept. A more detailed analysis would have to represent the vast amount of other potentially harmful impacts on the society or the environment and aggregate them in some way in order to arrive at a single, cardinal measure of insecurity. Apart from the extension of the impact measure, the conceptual deviations from the base-case consist in the evaluation of gradual, but sustained or permanent changes, which have a global effect and are unique in the sense that they have not been experienced before.

The fifth variation of the base-case concept consists in focusing on threats in the form of constant scarcity rather than impacts that change at a fast speed. As a measure for this we use the annual solar and wind energy potential of a country, which is limited by its land area and climatic conditions. The data for the different countries can be found in appendix 12.2.6. It is clearly an incomplete representation of the concept. A more detailed analysis would have to include all the other currently known energy sources. Apart from the different speed of impacts, the conceptual deviations from the base case consist in a focus on permanent and unique impacts. At least if we assume that renewable energy potentials don't change, since otherwise they wouldn't qualify as examples of constant scarcity.

The sixth variation of the base-case concept consists in focusing on threats in the form of slow stresses rather than impacts that change at a fast speed. As a measure for this we used the trend of electricity prices between 2003 and 2007.The data for this can be found in appendix 12.2.7. A more detailed analysis would have to include a larger dataset. Apart from the different speed of impacts, the conceptual deviations from the base case consist in a focus on more gradual changes, which due to their slow impact speed are necessarily more sustained and less frequent. Since some of the respective countries don't use locational pricing, the threat impacts are simultaneously spread on a national level.

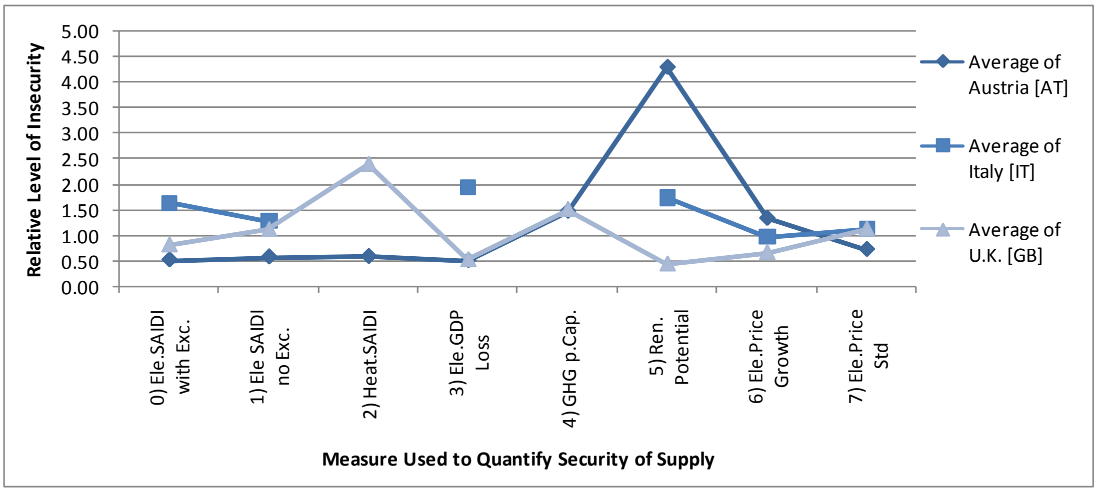
The seventh variation of the base-case concept consists in focusing on fast but gradual changes rather than fast phase-changes. As a measure for this we used the volatility of half-yearly electricity prices between 2003 and 2007. The data for this can be found in appendix 12.2.7. A more detailed analysis would have to use a higher resolution. The only conceptual deviation of this measure from the base-case consists in the different size of threat impacts, as the price change implied by a disruption is usually not reflected in market prices.

Table 2: Resulting energy security levels using different measures.

	0) Ele.SAIDI with Exc. [min/year] 2002-2007	1) Ele SAIDI no Exc. [min/year] 2002-2006	2) Heat. SAIDI [min/year] 2007	3) Ele.GDP Loss [%GDP] 2007	4) GHG p.Cap. [t CO2/year] 2007	5) Ren. Potential [TWh/a] 2007	6) Ele.Price Growth [%of mean] 2000-2007	7) Ele.Price Std [EUR/kWh] 2002-2007
Average of Austria [AT]	0.53	0.59	0.60	0.52	1.48	4.29	1.34	0.73
Average of Italy [IT]	1.64	1.29		1.94		1.74	0.98	1.13
Average of U.K. [GB]	0.83	1.13	2.40	0.54	1.52	0.46	0.68	1.14

The resulting values for the different measures of energy security are shown in Table 2. The government of a country that performs less well on one of the scales could use this information in order to assess the need for infrastructure investments to improve the security of its electricity supplies to a level that is comparable to that in other countries. However, the results of our case study show that whether or not there is a need to improve the security of electricity supplies in a country in order to catch up with other countries largely depends on the impact measure and the corresponding conceptual boundaries that are chosen. In order to visualize this, we convert the values from Table 2 into a dimensionless scale and display the security levels of the UK, Italy and Austria relative to each other for all of the measures in the same Figure 2. In the policy context, the results would of course be displayed on the respective absolute scales. But the impact of choosing different conceptual boundaries is better illustrated by the relative measures, because they allow the direct comparison between the performance of countries on different absolute scales. For all the measures where a larger value indicates a higher level of insecurity, we calculated the relative level of insecurity by dividing the value for each country by the average value of all countries. For all measures where a larger value indicates a lower level of insecurity, the division was done in reverse order. The result of this calculation is shown in Figure 2.

