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Indicators for energy security

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ABSTRACT

The concept of energy security is widely used, yet there is no consensus on its precise interpretation. In this research, we have provided an overview of available indicators for long-term security of supply (SOS). We distinguished four dimensions of energy security that relate to the availability, accessibility, affordability and acceptability of energy and classified indicators for energy security according to this taxonomy. There is no one ideal indicator, as the notion of energy security is highly context dependent. Rather, applying multiple indicators leads to a broader understanding. Incorporating these indicators in model-based scenario analysis showed accelerated depletion of currently known fossil resources due to increasing global demand. Coupled with increasing spatial discrepancy between consumption and production, international trade in energy carriers is projected to have increased by 142% in 2050 compared to 2008. Oil production is projected to become increasingly concentrated in a few countries up to 2030, after which production from other regions diversifies the market. Under stringent climate policies, this diversification may not occur due to reduced demand for oil. Possible benefits of climate policy include increased fuel diversity and slower depletion of fossil resources.

1. Introduction

There has been a recent revival of interest in energy security, stirred by high oil prices in the period up to 2008 and geopolitical supply tensions (IEA, 2007a,b,d; EC, 2006). There are different explanations for the recent high oil prices. The most accepted explanation is that they reflected rapidly increasing energy demand in Asia, underinvestment in energy supply in the late 1990s and early 2000 and further concentration of oil and gas reserves in a few politically less stable countries (CIEP, 2004). Other sources, however, attribute the recent high oil prices directly to depletion of (cheap) oil resources. Governments in different parts of the world have responded to the current situation by formulating policy to improve security of supply. In most cases, however, this ambition is not formulated in quantifiable goals. This partly comes from the fact that energy security has a rather elusive nature and it is highly context dependent. Still, the fact remains that governments see security of supply as a major objective for their energy policy. The fact that energy security is strongly related to other policy issues that concern the energy system (such as affordable energy and climate change and environmental policy) implies that it is important to study the energy security consequences of different development pathways. In order to do this, indicators for energy security are needed as well as a formal framework in order to link the notion to model-based scenario analyses.

In this paper, we aim to contribute to the development and use of more formal notions of energy security, by providing an overview of available indicators for (long-term) security of supply and discussing the strengths and weaknesses of these indicators. It is important to define energy security before discussing the merits and drawbacks of the various indicators. From the available literature, it is obvious that distinct perspectives on the meaning of the concept exist. Therefore, we will first try to frame the concept on a level of abstraction such that currently existing visions can be included. Next, we discuss indicators for energy security that have been proposed over the years. These are reviewed in order to attain insight into their conceptual differences and the perspectives on energy security from which they were conceived. This allows for a schematic ordering of the indicators with regard to the elements of energy security that the indicators focus on. Thus an overview of indicators is provided with regard to their emphasis.

In order to evaluate these indicators in a more practical sense, we will apply a selection of them to assess the future security of supply with a focus on Western (OECD) Europe, partly in relation to the consequences of stringent climate policy. The analysis illustrates the type of information provided by different indicators,

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which implies that conclusions of the analysis are conditional upon the simplifications that were made, as is indicated in the discussion. Since energy security is foremost a concept that is concerned with future developments, we apply model-based scenario analysis. The model used is the TIMER model (de Vries et al., 2001; van Vuuren, 2007), a simulation model of the world energy system that distinguishes 26 world regions.

The paper is structured as follows. In Section 2 the concept of energy security and its various dimensions is investigated. In Section 3 an overview of indicators for energy security found in the literature is presented. Section 4 provides the projections of some indicators up to 2050. A discussion of the methods and results is given in Section 5. Finally, Section 6 presents the main conclusions.

2. Energy security: a framework for the concept

2.1. Background

The interest in energy security is based on the notion that an uninterrupted supply of energy is critical for the functioning of an economy. However, an exact definition of energy security (or its synonym security of supply (SOS)) is hard to give as it has different meanings to different people at different moments in time (Alhajji, 2007).[1] It has traditionally been associated with the securing of access to oil supplies[2] and with impending fossil fuel depletion. Specifically, the 'oil crises' in the 1970s and 1980s made the dependence on oil exporting countries in the Middle East evident. With an increase in natural gas use, security concerns also arose for natural gas, widening the concept to cover other fuels. Because oil is nowadays a globally traded commodity, physical shortages show up in the price of oil on the world market, in the form of a long-term increase and of short-term fluctuations (IEA, 2007a; Toman and Michael, 2002). As a result, SOS concepts have partly moved away from a purely physical definition of fossil fuel occurrences (used mostly by geologists) to one that also incorporates the price of energy (with especially an economical interest) (Jenny and Frederic, 2007). Furthermore, energy conversion and transport are also mentioned in relation to SOS as disruptions can occur anywhere in the supply chain (Jenny and Frederic, 2007; Scheepers et al., 2007). In some cases, the ability of the system to cope with extreme events, such as hurricanes (Katrina) or strikes and terrorist actions is also mentioned in the context of SOS (Chevalier, 2005). Lastly, the political stability of supplying and transit countries appears in SOS discussions (IEA, 2004a,b,c, 2007a; Chevalier, 2005; Jansen et al., 2004) since uproar could also restrain supply.

The concept and definitions of energy security have thus widened over time. In present day definitions (see Chevalier, 2005; IEA, 2007d; APERC, 2007; CIEP, 2004) four main elements can be identified. The first and most dominant element (included in all definitions) is the availability of energy to an economy. This entails an element of absolute availability or physical existence (fossil resources are essentially finite). Next, there is an element of accessibility due to the large spatial discrepancy between consumption and production of resources. Acquiring access often carries geopolitical implications. Furthermore, there is an element of costs in most interpretations of SOS. Finally, some definitions also include an element of environmental sustainability (e.g., related to the availability of tar sands or bio-energy). One may question whether SOS should be broadly defined, as very wide definitions may erode the concept and make it equal to even broader concepts such sustainable development. However, as we aim to be inclusive to the whole literature on SOS we start from the broad definition. We will adhere to a classification scheme proposed by the Asia Pacific Energy Research Centre (APERC, 2007), by classifying elements relating to SOS into:

- Availability – or elements relating to *geological* existence.
- Accessibility – or *geopolitical* elements.
- Affordability – or *economical* elements.
- Acceptability – or *environmental* and societal elements.

It should be noted that these are by no means isolated categories but subject to a complex interplay.

2.2. Dimensions in time

With regards to the time frame considered, one can distinguish different views on the security of energy supply. A distinction is often made between short-term and long-term energy security (IEA, 2007a). The former being concerned with (the mitigation of) disruptions, while the latter deals with more structural aspects of the energy system, and as such the causes of these disruptions. Although the two are connected, as underinvestment in long-term SOS leads to increased risk of disruptions (IEA, 2007d), we will confine ourselves to long-term SOS in this paper.

2.3. Different perspectives

SOS is very context and perspective dependent. Therefore, it is insightful to look at these four aspects of SOS in view of future developments of the world and one's perception of these developments. An important factor is the question of how the world develops with regard to the extent and nature of globalisation (Hoogeveen and Perlot, 2005). A trend towards multilateralism, market trust and cooperation in the international system will most likely reduce concerns over dependence on other regions, and attention is likely to shift to matters like sufficient production capacity in order to bring resources to a global market. In such a world, attention on geopolitical factors is likely to be low, while physical availability and production costs could be more important. Conversely, increasing competition between regions will raise political barriers between regions and increase focus on energy independence. In such situation, SOS is likely to focus on accessibility to resources.

Next, there clearly is a tension between environmental targets and low energy costs. Responding to environmental challenges (climate change, other environmental targets) leads, in general, to higher energy-system costs. Interestingly, one finds that world-views emphasizing the need for low energy costs as a condition for economic growth exhibit at the same time optimism with respect to environmental threats and resource scarcity. On the other hand, concern about environmental consequences and physical depletion tends to coincide with less emphasis on low energy costs.

The above dichotomies of regionalisation versus globalisation and of economic efficiency and technology optimism versus a prime focus on equity and solidarity are also the basis of the IPCC's Special Report on Emission Scenarios (SRES) scenario set (Nakicenovic et al.,

[1] While some authors distinguish between the concepts of energy security and security of supply, here we use them interchangeably.

[2] According to the IEA; this preoccupation with oil stems from the fact that 'electricity, gas and coal were national fuels, often delivered through state owned enterprises exercising a monopoly. There might be occasional threats to continuity of supply, notably as a result of strikes; but these were issues to be resolved by negotiation between parties within the national industry who, ultimately, shared a common interest in continuity of supply.' http://www.iea.org/Textbase/work/2002/eurelectric/priddle.pdf Security of Supply in Liberalised Electricity Markets by Robert Priddle.

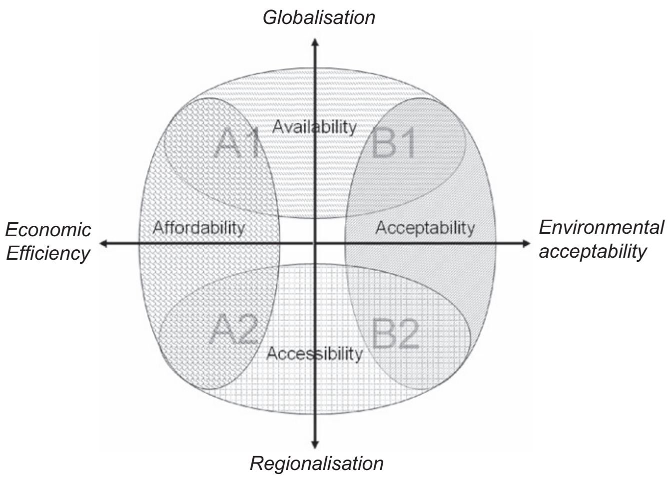

Fig. 1. The 'energy security spectrum'; the four dimensions of energy security and their relation to global orientations.

