

The Security of Energy Supply and the Contribution of Nuclear Energy



**The Security of Energy Supply
and the Contribution of Nuclear Energy**

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Foreword

A commonly asked question is what contribution can nuclear energy make to improve the security of energy supply. This study, which examines a selection of OECD member countries, validates the often intuitive assumption that, as a largely domestic source of electricity with stable costs and no greenhouse gas emissions during production, nuclear energy is well-placed to make a significant, positive contribution. With the help of a series of transparent and policy-relevant indicators, the study shows in particular that nuclear energy has indeed contributed to improving energy supply security in OECD countries in a significant manner during the past 40 years. It achieved this result by diversifying the energy mix, and in particular the electricity mix, as well as by reducing the overall share of fossil fuels imported from outside the OECD area.

The study first discusses the notion of energy supply security and presents the various definitions and approaches that experts have formulated in order to examine this issue, considering both an “internal dimension” concentrating on the features of the electricity sector, and an “external dimension” focused on geopolitical issues. Consistent with the mandate of the Ad hoc Expert Group on Nuclear Energy and Security of Supply “to identify a relevant quantitative approach to measuring the contribution of nuclear energy to security of supply”, the study then presents a broad range of indicators and models that quantitatively assess a country’s level of security of energy supply. It subsequently develops a specific composite indicator that allows the measurement of the level of security of energy supply as well as the contribution of nuclear energy over the past 40 years, for those OECD countries for which a consistent data set was available.

Finally, the study seeks to identify the implications of these findings for broader processes of public opinion formation and attitudes towards nuclear energy and security of supply in OECD countries. It shows that nuclear energy is viewed more dispassionately when seen as a solution to the combined issues of supply security, cost stability and greenhouse gas emissions.

Acknowledgements

The study on *The Security of Energy Supply and the Contribution of Nuclear Energy* was initiated by an ad hoc group of experts under the guidance of the NEA Committee on Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle (NDC). The members of the Expert Group nominated by NEA member countries are listed in Annex 1. The original project was part of the 2007-2008 NDC Programme of Work under the heading “Nuclear Energy and Security of Supply”. Mr. Ronald Hagen (United States) and Dr. Henk Wels (Netherlands) were respectively Chair and Vice-Chair of the Expert Group. Two smaller break-out groups on “Definitions” and “Models” were moderated respectively by Professor William D’haeseleer (Belgium) and Dr. Koji Nagano (Japan).

The study was initiated under Mr. Stan Gordelier, Head of the NEA Nuclear Development Division until July 2009, with the support of Mr. Pal Kovacs, responsible Administrator. Dr. Ron Cameron, as the new Head of the NEA Nuclear Development Division, took up the study in spring 2010. The project drafting team consisted of Dr. Jan Horst Keppler, Principal Economist,

Dr. Alexey Lokhov, Nuclear Energy Analyst and Ms. Lucie Liversain, Intern. Chapter 1, “The Security of Energy Supply and the Contribution of Nuclear Energy – Concepts and Issues”, was written by Dr. Jan Horst Keppler integrating material provided by the Expert Group and, in particular, by Professor William D’haeseleer. Chapter 2, “Indicators and Models for Measuring Security of Energy Supply Risks”, was written by external contributors, Mr. Jaap Jansen and Mr. Adriaan van der Welle of the Energy Research Centre of the Netherlands (ECN), integrating material provided by the Expert Group and, in particular, by Dr. Henk Wels and Dr. Koji Nagano. Chapter 3, “Evolution of the Security of Energy Supply in OECD Countries”, was written by Dr. Alexey Lokhov. Chapter 4, “Public Attitudes towards Nuclear Energy and Security of Energy Supply” was written by Ms. Lucie Liversain, based on material provided by the Expert Group and a group of students from the *Institut d’études politiques* (IEP), Paris, co-ordinated by Ms. Alena Pukhova. Chapter 5, “Conclusions”, was written by the project team.

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Executive Summary

THE SECURITY OF ENERGY SUPPLY AND THE CONTRIBUTION OF NUCLEAR ENERGY

E.1 Security of energy supply in the OECD area

The continuous availability and affordability of energy and, in particular, electricity supply is an indispensable condition for the working of a well-functioning modern society. This is especially true for advanced industrial or post-industrial societies, where electricity provides the services essential for production, communication and exchange. Unsurprisingly, governments of OECD countries are thus concerned with understanding the factors influencing the security of energy and electricity supplies and seek to develop policy frameworks and strategies to enhance them.