Figure 2: Result of using different measures for the assessment of energy security.



We can see that the choice of different energy security concepts has a strong impact on the resulting quantification of energy security levels for different countries relative to each other. In addition to the difference in relative security levels, different concepts are likely to cause simultaneous changes in the evaluation of the security for all of the countries, which cannot be shown in this graph. For example the exclusion of exceptional events in the first variation will not only change the security level of countries relative to each other but also lead to a lower risk level in all of the countries compared to the concept in the base case where these events are included. But even if we neglect these changes, the graph illustrates the importance of choosing the right conceptual boundaries.

8 Drawing the Border between Energy Security, Economic Efficiency and Sustainability

From an academic perspective, an important goal is the clear conceptual separation of the policy objectives of energy security, economic efficiency and sustainability. In our view this could be achieved by three distinctions.

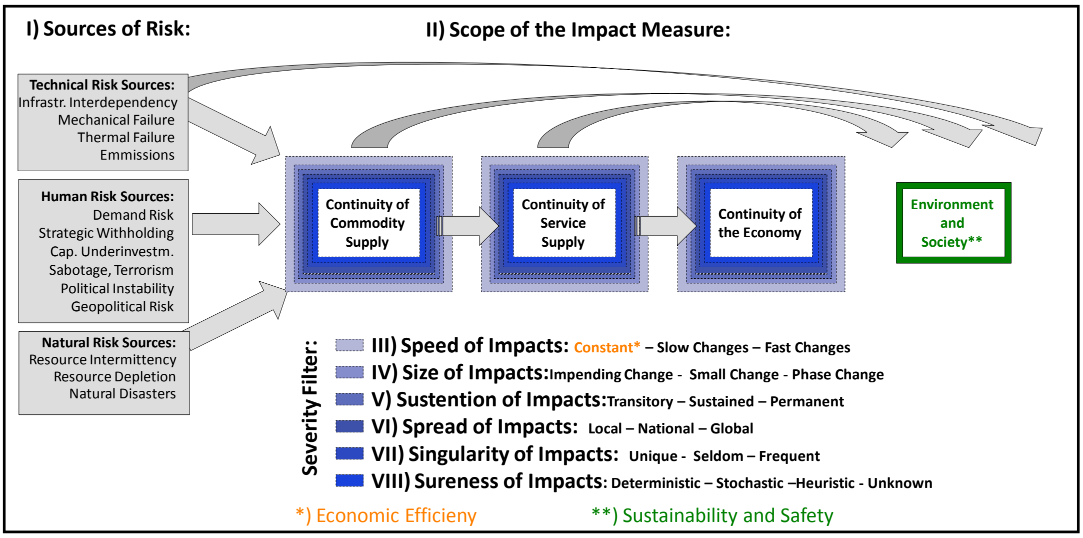
The first distinction we propose is between threats that have an impact on the supply chain and impacts of the supply chain on the environment. The concept of energy security could be limited to the impacts on the continuity of commodity and service supplies and resulting continuity of the economy, while impacts on human safety and environmental sustainability are treated as separate concepts. Some events affect all these categories at the same time. For example a nuclear accident or a fire on an oil-rig have a simultaneous impact on the continuity of supplies, the safety of the population and environmental sustainability. For other events there is a time delay between the effects. For example CO2 emissions directly impact the sustainability of a system but have a delayed impact on the continuity of supplies and on human safety in the form of floods and storms caused by climate change. In both cases these risks are an important area of overlap between the concepts of energy security, sustainability and safety. It should be noted that the concept of safety has not been treated as a separate policy goal, but seems to be treated as a part of either energy security or sustainability. In our view safety is different from energy security, in that it concerns impacts of the supply chain on the environment as opposed to impacts of the environment on the supply chain. It is also different from the concept of sustainability, in that sustainability is mainly concerned with long-term goals including society and environment, while safety specifically focuses on fast, short-term impacts on the society. A more detailed discussion of the concept of safety is however outside the scope of this paper.

The second distinction we propose is between the description of supply continuity and value judgments about the worth of different continuity levels. The concept of energy security could be limited to the measurement of commodity, service and economic continuity levels, while value judgments about the desirability of continuity level are addressed by the policy goal of economic efficiency. The pricing of continuity levels would then be an area of overlap between energy security and economic efficiency in the same way as the appropriate pricing of environmental externalities is an overlap between economic efficiency and sustainability.

The third distinction we propose is between constant scarcity and changes of scarcity levels. The concept of energy security could be limited to changes of scarcity levels, while the impact of constant scarcity levels would belong to the concept of economic efficiency. On longer time-scales, any scarcity level is subject to change. The analysis of very slow changes in scarcity is therefore an area of overlap between economic efficiency and energy security.