2000b). In SRES, they were used to define 4 different storylines for future scenarios of greenhouse gas emissions. These scenarios are: A1 (high level of globalisation and focuses on economic efficiency), B1 (high level of globalisation and focuses on equity), A2 (low level of globalisation and focuses on economic efficiency) and B2 (low level of globalisation and focuses on equity). The scenarios are shown in Fig. 1 in relation to the two axes in the schematic classification of storylines. Given our earlier discussion on SOS concepts, we can use these same axes to also map the four dimensions of SOS. This offers a schematic framework to discuss different SOS definitions in the context of divergent expected developments (laid down in narratives) in the future.

3. Indicators for energy security

Over the recent years there have been quite some attempts to devise indicators for SOS. Whereas some deal with one aspect of SOS, others attempt to capture several relevant elements in a single aggregated indicator. In the next section, we give an overview of the indicators found in the literature. We distinguish between disaggregated or simple indicators and aggregated indicators. In view of the broadness of SOS and its subjective nature, one should carefully consider the role of SOS indicators. Some of the authors of the indicators discussed below seem to aim in capturing SOS in some kind of objective quantitative metric, which could be used in policy making (allowing to set targets in a similar way as setting greenhouse gas reduction targets). Given the discussion above, we consider most indicators to have a much more heuristic role – capturing a particular aspect of SOS and indicating a relative position or direction of change. Most indicators are therefore also only valuable in a certain context. This point is even more important for indices that all include some form of subjective weighting. We will come back to this in the discussion section.

3.1. Simple indicators

3.1.1. Resource estimates

The actual existence or availability of energy sources is crucial for SOS and hence the available (remaining) resources can be used as a direct indicator for SOS. Unfortunately, large uncertainties surround the amounts of hydrocarbon resources and their extraction potentials. There are a few studies that provide estimates of fossil resources. The best known one is that of the United States Geological Survey (USGS) (USGS, 2000). Although called "one of the most independent and reliable sources of data" (Mulders et al., 2006), 'pessimists' or proponents of the peak oil theory argue that the USGS estimates are overly optimistic (Greene et al., 2005). Thus there is no consensus on the available resources.

3.1.2. Reserves to production ratios

The reserves to production ratios (also called R/P ratios or RPRs) are often used as indicator of SOS (Feygin and Satkin, 2004). These indicators indicate the years of production left at current production levels. As neither reserves nor production rates are fixed, a combination of these factors will also be a dynamic quantity.[3] In practice, constant factors are usually used for both. While expressing the available reserves in terms of current production is relatively easy to interpret (communicative), the indicator may be somewhat too simplistic in case of rapidly changing demand and/or highly uncertain reserve estimates. However, if one uses projected production levels instead of current ones (yielding so-called dynamic RPRs), the indicator becomes less transparent.

3.1.3. Diversity indices

Diversity in energy (fuel) type and geographical source is thought to be an important means to hedge against supply risks (Jansen et al. (2004); APERC, 2007) and diversity amongst suppliers a means of hedging against market power (IEA, 2004a, 2007b). A quantitative measure of either form of diversity can therefore serve as an indicator of SOS. Stirling (1999) argues that an index of diversity should consider three key elements : Variety (the number of categories), Balance (the spread across categories) and Disparity (the degree to which the categories are different from each other). However, no such index exists given the difficulty to define disparity. Hence, in the absence of an appropriate measure of disparity, the indices that measure only two of the three key elements of diversity are formally called indices of 'dual concept' diversity. Two of these indices are described in Appendix A.

In the absence of a decent measure of disparity, the categorization of options influences the outcome of these indices, introducing some form of subjectivity (or arbitrariness). In other words, the question with what degree of resolution categorization should be done to provide an useful indicator cannot be objectively answered. Another element is the question whether diversity really helps to ensure SOS. While fuel diversity does provide resilience against physical supply disruptions, physical disruptions are more and more translated into price shocks, which can spill over from one market to another. One may discuss how important these correlations are. Awerbuch and Berger (2003) mention significant diversification when correlation coefficients between energy prices are below 0.7.[4]

Diversity indices provide a means of quantifying the diversity in energy supply in a formal way, although the classification is still value-laden. Furthermore, various fuels carry different risks of disruptions which are not taken into consideration in this formal indicator.

3.1.4. Import dependence

Measures of import dependence are amongst the most commonly used indicators for SOS. Various disaggregations with

[3] This becomes evident when looking at past claims on resource availability, such as Sir Eric Drake's, who in 1974 claimed that "*The declining reserves will be insufficient to support the forecast demand after about 1978 when the demand may be limited by the availability of crude oil*". In reality, new reserves have supported further increase in production.

[4] See Section 4.1.7 on Mean Variance Portfolio Theory.

regard to fuels and regions are possible, expressed in either physical or monetary terms. An example of such an indicator is the import of oil, often expressed relative to oil consumption (Alhajji and James Williams, 2003). For SOS purposes, it would appear most practical to look at net imports. In the case of a country or region acting as a transport hub, or simply in the context of freely traded commodities, subtracting the exported energy (or oil/gas/electricity) provides a more realistic view of actual dependencies.[5]

Also more refined import dependency indicators exist. Besides import shares, the Asian Pacific Energy Research Centre applies a combined measure of diversity and import dependence (APERC, 2007). To this end, the Shannon index is adapted to measure an economy's import dependence weighted with its fuel diversity:

$$\mathrm{NEID} = \frac{\sum_i m_i p_i \ln p_i}{\sum_i p_i \ln p_i} \quad (1)$$

with m_i the share in net imports of energy carrier i, and p_i its share in total primary energy supply (TPES).[6] Here, a higher value implies a lower SOS. With a specification of the fuel's role in the energy mix, this indicator provides a more refined indication of import dependence as the simple import numbers and is useful as such.

On a global level, one can also consider the international trade in energy carriers to be an indicator of (mutual) dependence. Energy trade (total or fuel specific) in absolute terms can be considered an indicator, but also the share of global demand that is traded internationally.

In summary, import shares provide a straightforward and insightful indicator that does not require specific expertise to comprehend. The indicator is often used. If global energy markets are assumed to function optimally, it can be argued that import dependence is less relevant to SOS. In a more regionalised world, where trade barriers and a paradigm of competition rather than cooperation prevails, import shares form a useful indicator as the access to energy sources is an important element of SOS. Thus, it matters where one positions the world along the vertical axis in Fig. 1.

3.1.5. Political stability

The political situation in supplier countries is of importance to the security of the energy supply because governments control either the actual energy supply or the conditions under which other parties develop these. To our knowledge, only three studies have attempted to quantify the qualitative element we have dubbed 'political stability' for use as a measure of SOS. The IEA uses the ICRG political risk rating[7] (IEA, 2004a). In a follow-up report the IEA bases its political risk measure on the average of two of the six World Bank's Worldwide governance indicators: 'Political stability and absence of violence' and 'Regulatory quality' (IEA, 2007a). Jansen et al. (2004) base their measure of long-term socio-political stability on the UNDP's human development indicator (HDI).

It can be debated to what extent objective stability of a regime is actually meant when the term political stability is used in discussions on SOS, and not the willingness to trade or the stance towards specific regimes (such as between USA and Venezuela). In any case, it is not straightforward to relate these concepts to simple indicators (e.g., the HDI would seem rather ill grounded to serve as an indicator for either). Unfortunately, too, commercial political risk assessments are often proprietary.

3.1.6. The energy price

In a well functioning market, price functions as a balancing mechanism for demand and supply. Prices thus give an indication of the supply in relation to demand, while they are also considered as a measure of economic impacts. Finally, they also reflect scarcity and thus depletion of energy resources. The oil price plays a special role. Being a dominant energy carrier in most parts of the world, the oil price is seen as a crucial SOS indicator. A difficulty, in using oil prices, however, is that these prices are influenced also by other factors (speculation, strategic communication, short-term shortages). For use in scenarios, it should be noted that historically it has proven to be extremely difficult to model oil prices accurately. The use of oil prices as SOS indicator is mainly useful relative to other scenarios (what-if type of questions).

3.1.7. Mean variance portfolio theory

Mean variance portfolio (MVP) theory stems from financial economics. It can be applied to electricity generating mixes (Awerbuch, 2006; Awerbuch and Berger, 2003) or the wider energy system (Lesbirel, 2004), by not only taking into account the unit generating costs but also the variance in fuel costs and the correlations amongst different fuel costs. Rather than yielding one optimal generating mix, portfolio analysis provides an 'efficient frontier', a limit in the cost-risk domain beyond which (energy) investment portfolios cannot be made less costly without increasing their risk, or vice versa cannot be made more risk adverse without increasing their cost. Moving along this frontier represents different trade-offs between risk and cost. As such, MVP is an optimisation method rather than an indicator as are the others discussed here.

One unique element of this approach, which simultaneously constitutes its main point of criticism, is that it assumes past data to form a sufficiently firm ground for future projections. Data on costs of fuels in the past are used to estimate the risk and magnitude of future price movements. This has been opposed by Stirling (1999), who argues that under conditions of ignorance[8] no basis exists to assume that historic patterns will repeat themselves.[9]

Because fuels are substitutes or because prices are coupled (as with gas in parts of Europe, where its price is coupled to that of oil), price shocks in one market can have spill-over effects on others. Contrary to 'traditional' ways of measuring diversity, the MVP does address this issue.

3.1.8. Share of zero-carbon fuels

The Asia Pacific Energy Research Centre (APERC) uses an economy's efforts to switch away from a carbon intensive fuel portfolio as an indicator for acceptability. This is done by taking into account the share of renewables and nuclear in total primary energy supply (APERC, 2007). With regards to climate change, it

[5] The other way around however, certain dynamics remain unnoticed. Iran for instance is a net oil exporter. But due to its insufficient refinery capacity imports a substantial amount of its gasoline (IEA, 2007a). This entails dependencies that under the definition of net imports (or in this case exports) remain largely unnoticed.

[6] The original definition appears somewhat different (APERC, 2007), but after rewriting comes down to the above.

[7] for more info see http://www.prsgroup.com/ICRG.aspx.

[8] Stirling starts his elaborate work on diversity (Stirling, 1999) with a discourse on incertitude: the whole spectrum of uncertainty and risk, arguing that when it comes to energy systems, we are in a state of ignorance, where outcomes are poorly defined and no basis exists to assign probabilities to them (Stirling, 1999). As such, the idea that past data can provide probabilities to base future decisions on is rather heroic.

[9] An approach has been developed that aims to combine the probabilistic mean variance portfolio approach with a more precautious method advocated by Stirling. This method consists of adding the outcomes of both methods on a weighted basis, where the weight factor represents the level of trust in historic trends as a guide for the future (Awerbuch et al., 2006).

would be more adequate to take the carbon content (g/GJ) into account. It should be noted that acceptability concerns also exist regarding other energy options, e.g., nuclear energy.

3.1.9. Market liquidity

Market liquidity relates to the capacity of markets to cope with fluctuations in supply and demand and is therefore relevant to a discussion of SOS. The IEA included a market liquidity measure in their information paper on SOS (IEA, 2004a), defined as the exponential function of the ratio of a country's consumption over the total of that fuel available on the market. The concept of market liquidity is also linked to price elasticity. For stock markets, it has been suggested to use a coefficient of elasticity of trading (CET) as an indicator of market liquidity (Datar, 2000), defined as the relative change in trading volume over the relative change in price. Values below unity indicate an inelastic market, while values above unity indicate elastic markets.

3.1.10. Demand-side indicators

Also a range of demand-side indicators has been proposed in relation to SOS, mostly as they are relevant for the size of impacts of energy shortages. Important indicators include the energy or fuel intensity of the economy. Both indicators are relevant as they indicate the dependence of economies for energy – and therefore also the sensitivity to price changes. It has also been proposed to use energy intensity indicators relative to a benchmark. Oil use per capita plays as an indicator a similar role.

Another category of indicators relates SOS to energy expenditures (Kendell and James, 1998). Here one may argue that high expenditures are indicative of great difficulties in supplying resources. Moreover, expenditures directly relate to affordability, one of the key dimensions of SOS. For this purpose, it is useful to monitor expenditures vis-à-vis income measures. For the poor, other indicators may be envisioned that rely less on monetary values – an example is the availability of traditional biomass in the face of growing food requirements (Van Ruijven et al., 2008). Such indicators, however, have as yet hardly been used in the context of SOS indicators. Finally, some indicators focus on the question in which sector energy is used, identifying sensitivity to SOS problems (e.g., the share of oil used in the transport sector, since the transport sector is specifically inelastic and has little substitution options).

3.2. Aggregated indicators (or indices) for energy security

3.2.1. Shannon index based (Jansen et al., 2004)

Jansen et al. (2004) used the Shannon index (see Appendix A) as the heart of their aggregated indicator. They applied a combined Shannon index that captures fuel diversity but also diversity in suppliers for the share of imports of each fuel. These suppliers are also attributed a political stability factor, based on a modification of the UNDP's human development indicator. Thus more weight is given to the suppliers that are thought to be political stable. Also, resource depletion is taken into account through the inclusion of a depletion index for the exporting regions and home region considered. This index rests on the assumption that markets will respond to information on reserve/production ratios if these drop below a value of 50 (Jansen et al., 2004). The resulting indicator is mathematically represented in Appendix C.

While this aggregated index captures several parts of the SOS concept, the balance between different elements (fuel diversity, import dependence/diversity, political stability and depletion) lacks a fundamental ground, and as such remains arbitrary (IEA, 2007a). A similar critique holds for the assumption of the threshold for reserves-to-production ratios (IEA, 2007a). The import diversity measure emphasizes the accessibility element of SOS – which might not be as relevant under all scenarios/worldviews.

3.2.2. The IEA's energy security index

The IEA constructs two indicators for SOS. One deals with the physical unavailability, which is applied to markets where prices are regulated. This indicator is defined as the share of a country's total energy demand met by pipe-based gas imports purchased through oil – indexed contracts. The rationale behind this is that pipelines generally do not allow consumers to switch to other suppliers in case of a supply disruption, as opposed to LNG based trade. Secondly, the oil indexing of gas prices prevents market forces from mitigating supply disruptions.

The other indicator deals with price risks stemming from supply (or sellers) market concentration. The assessment of supply concentration is done by means of a Herfindhal–Hirschman Index (see Eq. (2), Appendix A). A measure of political stability is also included, giving extra weight to politically instable countries based on two of the six 'worldwide governance indicators' of the World Bank (see 4.1.6). The supply concentration measure for each fuel market is weighted according to the fuel's share in primary energy supply to assess a country's vulnerability to these concentration risks. The resulting supply concentration measure ESI_{price} is mathematically represented in Appendix D.

Here too, the balance between the parameters for supply concentration and political stability is arbitrary. On a more conceptual level, classifying supply concentration as the sole indicator of SOS stems from a particular perspective that has a firm trust in the functioning of (liberalised) energy markets. Dynamics of other aspects of SOS, such as depletion, are ignored.

3.2.3. S/D index

The 'supply–demand (SD) index' for long-term SOS (Scheepers et al., 2007) has been designed on the basis of expert assessments on all possible relevant aspects of SOS and covers demand, supply, conversion and transport of energy in the medium to long term. The values of each of the individual elements are determined by scoring rules which are simple functions of shares, supply origins, efficiencies, reserve factors, network capacity, refinery and storage capacity to name a few. The functions are deliberately kept simple in favour of transparency, which translates to mostly linear and step-functions where arguably more complex dynamics play a role. The factors are weighted on the basis of expert judgements.

The main difference with the other indicators considered here is that the SD index attempts to grasp the whole energy spectrum, including conversion, transport and demand, since a decrease in energy use lowers the overall impact of supply disruptions. This demand aspect is not included in any other indicator. Due to its comprehensiveness, the S/D index suffers from limited transparency as well as an extensive amount of weighing factors, even if these are deliberately made explicit.[10]

3.2.4. Willingness to pay

Bollen (2008) has constructed a 'willingness to pay function' for SOS for implementation in the MERGE model. It is designed to represent what percentage of GDP a country is willing to spend in order to lower the SOS risks. It is assumed that this willingness is higher for higher SOS risks, as indicated by: (1) high import

[10] Martin Scheepers, in personal communication with the author, declared that subjective nature of the concept of SOS was a motivation to make the subjective weight factors in the S/D index explicit. (Personal communication with Scheepers (30 August 2007)]).

quotes; (2) high shares of oil and gas in TPES and (3) high-energy intensities. The function is of the form

$$IMP_{t,r} = Ai^{\alpha}_{t,r}c^{\beta}_{t,r}E^{\gamma}_{t,r} \quad (2)$$

where IMP is the willingness to pay to avoid a lack in SOS (% of GDP); i is the import ratio of the fuel; c is the share of the fuel in TPES; E is the Energy intensity; A is a region specific calibration constant, relating to the SOS at $t = 0$; α, β, γ are the exponents with a value of 1.1, 1.2, 1.3, respectively.

The above measure is calculated for oil and natural gas only, as these are considered the main sources subject to potential SOS risks. The exponents α, β and γ are greater than 1, based on the assumption that the SOS risk increases faster as the dependency increases. The function is calibrated based on the investments nations have made in order to improve their SOS.[11] An interesting element here is that SOS is expressed in monetary terms. As such, this indicator intends to make SOS directly comparable to other cost estimates. However, in its application only one unique calibration is used (see previous footnote). Given our earlier emphasis on the worldview related interpretation of SOS this is rather unfortunate – and further development may focus on allowing for multiple calibrations. High values for α may for instance correspond to an A2 (Fig. 1) interpretation of SOS.

3.2.5. Oil vulnerability index (OVI)

Gupta (2008) computes an aggregated index of oil vulnerability based on seven indicators: (1) the ratio of value of oil imports to GDP; (2) oil consumption per unit of GDP; (3) GDP per capita; (4) oil share in total energy supply; (5) ratio of domestic reserves to oil consumption; (6) exposure to geopolitical oil supply concentration risks as measured by net oil import dependence, diversification of supply sources, political risk in oil-supplying countries, and (7) market liquidity (Gupta, 2008).

These are combined to yield an overall index, where the weighting is based on a statistical method called principal component analysis (PCA). In this method, the covariance of the indicators above is used to assign weights, rather than (subjective) expert judgments. This greatly increases the robustness of the results. However as with MVP, extrapolating statistical variance to obtain future projections may lead to concerns over this very same robustness.

3.3. Indicators in relation to the various elements of energy security

It is important to realize that the adequacy and relevance of the different SOS indicators depends on the context of use. Using the previously given four quadrants to outline possible SOS interpretations (Fig. 1), we map the indicators discussed so far onto the raster of perspectives or worldviews behind these four quadrants (Fig. 2). Appendix E discusses for each indicator the main arguments for the positioning in Fig. 2.