The resulting boundaries of the energy security concept are illustrated in Figure 3.

Figure 3: Suggested conceptual boundaries of energy security.



9 Context Specific Boundaries of Energy Security

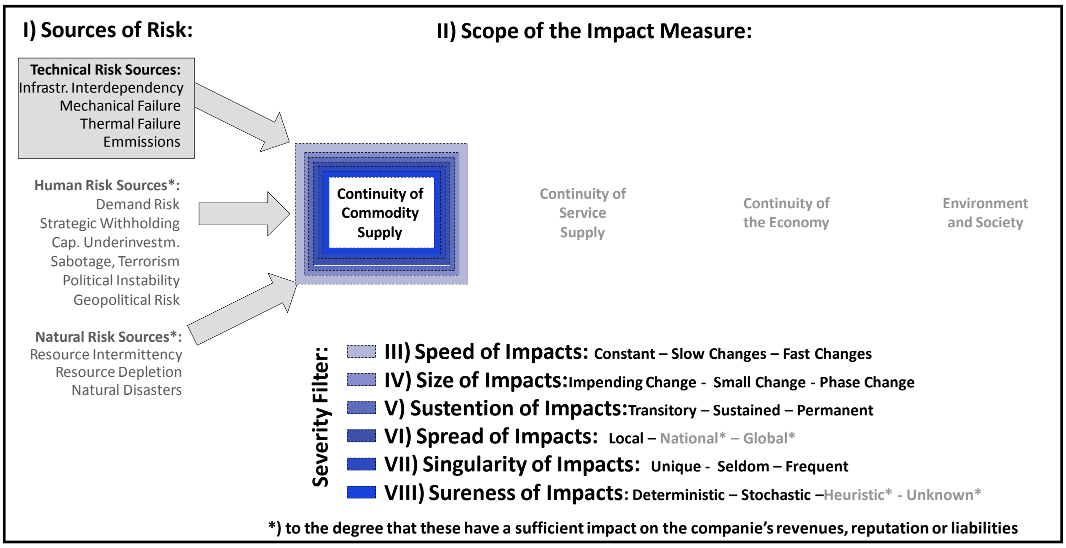
In addition to the academic distinction between security, efficiency and sustainability further criteria can be introduced to limit the concept of energy security. Whether or not a certain aspect shall be included within an analysis of supply security is essentially a subjective decision. It will be influenced by the context of the analysis, the degree of risk aversion and pragmatic considerations about the feasibility of the measurement. Depending on the context of the analysis and the audience for which it analysis is conducted different conceptual boundaries could be relevant.
In this paragraph we illustrate this by describing the security concept for each of the perspectives in Table 3.

Table 3: Different Perspectives on Energy Security.

Perspective	Goal
Private Utility	Meet contractual liabilities and build up reputation
End Consumers	Ensure delivery of services
Public Servant	Avoid the disruption of services or the economy

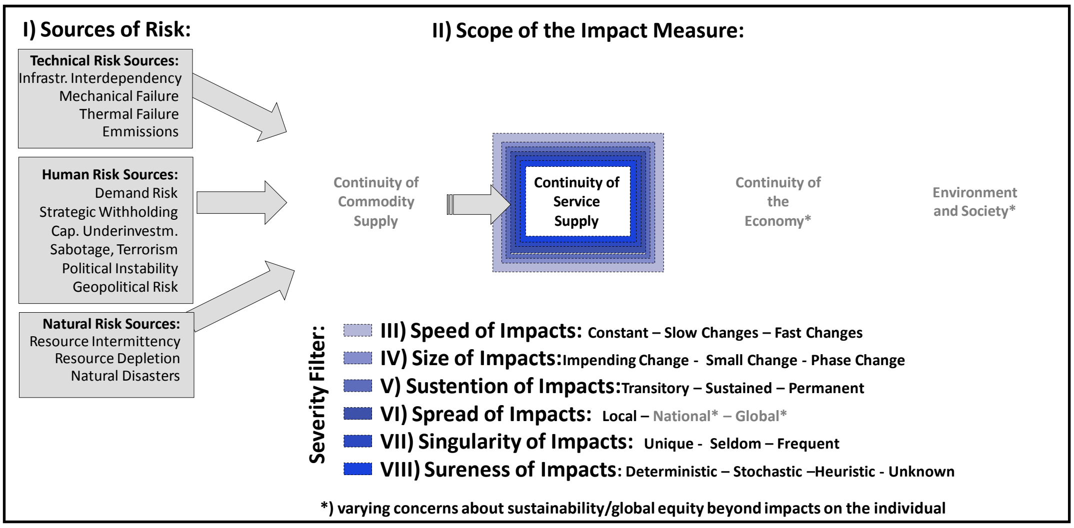
From the perspective of a private utility an important goal is to meet the liabilities imposed by regulations and contracts and build a reputation with customers. This could lead to an implicit limitation of the security concept to those commodities, risk sources, impact measures, spreads and sureness levels for which the company will be held responsible either directly, through contracts and regulations, or indirectly, through the impact on the reputation of the company. Externalities and force majeure events caused by certain natural and human risk sources, which typically have a national or global impact and are less sure would only be relevant to the degree that they have a sufficient impact on the company's revenues, reputation or liabilities. The scope of the impact measure would be limited to the continuity of commodity supplies. The resulting boundaries of the security concept are illustrated in Figure 4.