To provide an example of the importance of SOS concepts for the relevance of indicators: some of the indicators clearly focus on the aspects of affordability and acceptability. Their adequacy should be judged in relation to the preference of or emphasis on economic over environmental values. For instance, energy price (3.1.7) and demand (3.1.10) oriented indicators may be considered highly relevant in an economic efficiency oriented perspective (the left part of Fig. 1), whereas the share of zero-carbon fuels (3.1.8) will be seen as rather irrelevant or at best second order. In

[11] Specifically, France's investment programme in nuclear energy starting in the 1970s serves as reference point. From this it is inferred that France's willingness to pay for avoided SOS risks is in the range of a few per mille of GDP per year.

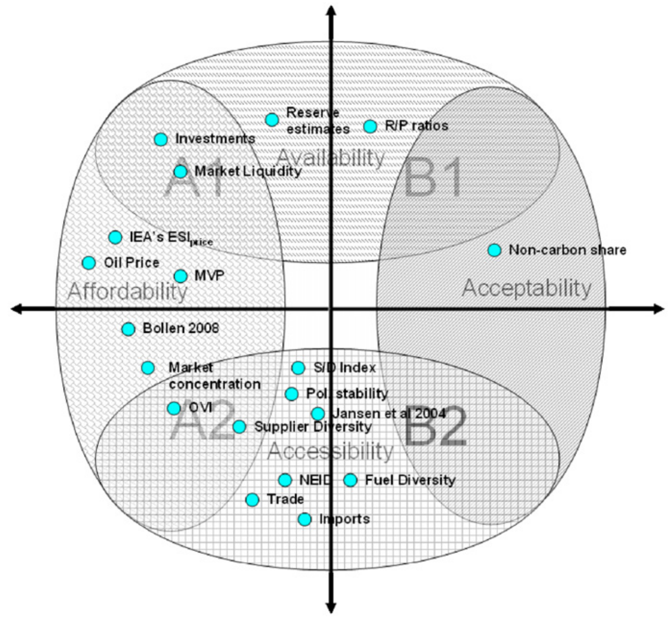

Fig. 2. The indicators considered in this study and the elements of the energy security spectrum they focus on.

some cases, using a set of indicators from different positions in Fig. 2 may help to broaden SOS considerations, and make them more relevant for different worldviews. In that context, it should be noted that not only the indicators themselves are context dependent, but also their actual elaboration (as briefly addressed for the diversity indicators and the willingness-to-pay index).

Table 1 provides an overview of the indicators and their required input data. As indicated in the introduction, we consider it important that indicators can also be used in analytical and prognostic studies using models. Therefore, the table also indicates the applicability in large-scale long-term energy models. Short-term variations in price, such as required for MVP theory, cannot be taken into account in such energy models and thus we have labelled these types of indicators as not applicable. In fact, given the known problems in projecting fuel prices, one may argue that it is uncertain whether these indicators can be usefully applied at all. Finally, we have indicated in the table whether the indicators are currently, to our knowledge, used in energy policy making.

4. Application in model-based scenario context

4.1. Application of selected indicators to SOS in Western Europe

As a practical application, we apply some of the indicators discussed above to the issue of energy security of supply in the next few decades, with a special reference to Western Europe. As indicated before, an evaluation of energy security does strongly depend on the context (development pathways), in terms of the actual situation but even more importantly in terms of the implication of certain developments.

Scenarios are used to explore different futures (De Vries, 2006). Typical alternative pathways that are explored in scenario analysis include: (1) market-focus scenarios, (2) adaptation of the first category, with certain corrections (reformed markets), (3) sustainable development pathways, (4) regional competition and (5) business-as-usual pathways (see, for instance, Van Vuuren, 2007). The SRES scenarios (Nakicenovic et al., 2000b), introduced in

Table 1
Overview of SOS indicators in the literature.

Indicator	Input data required	Scenario analysis with TIMER?	Current use in policy making?
Simple indicators			
Resource estimates	Quantity and likelihood of occurrence of fossil resources	+	Qualitatively
Reserve to production ratios	Resource estimates and production figures (at country or global level)	+	Qualitatively
Diversity indices	Shares of fuel in TPES or shares of suppliers in import	+	No
Market concentration	Shares of producers in the market	+	No
Import dependence	Import quotes of energy carriers	+	Yes
NEID (net energy import dependency, APERC)	Import quotes and shares of fuel in TPES	+	No
Political stability	Depending on the paradigm; HDI, various political risk ratings		Qualitatively
Oil price	The oil price		Yes
Mean variance portfolio	Share of generating technology/fuel in TPES; (expected) cost per unit of energy; (expected) short term variance in this cost		No
Non carbon	Share of fuel in TPES; carbon emission (*y*/*n*)	+	Yes
Market liquidity	Available fuel on the market/production, consumption/import needs	+	
Energy or oil intensity	PES (total or per fuel), GDP	+	Yes
Oil/energy expenditures	TPES, GDP, energy cost (fuel specific)	+	Limited
Energy or oil use per capita	TPES, population	+	Limited
Share of oil in transport sector	Sectoral energy use, total oil use	+	Limited
Share of transport sector in total oil use	Sectoral energy use, total oil use	+	Limited
Aggregated indices			
Jansen et al. (2004)	Shares of energy carrier in TPES; import quotes, shares of suppliers in imports; HDI and RPR per country/region	+	No
IEA's ESI_{price}	Share of producer in market (based on net exports), political risk rating per producers, shares of prim. Energy carrier in TPES. Additionally supply available on the market; global RPRs for fossil fuels.	+	No
S/D Index	Fuel shares in TPES, import shares, supplier shares in imports, long- or short-term contracts, energy intensity, detailed information on conversion and transport not further specified here (see Scheepers et al. (2007))	+	No
Bollen (2008) MERGE	Import quotes; fuel shares in TPES; energy intensity; historic calibration	+	No
OVI (Gupta 2008)	Import quotes, GDP, oil price, TPES, shares of oil suppliers, ICRG	+	No

Section 3.3 to frame different notions of energy security, explore several of these futures. Energy security indicators are likely to develop in different ways in each of these scenarios. However, as the focus here is more on exploring the applicability of different indicators, we use a simpler approach in which we confine ourselves to two scenarios: an OECD baseline scenario and a stringent climate policy scenario.

These scenarios have been elaborated using the TIMER model, which is energy-system model describing long-term developments of the energy system (van Vuuren and de Vries, 2001; Van Vuuren, 2007). The OECD baseline (OECD-B) scenario describes a world under medium assumptions for factors such as economic growth, population and technology development (OECD, 2008; MNP, 2008). It assumes no major shifts in current policy regimes and shares many qualitative assumptions with the SRES A1 storyline (economic focus) – but in terms of quantitative assumptions it is more comparable to the SRES B2 scenario. On the basis of this OECD-B scenario, a second scenario has been developed that aims at stabilisation of greenhouse gas concentrations at 450 ppm CO_2-eq by 2100 (see also Van Vuuren et al., 2007). This stringent climate policy scenario (OECD-CP) is implemented by the forced imposition of a carbon tax which induces emission reduction by means of energy efficiency improvement, fuel switch, and use of technologies with carbon capture and storage.

Carbon emissions are reduced by about 40–50% in 2050 compared to 2000. In Table 2 we show the position of these two scenarios vis-à-vis the SRES scenarios. In the discussion section, we discuss the implications of using the OECD scenario vis-à-vis alternative 'SRES futures'. Under the OECD baseline scenario, global energy demand is projected to increase to 865 EJ in 2050 (MNP, 2008, OECD, 2008), of which demand for oil constitutes 288 EJ. In the OECD-CP (450 ppm) scenario, oil demand declines to 132 EJ/yr and total primary energy use to 635 EJ/yr by 2050. With this application we gain more insights into the adequacy of indicators as a policy tool for present and future energy security developments. In our discussion, we do not focus on the differences in environmental indicators between these scenarios (acceptability). Still, the OECD-CP scenario per definition has a much lower greenhouse gas emission than the OECD-BL scenario. As a co-benefit of climate policy, also the emissions of air pollutants are significantly reduced (see also Mayerhofer et al., 2002; van Vuuren et al., 2006).

4.2. Oil

The projected increase in oil demand implies that in the OECD-B scenario, globally the conventional proven oil reserves are depleted around 2035 and production needs to come from speculative resources (Fig. 3) and unconventional oil reserves. In contrast, the lower oil demand of the climate policy case implies that a substantial amount of the estimated and speculated reserves are still in place even in 2050. For Western Europe specifically, domestic proven oil reserves are projected to be depleted by 2025 in the baseline, as are most of the conventional

Table 2
Position of the OECD baseline and climate policy scenario versus the IPCC SRES scenarios.