Figure 4: Boundaries of a private utility's energy security concept.



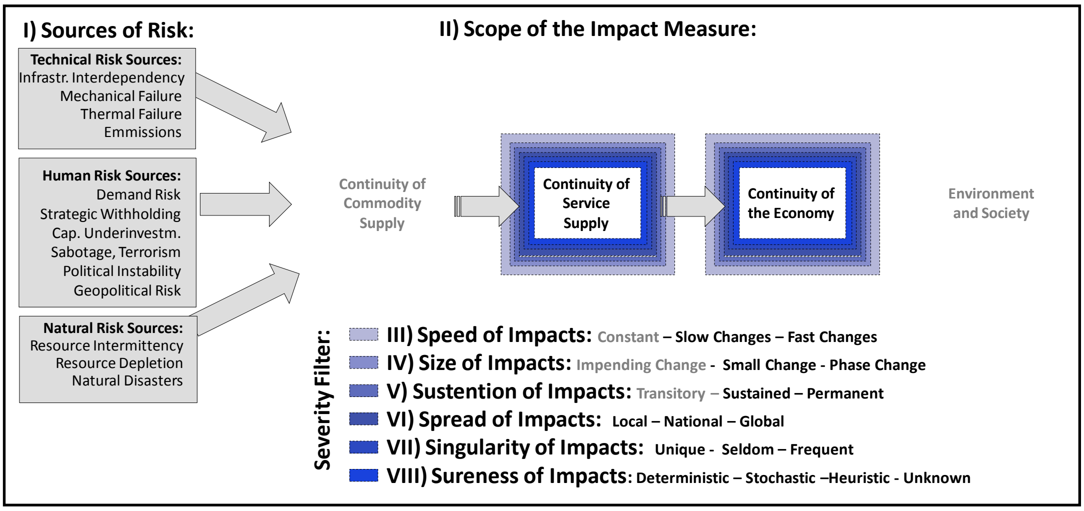
From the perspective of private consumers an important goal is to protect themselves against the disruption of services. This could lead to a limitation of the security concept to the scope of impact measures and spread of the impacts that affect each consumer. The degree to which impacts of risks on neighbouring regions, or the economy and the environment are taken into account will vary between different consumers but usually not cover the total amount of potential damages. The resulting boundaries of the concept are illustrated in Figure 5.

Figure 5: Boundaries of private consumers' energy security concept.



From the perspective of a public servant, in addition to the continuity of service supplies, it is also important to take into account the impact of service supply continuity on the continuity of the economy. Threats with a low severity might be of less concern as they provide signals to private actors. This could lead to an exclusion of impending and transitory impacts threats. To the extent that this is feasible the analysis would include threats of all sureness levels including ways to protect against unknown risks. The scope of the impact measure could be limited to the continuity of service supplies and the continuity of the economy while impacts on the environment would be considered under the policy goal of sustainability and safety. The resulting boundaries of the security concept are illustrated in Figure 6.

Figure 6: Boundaries of a public servant's energy security concept.



Due to the relevance of different concepts depending on the context and the audience of an analysis, it would be more precise to indicate the scope of the impact measure by labelling studies as assessments of gas, electricity, oil, heat and transportation supply continuity etc. - if an individual fuel or service market is analysed- and as assessments of commodity supply continuity, service supply continuity and their impacts on the continuity of the economy - if a variety of different fuel or service markets are analysed. Limitations along the other dimensions should also be mentioned within the studies themselves. If the conceptual limitations of a study are ignored, this may lead to inefficient investment decisions and short-sighted regulation. A precise specification of the conceptual framing should thus be an important part of any analysis of energy security.

10 Conclusions

Based on a review of security of supply literature, we found that the common concept behind all energy security definitions is the absence of, protection from or adaptability to threats that are caused by or have an impact on the energy supply chain. Due to the difficulty of measuring all these threats at the same time, individual authors implicitly or explicitly limit the concept of energy security along one or several of the following dimensions: the sources of risk, the scope of the impact measure, and the speed, size, sustention, spread, singularity or sureness of impacts. In a small case study we have shown, that the choice of conceptual boundaries has a large impact on the results. A description of the framing should thus be an explicit part of any attempt to quantify the energy security of a country.

We have then proposed a set of conceptual boundaries that improve the distinction between the policy goals of security, sustainability and economic efficiency. The resulting concept, which is at the core of energy security concerns, should in our view best be relabelled to the less ambiguous term of ‘energy supply continuity’. It is an umbrella term for the concepts of ‘commodity supply continuity’, ‘service supply continuity’ and resulting impacts on the ‘continuity of the economy’. The additional meanings that are attached to the term of ‘energy security’ are largely contained in other policy goals. The suggested limitation would therefore not remove these concerns from the policy agenda but only reduce double counting and avoid the problem of securitization (Buzan, Wæver, and Wilde 1998).