	SRES				OECD	
	A1	A2	B1	B2	OECD-B	OECD-CP
Main focus (archetype)	Economic optimism	Regional fragmentation	Global sustainability	Regional sustainability	Business as usual	Reformed market
Environmental policy	Reactive	Reactive	Pro-active; no explicit climate policy	Pro-active; no explicit climate policy	Reactive	Reactive except for stringent climate policy
Openness	Connected world	Competition	Connected world	Regional focus	Connected world	Connected world
Global population (2050)	8.2	10.4	8.2	9.0	9.1	9.1
Global economic growth (2050)	22.7	9.7	18.3	14.5	15.2	15.2
Primary energy use	1250	978	805	863	865	635

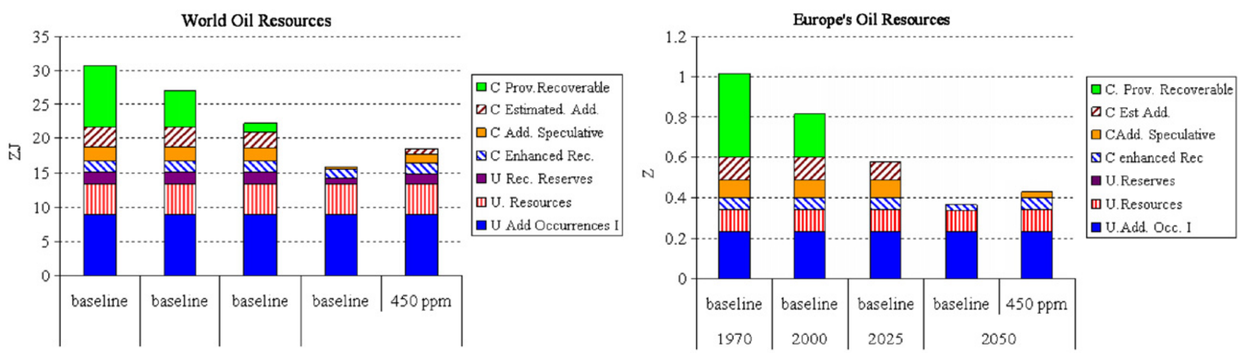

Fig. 3. Oil resources of the world and those of Western Europe. Depletion under baseline and climate policy scenario.

estimated and speculative reserves by 2050. Under the OECD-CP scenario, a fraction of these uncertain resources is expected to still be in place in 2050. In each of the scenarios, the increasing scarcity of oil is reflected by the use of more speculative resources. Thus, depletion of oil is significantly reduced in the climate policy scenario. In a perspective on oil security with a focus on availability, there are clear positive co-benefits of climate policy for energy security (B1).

The available indicators also show increasing concentration of supply. In the OECD-B scenario, the majority of the increase in oil production from 2000 to 2025 will come from the Middle East. This is consistent with IEA's World Energy Outlook (IEA, 2007a,b,c,d). However, after 2030 the TIMER model expects the share of the Middle East in world oil production to decline as production of unconventional oil production from Canada and, to a lesser extent, South America start to increase. Furthermore, conventional oil production in Brazil and Russia increases. This implies a decline in production and market concentration after 2030. In the climate policy scenario, lower oil demand leads to a situation where oil production will still predominantly come from the cheaper reserves in the Middle East and Russia. As a result, supply concentration is higher in 2050 (Fig. 4). Interestingly, from a perspective emphasizing accessibility/supply concentration (especially A2), the synergy between climate policy and energy security will therefore not be as evident. At the same, lower demand also implies lower Western European imports (see further).

4.3. Natural gas

For natural gas the global, currently proven conventional reserves are projected to be depleted under the OECD-B scenario by 2050, with projected world natural gas use of 221 EJ/yr against 184 EJ/yr in the OECD-CP scenario. In both cases, a fair amount of the estimated and speculative conventional resources is expected to be still in place by then so that unconventional reserves will not be exploited in the period considered. In the TIMER model (and in most models) demand for natural gas is not reduced as severely by climate policy as demand for oil and coal, mostly due to its lower carbon content. Consequentially, depletion of natural gas resources is comparable in the two scenarios. For Western Europe specifically, the situation is somewhat different as domestically proven conventional natural gas reserves are projected to be depleted by 2025 in both the OECD-B and OECD-CP scenario. After 2025 supply will have to come from speculative resources and/or imports. In other words, for natural gas climate policy seems to have no real co-benefits from an availability perspective. Future supply diversification will depend on the pipe-line infrastructure and/or development of major LNG transport. In the TIMER model, production and trade are mainly driven by price differences – and as a result "new connections" between regions are made if price differences provide an incentive and existing trade limitations are assumed to disappear. Under these assumptions, natural gas production in the OECD-B scenario initially becomes geographically more diversified, in contrast to oil, because several potential suppliers have produced relatively little natural gas so-far. After 2020, however, Russian and Middle Eastern production is projected to become more dominant and both the production and export concentration indicators increase for the given assumptions on trade. Growth in Russian production is projected to level off in 2030 and be surpassed by the Middle East as the largest producer of natural gas. Depending on, amongst others, the LNG-developments, the Middle East produces by 2050 still over one third (37%) of world natural output. The projection under the OECD-CP scenario differs only slightly, having a somewhat lower supply concentration.

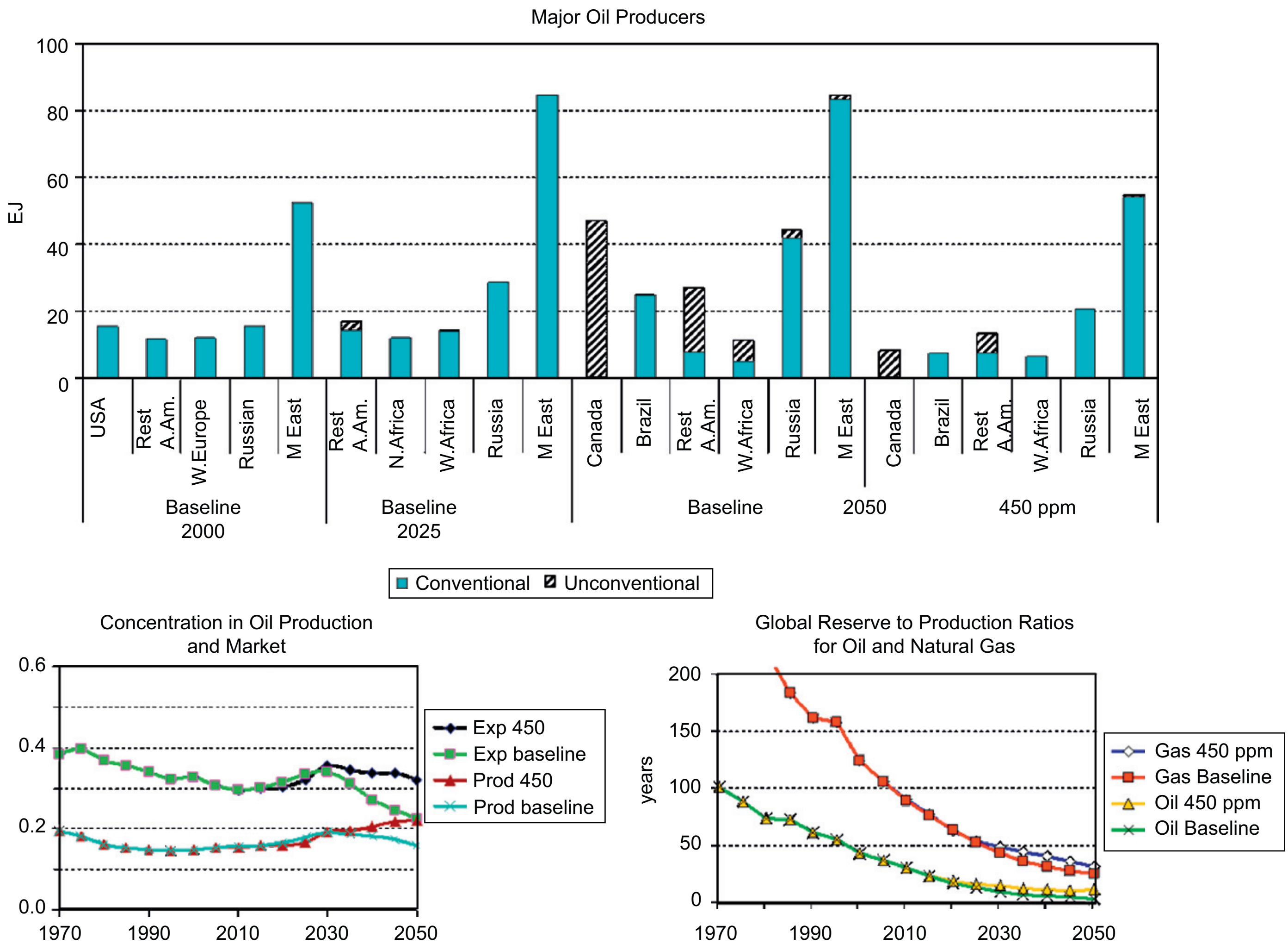

Fig. 4. The five main oil producers in respective years. Concentration in the production and export market for oil (with 0 a perfect market with equal shares for an infinite number of suppliers and 1 a monopoly); RPRs for oil and gas.

4.4. Coal

The global proven reserves of coal are very large and this will still be the case by 2050. Additional recoverable reserves are huge, in the range of 100 ZJ. This translates into a high RPR for coal, although it declines from a current 167 years to 81 in 2050. In the OECD-CP scenario global coal production is reduced by as much as 139 EJ/yr in 2050 compared to the baseline. Supply is expected to become slightly more concentrated.

4.5. Trade

One consequence of the rising world energy demand is an increase in internationally traded energy. Fig. 5 shows the share of total energy demand met through international trade, as well as the shares of dominant fossil energy carriers and modern biofuels. With international energy trade increasing in both absolute and relative terms, regions become more dependent on each other. As a result, the risk and consequences of a disruption will increase.

The major differences in the OECD-CP scenario are the lower oil trade in absolute terms (−100 EJ/yr), partially substituted by an increase in biofuel trade (+40 EJ/yr). Also global coal use (−139 EJ/yr) and thus trade (−26 EJ/yr) are lower than in the OECD-B scenario. This implies that indicators that are related to the acceptability perspective (emphasized in the A2 and B2 perspective) show a clear decrease in energy security under the baseline scenario, which could partly be offset by a stringent climate policy.

4.6. Imports

As a result of mildly declining oil use, under the OECD-B scenario the oil import share in Western Europe remains high and more-or-less constant (between 60% and 70%). The larger part of the oil import is projected to come from the Middle East, with a smaller share coming from Russia. By the end of the scenario period, the shares of the Middle East and Africa decline in favour of domestic production and unconventional oil from Canada in particular. In the OECD-CP scenario, the oil import in Western Europe will decline significantly in absolute terms but only marginally in relative terms with respect to the OECD-B situation.

For natural gas, Europe's dependency on imports is projected to increase, reaching over 60% in 2050. Most of this demand is met by natural gas from the former Soviet Union and consequently the import diversity for natural gas is rather low. Based on these indicators, it is understandable that in Europe the discussion of SOS centres around natural gas. In the OECD-CP scenario, gas imports decline roughly 5%-points in the last decades of the

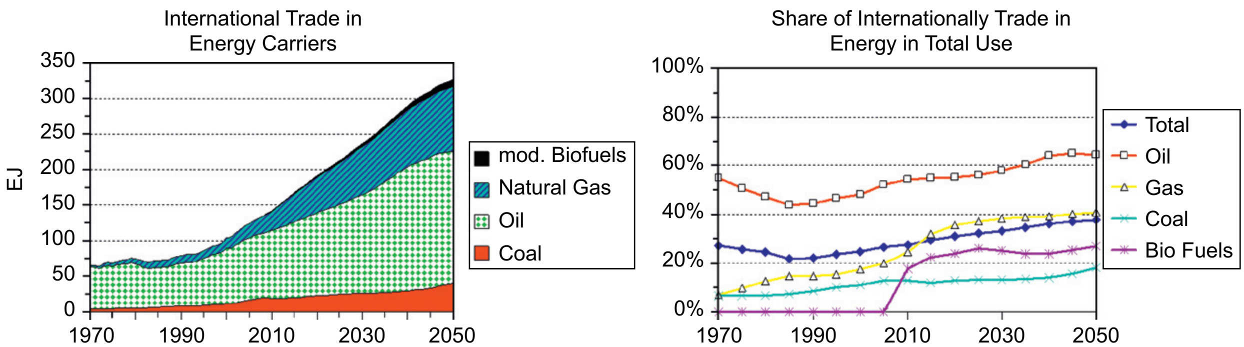

Fig. 5. Trade in energy carriers; Absolute and as share of the carrier's total global demand. Based on (crude) net exports divided by respective PES. No trade is modelled for nuclear, wind/solar and hydro. OECD baseline scenario.

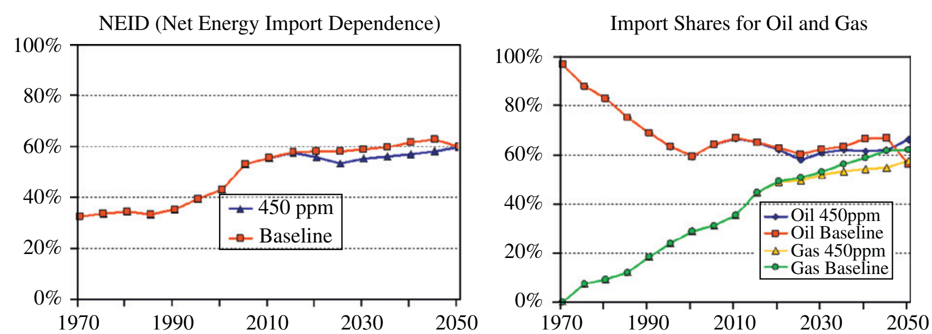

Fig. 6. NEID indicator (APERC, 2007) a combined measure of imports and diversity, and import shares for oil and gas.

projection period in comparison with the baseline; the diversity in suppliers remains the same. These outcomes suggest, again, that accessibility oriented indicators show a decreasing SOS for oil and natural gas, while climate policy has co-benefits in the case of oil but not or much less for natural gas.

4.7. Fuel diversity and demand-side indicators

Fuel diversity indicators such as the Shannon index strongly depend on the number of different energy carriers accounted for (see also Section 3.1.3). In most models – and also in the TIMER model – the number of different energy carriers taken into account is limited to about 10 primary energy carriers, providing a natural focus for these types of indicators used at high aggregation level. Besides, we emphasize comparative trends more than absolute values. In Western Europe the growth of electricity from solar/wind and of modern biofuels contributes to an increase in fuel diversity, as measured by a Shannon index of diversity (see Appendix A for details). In the OECD-CP scenario the increase in renewables is much larger, but the resulting benefits for fuel diversity are offset by a substantial decrease in the share of coal in TPES. Contrary to China, for instance, where the share of coal is so large that a decrease actually improves diversity, in Europe a decrease in the coal share does not improve fuel diversity (Van Vuuren et al., 2003).

Another interesting trend is that in all countries oil use is becoming more and more concentrated in the transport sector (as it is substituted by natural gas and coal in other sectors such as power generation). This sector is rather inelastic with regard to price changes, and as such is vulnerable to disruptions. In Europe, the share of the transport sector in oil use increases from a current 72–92% in the 2050 in the OECD-B scenario; climate policy is unlikely to curb this trend. The calculations also show that prices for oil and natural gas are projected to rise the coming decades. With regards to this though, it should be noted that prices in the TIMER model are subject to a large number of simplifications. These prices should be interpreted as a trend that is mainly depletion driven. Based on this, one can expect the SOS to decline if expressed in terms of affordability. This gets even worse with climate policy as it leads to even higher energy costs (Fig. 6).

4.8. Aggregated indicators

The IEA's ESI_{price}, describing concentration in fossil fuel supply, is constant for Western Europe in the OECD baseline, as is shown in Fig. 7. Climate policy will lower the ESI a bit, as an increased concentration in the oil supply market is offset by a decrease in fossil fuel use. The indicators proposed by Jansen et al. (2004) show a rather stable trend over the projection period. Here, climate policy tends to lead to a somewhat higher SOS (Fig. 7). The supply–demand index also shows a rather stable trend over the projection period, with surprisingly little change in the OECD-CP scenario. Groenenberg et al. (2006) have shown that climate policies (energy efficiency and targets for renewables) can lead to as much as a 10% increase in the S/D index by 2020 for the EU-25. In our variant[12] of the S/D index, the change for Western Europe under the 450 ppm climate policy scenario is insignificant in 2020 compared to the baseline. This steady behaviour over time and insensitivity to different scenarios of the S/D Index may stem from the high level of aggregation.

Indices obviously are designed to combine different aspects of SOS. Such a combination will always imply a certain weighting

[12] The S/D Index was adapted in order to be included in the TIMER model; the scope of the original index is on EU member states, whereas ours is on 26 world regions. Also, some scoring rules were changed.

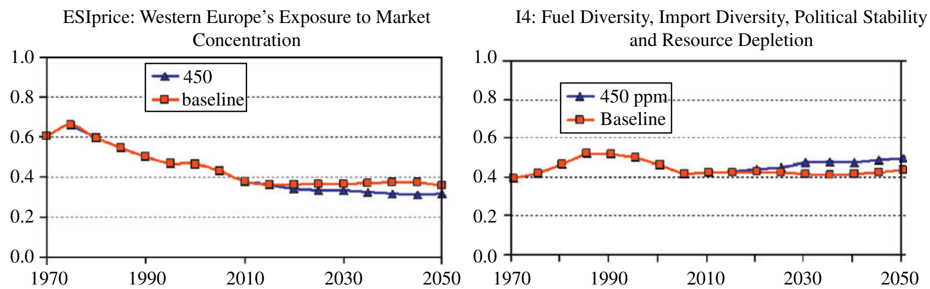

Fig. 7. Aggregated indicators suggested by IEA, 2007a,b,c,d and Jansen et al., 2004.

Table 3
Relative contribution of different aspects in the SOS indices of Jansen et al. (2004) and IEA's ESI. The table shows the change in indicator value from removing different elements (in the order as they are listed).

Relative contribution to indicator value			
(Averaged over 4 regions)		2025 (%)	2050 (%)
Jansen et al. (2004)	Import diversity	19	25
	Political stability	2	1
	Resource depletion	15	16
IEA's ESI_{price}	Political stability	70	55
	Resource depletion (additional)	53	71

and thus a bias towards one or the other perspective or worldview. In that context, Table 3 shows the relative change in indicator value with each successive additional measure included for both the the IEA's ESI_{price} and the indicators proposed by Jansen et al. (2004). As some of the underlying indicators attempt to measure the same phenomena, the very different composition of these indicators again emphasizes the arbitrary character of SOS indicators.

4.9. Alternative scenarios

As SOS is strongly context dependent, here we explore briefly some consequences of alternative future scenarios, i.e. the SRES scenarios. As indicated in Table 2, OECD-B is a "medium" scenario which shares elements of the A1 storyline but uses lower growth assumptions as in the B2 storyline. Under the A1 scenario (cf., Table 2 and Fig. 1) a major focus of a SOS policy would be to ensure a low-cost energy supply and avoid global depletion of resources. The high economic growth in this scenario and the reliance on fossil fuels imply that resources would be depleted faster than the in the OECD-B scenario. Several trends described for OECD-B may therefore be even more clearly visible in the A1 scenario (earlier depletion; stronger reliance on import). The main SOS question in this world would be whether alternatives to conventional fossil fuel supply (renewables, nuclear, unconventional resources) can be developed fast enough to continue provision of low costs energy.

In the A2 scenario (Table 2) a major focus of a SOS policy would be to ensure accessibility – given the emphasis on regional economic growth. This, and reduced trade, will imply a major focus on domestic energy resources. In the short term, import trends in OECD-B may therefore be very different in an A2 world. However, a major question here is whether sufficient domestic resources are available. If not, local depletion will in the future have to be substituted for by increased imports, thus eroding the original policy effort. In the B1 world the focus on renewables and efficiency leads to a lower fossil fuel use than in OECD-B. Because assumptions on energy trade, however, are similar, trends with regard to depletion and import dependence are likely to be somewhat delayed. A challenge in the B1 scenario would be whether renewable energy resources are sufficiently and timely available to find synergy between SOS and environmental policies. Finally, developments in the B2 world would be similar to the OECD baseline.