Depending on the audience and the context of the analysis, further limitations of the concept may apply. These limitations should be pointed out, since a reliance on a partial analysis could lead inefficient investment decisions and short-sighted regulation. This is a topic that could be explored in further analysis.

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12 Appendix

12.1 Security of Supply Definitions

Author (Year)	Title	Security of Supply Definition
Andrews (2005)	Energy Security as a Rationale for Governmental ction.	"I use Yergin's definition: "The objective of energy security is to assure adequate, reliable supplies of energy at reasonable prices and in ways that do not jeopardize major national values and objectives"
Bazilian et al. (2007)	Security of Supply in Ireland	„A broad definition of SOS in used in this series of reports. Based on international experience to date, a country's energy security policy generally comprises measures taken to reduce the risks of supply disruptions below a certain tolerable level. Such measures should be balanced to ensure that a supply of affordable energy is available to meet demand. Security of energy supply thus encompasses both issues of quantity and price. However, time is also a key parameter, as a sudden price hike will have very different effects on both society and the economy compared to those of a long-term price increase. Insecurity in energy supply originates in the risks related to the scarcity and uneven geographical distribution of primary fuels and to the operational reliability of energy systems that ensure services are delivered to end users."
Bohi and Toman (1993)	Energy security: externalities and policies.	"Energy insecurity can be defined as the loss of welfare that may occur as the result of a change in price or availability of energy"
Checchi et al. (2009)	Long-Term Energy Security Risks for Europe: A Sector-Specific Approach.	"The literature is divided between those who interpret energy security from an economic perspective and those who stress its political and strategic side….The literature is further divided between those who see the security of supply as exclusively related to energy and those who like to couple it with the environmental dimension…. Although there is no common interpretation, it is possible to identify a number of features that are always included, namely physical availability and prices"
Creti and Fabra (2007)	Supply security and short-run capacity markets for electricity.	„in the short-term, supply security requires the readiness of existing capacity to meet the actual load; supply adequacy, instead, refers to the "long-run performance attributes of the system in attracting investment in generation, transmission, distribution, metering, and control capacity so as to minimize the costs of power supplies"
Doorman et al. (2006)	Vulnerability analysis of the Nordic power system.	„system vulnerability, which is defined as the system's inadequate ability to withstand and unwanted situation"
DTI (2002)	Joint Energy Security of Supply Working Group (JESS) First Report.	"Insecurity of energy supply, in the form of sudden physical shortages, can disrupt the economic performance and social welfare of the country in the event of supply interruptions and/or large, unexpected short-term price increases. Supply interruptions to the gas system are also hazardous in terms of risk of gas inhalation and explosions. No energy form and no source of supply can offer absolute security, so improving security of supply means reducing the likelihood of sudden shortages and having contingency arrangements in place to limit the impact of any which do occur."
EC(2000)	Green Paper - Towards a European strategy for the security of energy supply.	„strategy for energy supply security must be geared to ensuring, for the well-being of its citizens and the proper functioning of the economy, the uninterrupted physical availability of energy products on the market, at a price which is affordable for all consumers (private and industrial), while respecting environmental concerns and looking towards sustainable development"
Grubb et al. (2006)	Diversity and security in UK electricity generation: The influence of low-carbon objectives.	„security of supply, for the purposes of this paper it can be defined as a system's ability to provide a flow of energy to meet demand in an economy in a manner and price that does not disrupt the course of the economy. Symptoms of a non-secure system can include sharp energy price rises, reduction in quality (e.g. brown-outs), sudden supply interruptions and long- term disruptions of supply. „