5. Discussion

Capturing a broad notion as SOS in indicators inevitably leads to simplification. Moreover, while indicators suggest some form of scientific objectiveness, their value cannot be interpreted independent from the context. Indeed, one may question whether the indicators make much sense as real metrics, instead of (subjective) relative position or trend. In this article, we have discussed SOS in a broad, comparative and dynamic context in order to include all dimensions of SOS in the literature. As a consequence, one cannot make firm, unambiguous statements. On the other hand, such a broad approach uncovers the different interpretations and trade-offs in the evaluation of the aspects of availability, affordability, acceptability and accessibility. For instance, environmental sustainability is traditionally not regarded as an element of SOS, although it is highly relevant for energy policy and in complex ways depends on other SOS aspects.

The indicators discussed in this study have clear limitations, certainly in combination with the simplifications usually made in large-scale long-term energy models.

- They do not capture the differences in transport modes that are used (e.g., pipelines or ships; and the associated risks, including flexibility). Only the IEA briefly touches upon it when distinguishing price risk and volumetric risks. However, energy models typically do not explicit model transport modes. Relatedly, energy security for natural gas critically depends on the available infrastructure such as (alternative) pipelines and LNG capacity. This is typically not captured in energy security indicators.
- Geopolitical relations are extremely hard to quantify and typically one has to rely on expert judgement. Global energy and/or economic scenarios may support such assessments.
- Energy models with a long-term focus are unfit to investigate price volatility, something that is considered damaging to consumers and hence relevant for a discussion of SOS. Indicators incorporating this (such as mean variance portfolio theory) can only be used in models with short-run dynamics.
- Trade in energy carriers other than coal, oil, natural gas and modern biofuels is generally not modelled. Although there is trade in uranium and electricity derived from solar, wind and hydro is traded across borders, these amounts are typically small, even more so in view of the small shares in the fuel mix. Therefore this is deemed not significant for our results.

- The assumptions with regard to resources and costs of unconventional oil critically determine the (partial) transition from conventional to unconventional oil presented above. The degree to which these resources will be used depends on technology development, associated costs and public acceptance of the environmental consequences.
- The S/D Index is a complicated indicator, which gives rather similar results under different scenarios. In this study we have refrained from a sensitivity analysis, but the use of this indicator could benefit from it, especially since it was originally designed for a cross-member state comparison in the EU 25. The high level of aggregation may contribute to the rather ambiguous results of this indicator, in the sense that the large number of parameters tends to balance out different aspects at the aggregate level.

Given the subjective and context-dependent nature of the SOS concept, in assessing energy security trends one may prefer to use a wide range of indicators that cover the different relevant aspects. Indices that cover multiple dimensions of energy security are inherently subjective, as there is no fundamental basis to assign weights on. This is shown here for two indices (Jansen et al., 2004 and IEA's Energy Security Index) in Table 3, which in fact measure very similar factors. The effect each has on the final indicator value is significantly different however. We argue that such indicators are most useful to point out important trends in a dynamic, comparative framework rather than to focus the specific outcomes from these factors.

6. Conclusions

In this study, we have made an overview of indicators of SOS in the literature and used them in scenario analysis. We emphasize that there are different perspectives on SOS. We have classified these perspectives and according elements of the energy system on which they focus into the four categories (after APERC, 2007): Availability, Accessibility, Affordability and Acceptability. Furthermore have we applied a selection of these indicators in model-based scenario analysis, with a focus on Western Europe and the interactions with a low concentration stabilisation scenario. Our main conclusions are presented below.

6.1. *Focussing on different aspects of energy security yields different outlooks*

Energy security or SOS as a concept is open to various interpretations. As indicators are designed from specific perspectives on SOS, they as such focus on different elements of the SOS 'spectrum'. Therefore, we consider it not possible to unambiguously assess SOS based on a single indicator. Rather, we have attempted to classify the indicators with regard to the perspective from which they were designed and as a result the elements of the energy system they focus on. This is schematically represented in Fig. 2. The discussion in our case study for Western Europe shows that different aspects of energy security might move in very different directions. Based on the subjective character, one may also argue that for energy security indicators are useful to depict trend but their exact values have only a limited meaning.

6.2. *Trade-off between comprehensiveness and transparency*

Aggregation of various elements into one 'aggregated' indicator provides the potential pitfall of hiding the underlying dynamics from sight. Furthermore, it is difficult to obtain consensus on the absolute values of the weights assigned to each of the building stones of such indicators. The fact that these weights are (to a certain extent) inherently perspective dependent may also form an objection to their use in policy making. Thus, there seems to be trade-offs between comprehensiveness, transparency and subjectivity. The closer one gets to encompassing all relevant elements the less straightforward the resulting outcome is.

6.3. *The availability of sufficient energy to meet growing global demand is not self-evident*

Our projections suggest that as a result of increased global demand, the conventional proven oil reserves could be depleted around 2035 after which oil production needs to come from speculative and unconventional resources. Climate policy as simulated in the 450 ppm stabilisation scenario will slow down depletion slightly, but the conventional proven reserves would still be depleted before 2050. The proven conventional reserves of natural gas are also projected to be depleted by 2050 in both scenarios. Coal reserves however are still abundant, and in view of current consumption will last more than 100 years.

6.4. *Access to energy is projected to undergo significant changes as consuming regions become increasingly dependent on imported energy*

We used several indicators in a case study for Europe, based on medium growth scenario. Under this scenario and using the IMAGE/TIMER energy model international trade in energy carriers is projected to increase considerably (by 142% in 2050 compared to 2008 under the OECD scenario). The increase in energy trade can be noted in many other scenarios. Not only does the absolute amount of traded energy increase, the share of total energy consumption that is traded internationally also increases from a current 27% to 38% in 2050. In the OECD scenario, the fraction of oil that is imported into Western Europe is projected to stay around 65% in the years up to 2050, whereas the import share of natural gas is projected to rise to 62% in 2050. As in the OECD scenario most of this gas will come from the Russia, import diversity is also fairly low for Western Europe. This result depends on the development of LNG as alternative transport mode.

Diversity in energy carriers on the other hand is projected to increase due to increased renewable consumption. Under the stabilisation scenario, where the increase of renewables in the energy mix is much larger, fuel diversity is higher, although partially offset by a decrease in coal consumption. The aggregated indicators that take a number of accessibility elements into account (Jansen et al., 2004 and S/D index) show a constant, stable trend under the OECD baseline scenario. Their level of aggregation may contribute to this, as different parameters balance out.

6.5. *Energy is projected to become more expensive*

The affordability of energy is projected to deteriorate as prices of fossil fuels rise in all scenarios. Next to that, the production of oil is expected to be concentrated in fewer regions the coming decades, only to diversify again towards 2050 as oil production from Canada and South America increase strongly. In case of reduced demand due to stringent climate policy, these more expensive resources may not be called upon and the diversity in production remains lower. On the other hand, gas production in the TIMER OECD scenario is projected to diversify up to 2025, after which it becomes more concentrated again. By 2050 the 2 major gas producers will be the Middle East and Russia. The IEA's combined measure which takes into account the exposure to these supply concentration risks shows rather steady exposure for Western Europe over the coming decades.

6.6. *The effects of climate policy on SOS are two-fold. There are co-benefits as well as undesired consequences*

Climate policy may bring ancillary benefits to SOS, the most notable being delayed fossil resource depletion due to reduced fossil demand and enhanced fuel diversity. However, supply concentration in the oil and coal markets is projected to be higher under the climate policy scenario compared to the baseline. In the case of oil, this is because with reduced demand for oil, the more expensive, and unconventional (both in terms of technology and region) resources are not developed. The different co-benefits and trade-offs imply that the usefulness of climate policy for energy security is perspective dependent. Climate policy reduces the depletion rate for oil (attractive from a B1 perspective). It also reduces energy imports (for instance in Western Europe) – but at the same time increases supply concentration (thus resulting in a mixed evaluation from an A2/B2 perspective). And while climate policy reduces the impact of depletion on oil prices, it also leads to an increased use of more expensive fuel-types (leading to a trade-off between climate policy and affordability).

Appendix A. : Dual concept diversity indices

The two indices mostly used to measure diversity are presented below. The first is the Shannon index (sometimes Shannon–Weiner of Shannon–Wiener index):

$$H = -\sum_i p_i \ln p_i \tag{A1}$$

with p_i representing the share of fuel i in the energy mix or the market share of supplier i. The higher the value of H, the more (dual concept) diverse the system is. This index rises monotonically with increasing variety and balance. Next, there is the Herfindhal–Hirschman index (HHI, also named Simpson index in ecology):

$$D = \sum_i p_i^2 \tag{A2}$$

with p_i again representing the share of fuel i in the energy mix, or the market share of supplier i. The lower the value of D, the more dual concept diverse the system is. The reciprocal of this quantity is therefore also used, so that a higher index value implies higher diversity. Fig. 8 shows the above two indices, as well as the complement of the HHI, for a simple system of 3 categories.

Various studies have applied the Shannon index or a variation of it to assess the fuel diversity (Grubb et al., 2005; Jansen et al., 2004; APERC, 2007; Li et al., 2008). Only Neff (1997) uses the HHI to assess fuel diversity (Neff, 1997). However, in case supply concentration (essentially a lack of diversity in suppliers) is calculated, the HHI is almost exclusively used (Percebois and Jaques, 2006; Grubb et al., 2005; IEA, 2004a, 2007a, Neff, 1997).[13] As discussed before, the indices display large similarities.