Hoogeven and Perlot (2007)	The EU's Policies of Security of Energy Supply Towards the Middle East and Caspian Region: Major Power Politics?	„ Security of supply is a general term to indicate the access to and availability of energy at all times (CIEP 2004). Supply can be disrupted for a number of reasons, for, example, owing to physical, economic, social, and environmental risks (EC 2001). The most important crises that have been instrumental in shaping the EU's security of supply policy are of a social and economic nature and were all crises in the GME region"
Intharak, N. et al., Asia Pacific Research Centre (2007)	A Quest for Energy Security in the 21st Century.	"This study defines energy security as the ability of an economy to guarantee the availability of energy resource supply in a sustainable and timely manner with the energy price being at a level that will not adversely affect the economic performance of the economy. Following the above definition, there are 3 fundamental elements of energy security that will be discussed in this study: (1) PHYSICAL energy security, the availability and accessibility of supply sources; (2) ECONOMIC energy security, the affordability of resource acquisition and energy infrastructure development; and (3) ENVIRONMENTAL SUSTAINABILITY, the sustainable development and use of energy resources that "meets the needs of the present without compromising the ability of future generations to meet their own needs". "
Jamasb and Pollitt (2008)	Security of supply and regulation of energy networks.	„Security of supply..often discussed in terms of physical availability of energy sources and their commodity price risk"
Jansen, J.C., and Seebregts, A.J. (2009)	Long-term energy services security: What is it and how can it be measured and valued?	"energy (supply) security" can be considered as a proxy of the certainty level at which the population in a defined area has uninterrupted access to fossil fuels and fossil-fuel based energy carriers in the absence of undue exposure to supply-side market power over a period ahead of 10 years or longer.
Joode et al. (2004)	Energy Policies and Risks on Energy Markets; A cost-benefit analysis.	"What is meant by 'securing the supply of energy'? According to politicians, it is guaranteeing a stable supply of energy at an 'affordable' price, no matter what the circumstances…From an economic point of view, however, the concept of security of supply is less clear. In general economic terms, energy security refers to "the loss of welfare that may occur as the result of a change in price or availability of energy" (Bohi et al., 1996)."
Joskow (2005)	Supply security in competitive electricity and natural gas markets.	"…what it is that I think policymakers mean when they express concerns about "supply security" in liberalized electricity and gas markets. First, they are concerned about "involuntary rationing" of demand… Second, policymakers are also concerned about high prices, or at least sudden increases in prices… Although perhaps an oversimplification, it is useful to group "supply security" concerns into two categories: (a) short run system operating reliability and (b) long run resource adequacy."
Jun, Kim and Chang (2009)	The analysis of security cost for different energy sources.	„Energy security can be defined as a reliable and uninterrupted supply of energy sufficient to meet the needs of the economy at the same time, coming at a reasonable price"
Keppler (2007)	International Relations and Security of Energy Supply: risks to Continuity and Geopolitical Risks.	"Traditional definitions of energy supply security combine a short-term notion of the continuity of physical supplies with long-terms notion of "affordable" prices, "competitive" prices" or "adequate prices". The risk management approach to the security of energy supplies argues that supply security s an issue dependent on the risk-adverseness of consumers. Its focus is thus not the absolute level of energy prices but the size and impact of changes in energy prices"
Kruyt et al. (2009)	Indicators for energy security.	„...elements relating to SOS: Availability – or elements relating to geological existence. Accessibility – or geopolitical elements. Affordability – or economical elements. Acceptability – or environmental and societal elements."
Le Coq, C., and Paltseva, E. (2009)	Measuring the security of external energy supply in the European Union.	"supply security, usually defined as a continuous availability of energy at affordable prices"
Lefèvre (2009)	Measuring the energy security implications of fossil fuel resource concentration.	„Energy insecurity can be defined as the loss of welfare that may occur as a result of a change in the price or availability of energy"

Lesbirel (2004)	Diversification and Energy Security Risks: The Japanese Case.	„ Energy security, like the concept of security itself is a contestable concept. Rather than seeking to define energy security comprehensively and while acknowledging different conceptions of it, I stress the notion of insurance against risks. An important aspect of energy security is the relative ability to insure against the risks of harmful energy import disruptions in order to ensure adequate access to energy sources to sustain acceptable levels of social and economic welfare and state power both nationally and internationally“
Lieb-Dóczy, Börner and Mc Kerron (2003)	Who Secures the Security of Supply? European Perspectives on Security, Competition, and Liability.	„Security of supply is fundamentally about risk. More secure systems are those with lower risks of system interruption.“
Loeschel et al. (2008)	Indicators of energy security in industrialised countries.	our adopted general definition of energy security (no major frictions to the economy caused by the energy system)
Mabro (2008)	On the security of oil supplies, oil weapons, oil nationalism and all that.	„Security is impaired when supplies are reduced or interrupted in some places to an extent that causes a sudden, significant and sustained increase in prevailing prices.“
McCarthy (2007)	Assessing reliability in energy supply systems.	„ Security includes the dynamic response of the system to unexpected interruptions, and its ability to endure them. Adequacy refers to the ability of the system to supply customer requirements under normal operating conditions“
Mulder, ten Cate&Zwart (2007)	The economics of promoting security of energy supply.	"From a political viewpoint, ensuring security of supply often means that a stable supply of energy needs to be guaranteed at 'affordable' prices, regardless of the circumstances. …From an economic viewpoint, however, the concept of security of supply is related to the efficiency of providing energy to consumers. …In this paper, we approach the issue of security of supply from the economic perspective"
Newbery (1996)	Development of Natural Gas Trade between East and West.	"Security in turn requires an analysis of the possible shocks that might disturb the original equilibrium"
Noel, P., and Findlater, S. (2010)	Gas Supply Security in the Baltic States: A Qualitative Assessment.	"For the purpose of this article "security of supply" (or gas supply security) refers to the ability of a country's energy supply system to meet *final contracted energy demand* in the event of a *gas supply disruption*."
Nutall and Manz (2008)	A new energy security paradigm for the twenty-first century.	„Interruption of the energy supply has been identified by many as the primary threat that faces global energy security.“
Ölz,, Sims and Kirchner (2007)	Contribution of Renewables to Energy Security.	This study defines energy security risk as being the degree of probability of disruption to energy supply occurring. A forthcoming IEA report on the interactions between energy security and climate change policy uses an analogous definition of energy insecurity as "the loss of economic welfare that may occur as a result of a change in the price and availability of energy"
Patterson (2008)	Managing Energy Wrong.	"The energy security that worries politicians concerns supplies of imported oil and natural gas, not the secure delivery of energy services, such as keeping the lights on."
Rutherford, Scharpf and Carrington (2007)	Linking consumer energy efficiency with security of supply.	"In the context of this paper, we will use the term energy security to refer to a generally low business risk related to energy with ready access to a stable supply of electricity/energy at a predicable price without threat of disruption from major price spikes, brown-outs or externally imposed limits."
Scheepers et al. (2007)	EU Standards for Security of Supply	"A security of supply risk refers to a shortage in energy supply, either a relative shortage, i.e. a mismatch in supply and demand inducing price increases, or a partial or complete disruption of energy supplies. ... A secure energy supply implies the continuous uninterrupted availability of energy at the consumer's site“

Spanjer (2007)	Russian gas price reform and the EU–Russia gas relationship: Incentives, consequences and European security of supply.	„Security of supply can broadly be divided into two parts: system security—the extent to which consumers can be guaranteed, within foreseeable circumstances, of gas supply—and quantity security—guaranteeing an adequate supply of gas now as well as in the future. This comprises not only gas volumes, but also price and diversification of gas supplies „
Stern (2002)	Security of European Natural Gas Supplies.	In a short paper there is limited space for a methodological definition of gas security.3 Perhaps the briefest way to deal with definitions is to say that this paper deals with the threats of supply and price disruptions arising from risks associated with the sources of gas supplies, the transit of gas supplies and the facilities through which gas is delivered. There are two major dimensions of these risks: • *short-term* supply availability versus *long-term* adequacy of supply and the infrastructure for delivering this supply to markets; • *operational* security of gas markets, i.e. daily and seasonal stresses and strains of extreme weather and other operational problems versus *strategic* security, i.e. catastrophic failure of major supply sources and facilities.
Turton and Barreto (2006)	Long-term security of energy supply and climate change..	„Security is measured as resources to consumption ratio (R:C)“
Vicini et al. (2005)	Security of Energy Supply: Comparing Scenarios From a European Perspective.	“Energy security is defined as the availability of a regular supply of energy at an affordable price (IEA, 2001a). The definition has physical, economic, social and environmental dimensions (EC, 2000); and long and short term dimensions.”
Wrigth (2005)	Liberalisation and the security of gas supply in the UK.	„security of gas supply’ : “an insurance against the risk of an interruption of external supplies“ (IEA 2003)“

12.2 Calculation of example measures

In this paragraph we display the data that was used for calculating the rough measures that represent each security of supply concept. The tables start at the left with the raw input data, while the columns on the right contain the security measure which was derived on the basis of the data.
The last row contains the sources (for the raw data) and a short description of the calculation process (for the output measure, in cases where it's not obvious).

12.2.1 SAIDI of electricity:

Indicator				Ele.SAIDI incl. Except. Events				
Unit				[min/year]				[local as % Avg]
Year	2002	2003	2004	2005	2006	2007	2002-2007	2002-20072
Austria [AT]	83.08	38.44	30.33	39.41	48.49	72.00	51.96	0.53
Italy [IT]	114.74	546.08	90.53	79.86	60.55	57.89	160.77	1.64
U.K. [GB]	101.33	72.68	87.33	61.04	89.43	0.00	81.28	0.83
Source	CEER (2008), p.129, Table Cos 2.5						Calcualtion	

12.2.2 SAIDI of electricity, excl. exceptional events:

Indicator				Ele.SAIDI no Exceptional Events				
[min/year]				[min/occ.]				[local as % Avg]
Year	2002	2003	2004	2005	2006	2007	2002-2007	2002-2007
Austria [AT]	35.23	38.44	30.33	31.35	48.07	45.50	38.15	0.62
Italy [IT]	108.88	96.88	76.52	65.74	53.84	52.47	75.72	0.77
U.K. [GB]	72.24	68.16	61.43	61.04	89.43	0.00	70.46	0.72
Source	CEER (2008), p.129, Table Cos 2.1						Calcualtion	

12.2.3 SAIDI of heat:

Indicator	Ele SAIDI	Gas SAIDI	Ele Heating	Gas Heating	Heat SAIDI	Heat SAIDI
Unit	[min/year]	[min/year]	[% total]	[% total]	[min/year]	[%average]
Year	2002-2007	2007	2001	2001	2007	2007
Austria [AT]	51.96	1.00	0.07	0.31	19.70	0.40
Italy [IT]	160.77					
U.K. [GB]	81.28	3.51	0.09	0.86	79.57	1.60
Source	CEER, 2008	Ofgem (2009) and Interview with E-Control (2010)	Statistik Austria (2001) and DCLG (2007)		Sum of Gas and Ele SAIDI weighted by their share of heat supply	

12.2.4 GDP loss due to electricity interruptions:

We calculated the customer average interruption duration (CAIDI) as the quotient between the system average interruption duration (SAIDI) and system average interruption frequency (SAIFI) of each country.
Under the assumption that the duration of interruptions follows an exponential distribution (with $\lambda = 1/CAIDI$), we calculated the percentage of interruptions $Out_{i,k}$ that have a duration *k* of less than 1 minute (k=k1), 1 hour (k=k2) and more than 1 hour (k=k3) for each of the countries *i* in our case study.