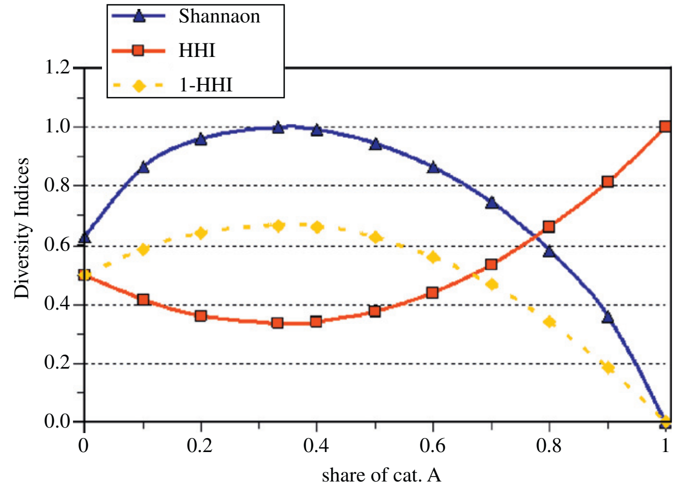

Fig. 8. (Normalised) Shannon index and HHI for a system of 3 categories, of which one is varied along the *x*-axis and the remainder is spread over the other 2 categories. High values for the Shannon Index imply high diversity whereas high values for the HHI imply low diversity. Hence its complement (1-HHI) is also shown. Maximum diversity when all have an equal share (here 0.3). Minimum when one has all (monopoly).

Appendix B. : mean variance portfolio (MVP) theory

For a simple 2-stock (or 2-technology) portfolio the expected portfolio return is given by Eq. (4) (from Awerbuch and Berger, 2003 and Awerbuch et al., 2006):

$$E(r_p) = x_i E(r_1) + x_2 E(r_2) \tag{B1}$$

with $E(r_p)$ is the expected portfolio return; x_i is the share of asset i in the portfolio; $E(r_i)$ is the expected return for asset i. Specifically; the mean of all possible outcomes, weighted by the probability of occurrence; e.g., for asset i: $E(r_i) = \sum p_i r_i$, with p_i the probability that outcome i will occur, and r_i the return under that outcome.

The risk is a function of the individual asset-risks, as well as their correlation;

$$\sigma_p = \sqrt{x_i^2 \sigma_1^2 + x_2^2 \sigma_2^2 + 2 x_1 x_2 \rho_{12} \sigma_1 \sigma_2} \tag{B2}$$

with ρ_{12} is the correlation coefficient[14] between the two return streams; σ_i is the standard deviation of the periodic returns of asset i.

Mean variance portfolio can be made to suit the analysis of energy portfolios, by interpreting expected returns as the reciprocal of unit generating cost (kWh/€ct or similar). The risk of an individual asset or energy technology is then given by the variance in generating cost, which is governed by fuel costs rather than capital costs. In order to make future projections, the risk for the future is given by past price fluctuations.

[13] The observation that the Shannon index is predominantly used while calculating diversity among fuels/generation options (Grubb et al., 2005; Jansen et al., 2004; APERC, 2007) and the HHI index is exclusively used in case of market concentration is interesting. Stirling (1999) in his elaborate work on diversity favours the Shannon index over the HH index, based for 2 reasons. First, the Shannon index retains rank ordering under variations of logarithm base, whereas the rank ordering of different systems changes as the exponent of the Simpson index changes. As there is no fundamental argument why the exponent should be 2, this raises doubts with regard to the firmness of the results obtained, since by

(*footnote continued*)
changing an apparently non-related parameter, the outcome will differ. Second, the Shannon index displays the property of additivity with respect to taxonomy. This means that when classifying options based on several criteria, the index score for the system classified according to criterion a, plus the index score for the system classified according to criterion b should amount to the same as the index score for the system classified according to the combined criterion *ab*. This is mathematically represented as $f(ab) = f(a)+f(b)$, with a and b sets of options under different classifications and f the index or function in question.

[14] The correlation coefficient between the portfolio components (the degree to which the (price) fluctuations correspond) either dampens or amplifies the risk, depending on whether the correlation is positive or negative.

Appendix C. : Shannon index

Jansen et al. (2004) devise 4 indicators which successively take into account more elements. The last (most complete) two are given below:

$$I_3 = -\sum_i c_i p_i \ln p_i \quad \text{(C1)}$$

where

$$c_i = 1 - m_i(1 - S_i^m / S_i^{m,\max}) \quad \text{(C2)}$$

and

$$S_i^m = -\sum_j h_j m_{ij} \ln m_{ij} \quad \text{(C3)}$$

with p_i is the share of primary energy source i in total primary energy supply; $i = 1, 2, 3, \ldots, M$: the number of primary energy sources; m_i is the share of net import in PES of source i; $S_i{}^m$ is the Shannon index of import flows of resource i; m_{ij} is the share of imports from region j in total import of source i; $j = 1, 2, 3, \ldots N$: index for (foreign) region of origin. N regions are distinguished. $S_i{}^{m,\max}$ is the maximum value of Shannon index of import flows of resource i. $(= -\ln\{1/N\})$; h_j is the political stability in region j, ranging from 0 (extremely unstable) to 1(extremely stable).

The indicator accounting for resource depletion:

$$I_4 = -\sum_i c_i^4 p_i \ln p_i \quad \text{(C4)}$$

with

$$c_i^4 = \{1 - (1 - r_{ik})(1 - m_i)\} * \{1 - m_i(1 - S_i^{m**} / S_i^{m**,\max})\} \quad \text{(C5)}$$

$$S_i^{m**} = -\sum_j r_{ij} h_j m_{ij} \ln m_{ij} \quad \text{(C6)}$$

r_{ij} = depletion index for resource i in import region j, subject to;

$$r_{ij} = \text{Min}\left\{ \left[\frac{(R/P)_{ij}}{50}\right]^a ; 1 \right\} \quad (a \geqslant 1) \quad \text{(C7)}$$

r_{ik} = depletion index for the home region k, for which the indicators are determined. R/P_{ij} = proven reserve to production ratio for resource i in region of origin j.

Appendix D. : Energy security index (ESI_{price}) (IEA, 2007a)

The International Energy Agency devised an indicator to measure a country's exposure to concentration in fossil fuel markets (IEA, 2007a):

$$ESI_{price} = \sum_f \left[\left(\sum_i r_i S_{if}^2 \right) \frac{C_f}{TPES} \right] \quad \text{(D1)}$$

with S_{if} is the share of supplier i in (fuel) market f. r_i is the political risk rating of country i. C_f/TPES is the share of fuel f in TPES.

Appendix E. : Indicator mapping rationale

Table A1 below provides the rationale for the positioning of the SOS indicators in Fig. 2. This should not be interpreted in an overly strict way. Roughly 8 areas can be distinguished, based on the 4 dimensions and the combinations of these 4 into 4 overlapping areas.

Table A1
SOS indicators and their relationships to different SOS dimensions.

Indicator	Rationale for position in SOS-spectrum	Main dimension of SOS			
		Av	Acs	Aff	Acp
Simple indicators					
Resource estimates	Physical existence of resources forms the basis for potential availability. If a classification based on economic feasibility is made, then a slight shift towards affordability.	X			
Reserve to production ratios	Physical availability and consumption translated into time frame of availability.	X			
Diversity indices	Depending on the application either accessibility (fuel div., supp. Div.) or affordability (supply concentration)		X	X	
Supply market concentration	See above		X	X	
Import dependence	A large determinant in accessing resources is the fact whether these are domestic or not.		X		
Net energy import dependency	A combined measure of 2 elements related to accessibility (import and fuel diversity) will most likely end up in the same realm		X		
Political stability	The political situation (including the alignment of political orientation between supplier and consumer) is an important determinant in the access to resources.		X		
Oil price	The affordability of energy is in its strictest interpretation almost similar to its (monetary) price.			X	
Mean variance portfolio	Relates the unit generating cost (affordability) to the variance therein.			X	
Non carbon	The negative consequences of energy consumption may hinder its societal acceptance.				X
Market liquidity (CET)	The (un)willingness to trade translates to price movements and thus the affordability of energy.			X	
Market liquidity (IEA)	When defined as own consumption in relation to amount available on the market, it is an indication of the vulnerability to price movements.			X	
Energy or oil intensity	These demand-side indicators provide an indication of the potential impacts of a disruption, be it physical or economical. As such they can be placed between availability and affordability.	X		X	
Oil/energy expenditures				X	
Energy or oil use per capita		X			
Share of oil in transport sector		X		X	
Share of transport sector in total oil use		X		X	

Table A1 (*continued*)

Indicator	Rationale for position in SOS-spectrum	Main dimension of SOS			
		Av	Acs	Aff	Acp
Aggregated indices					
Jansen et al. (2004)	With fuel and import diversity at its roots, and a political stability parameter, this indicator mainly focuses on the accessibility element, although the inclusion of a depletion function introduces an element of availability.		X		
IEA's ESI_{price}	Focusing on the root causes of market power and resulting uncompetitive pricing, this indicator can be placed in the affordability quadrant. Including political stability introduces an element of accessibility to the indicator, whereas including depletion (suggested in IEA, 2004a,b,c) introduce an element of availability.			X	
S/D index	Although very elaborate, the emphasis of this indicator is on accessibility, with import shares determining the supply score, and conversion and transport included. Including demand moves introduces an element of availability/affordability, but given the weight of this element it stays predominantly access-oriented.		X		
Bollen (2008) MERGE	This function translates SOS concerns into monetary terms, and as such can be placed in the affordability quadrant.			X	
OVI (Gupta 2008)	Predominantly monetary indicators and thus affordability, but also supplier diversity, political risk and reserves i.r.t imports. Based on the weights as described in Gupta (2008), pp1206 more towards acceptability than availability		X	X	

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