S

i	Country	Ele SAIFI	Ele SAIDI	Ele CAIDI		Out i,k	
		2002-2007	2002-2007	2002-2007	k=k1	k=k2	k=k3
		[occ./year]	[min/year]	[min/occ.]	[%of SAIFI]	[%of SAIFI]	[%of SAIFI]
i1	Austria [AT]	0.76	51.96	68.82	0.01	0.57	0.42
i2	Italy [IT]	2.90	160.77	55.51	0.02	0.64	0.34
i3	U.K. [GB]	0.79	81.28	102.66	0.01	0.43	0.56
	Source	CEER, 2008			Own Calculation		

Based on the outage cost per customer for different outage durations in the USA reported in (LaCommare and Eto 2004) we calculated the loss $VOLL_{j,k}$ for each sector *j* that is caused by an outage of duration *k* in % of the yearly GDP of that sector. We assume that this percentage remains equal across different countries. For the residential sector we assumed, that the GDP equals the total GDP of the country (a result which was derived in (de Nooij, Koopmans, and Bijvoet 2007)).

j	Sector	Damage per Outage with Duration k			Consumers in USA, 2001	Sectoral GDP of USA 2001	VOLL j,k		
		k1<=1min	1min<=k2<1h	1h<=k3			k=k1	k=k2	k=k3
		[$/cons.]	[$/cons.]	[$/cons.]	[Mio cons.]	[Bio US$]	[%Sector GDP]	[%Sector GDP]	[%Sector GDP]
j1	Residential	2.18	2.70	2.99	114.32	9010.77	0.003%	0.003%	0.004%
j2	Commercial	605.00	886.00	1067.00	14.94	6958.47	0.130%	0.190%	0.229%
j3	Industry	1893.00	3253.00	4227.00	1.58	2052.31	0.146%	0.251%	0.326%
	Source	La Commare (2004), table 10			La Commare (2004), table 4	BEA (2010)	For each interrupt. Duration, divide VOLL for all consumers by the sectoral GDP		

Based on the percentage of the total $GDP_{i,j}$ which the sectors *j* have in different countries *i*, we calculated the total loss of GDP for each countries under the assumption, that outage times are equally distributed between the sectors.
The total GDP loss of a country *i* due to electricity interruptions is thus estimated as:

$$GDP_i = \sum_{j=j1j3} \sum_{k=k1k3} Out_{i,k} * SAIFI_i * VOLL_{j,k} * GDP_{i,j}$$

Variable	Meaning
$Out_{i,k}$	Share of the interruptions in country *i* which are assumed to have a duration smaller than *t*
$SAIFI_i$	System average interruption frequency index for country *i*
$VOLL_{j,k}$	Share of the yearly GDP of sector *j* which is lost in an interruption of duration up to *k*
$GDP_{i,j}$	Share of the total GDP in country *i* which are provided by sector *j*

12.2.5 CO2 emissions per capita:

	CO2 per Capita [t CO2/(cap. Year)] 2007	CO2 per Capita [%of average] 2007
Austria [AT]	10842.27	0.99
Italy [IT]		
U.K. [GB]	11170.14	1.01
Source	Eurostat	

12.2.6 Renewable Energy Potential:

	Wind Potential [TWh/a]	Solar Potential [TWh/a]	Wind+Solar [TWh/a]	Wind + Solar [average as %local]
	2007	2007	2007	2007
Austria [AT]	466.00	3.20	469.20	4.29
Italy [IT]	1152.00	2.76	1154.76	1.74
U.K. [GB]	4409.00	2.46	4411.46	0.46
Source	EEA (2009)	EC JRC (2010)	calculations	

12.2.7 Electricity Price Trend and Price Volatility:

	Electricity Price [EUR/kWh]															
	2007		2006		2005		2004		2003		2002		2001		2000	
	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1
Austria [AT]	0.16	0.15	0.14	0.13	0.14	0.14	0.14	0.14	0.13	0.14	0.14	0.13	0.13	0.13	0.13	0.12
Italy [IT]	0.23	0.23	0.21	0.21	0.20	0.20	0.19	0.20	0.20	0.20	0.20	0.19	0.20	0.20	0.21	0.20
U.K. [GB]	0.13	0.13	0.12	0.10	0.09	0.09	0.09	0.09	0.09	0.10	0.10	0.11	0.11	0.10	0.11	0.11
Source	Eurostat, Households with average consumption of 3500kWh/a															

	Ele price Trend		Ele Price Std	
	[%of mean]	[local as % of avg]	[EUR/kWh]	[local as % of avg]
	2000-2007	2000-2007	2002-2007	2002-2007
Austria [AT]	1.1%	134%	0.008	73%
Italy [IT]	0.8%	98%	0.013	113%
U.K. [GB]	0.6%	68%	0.013	114%
Source	Calculation			