As a domestically produced, largely carbon-free source of electricity nuclear energy is, in principle, well-placed to play a constructive role in this context. However, before proceeding towards the demonstration of the contribution of nuclear energy, the complex concept of “security of energy supply” must itself be defined and made amenable both to the formulation of concrete policy objectives and numerical verification. A general starting point is the following consensus definition:

Security of energy supply is the resilience of the energy system to unique and unforeseeable events that threaten the physical integrity of energy flows or that lead to discontinuous energy price rises, independent of economic fundamentals.

Further analysis shows that “import dependency and diversification”, “resource and carbon intensity” as well as “infrastructure adequacy” are three key verifiable parameters that can be derived from this general definition. It is important, however, to keep in mind that these three parameters are not identical with energy supply security but continue to demand qualification and contextualisation in each individual case.

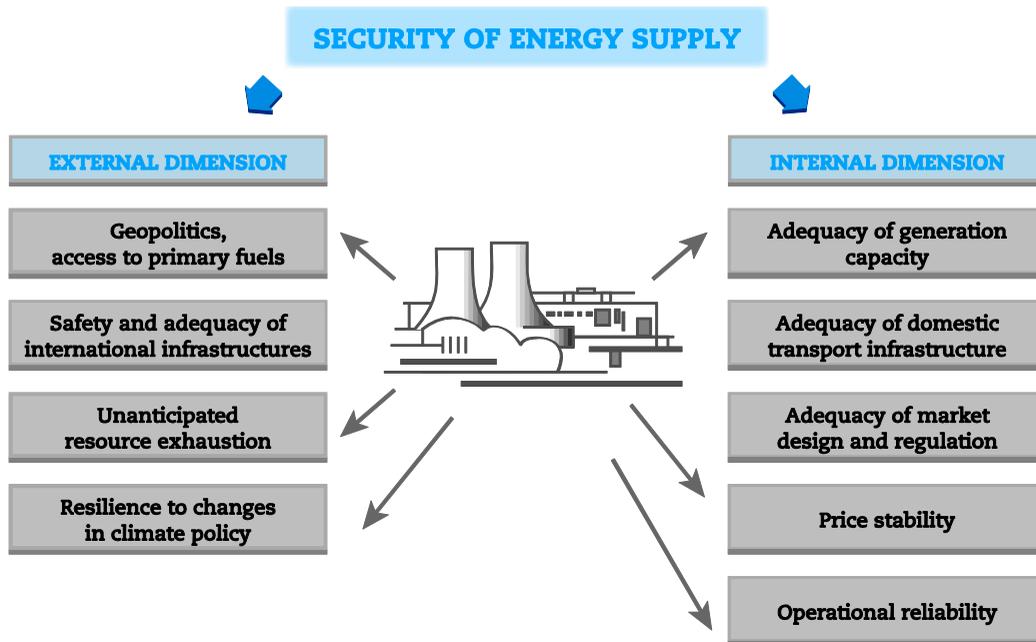
E.2 The importance of electricity and the two key dimensions of energy supply security

The sector in which security of supply issues pose themselves with the greatest insistence is the power sector. The need to balance supply and demand in power markets where electricity is non-storable and demand inelastic has always demanded close coordination between suppliers and the operators of electricity transmission grids.

Energy supply security is a classic example of an externality, i.e. of an issue that affects the well-being of individuals and society but which markets alone are not providing at adequate levels. Being a negative externality, energy supply risk constitutes a policy issue. This means private individuals cannot cover themselves for such risks due to their informational complexity and unquantifiable nature. This is where governments need to step in.

This study focuses on energy supply risks in two dimensions, the external or geopolitical dimension and the internal dimension that includes technical, financial and economic issues as illustrated in Figure E.1.

Figure E.1: Dimensions of energy supply security and the potential contributions of nuclear energy



E.3 The external dimension: import dependence, resource exhaustion and carbon policy

Geopolitical risk refers almost always to primary energy carriers (oil, gas, coal, uranium or renewables) since their location depends on the vagaries of geology and climate. Production and consumption are thus often physically far apart and take place in countries and regions with different histories, cultures and values. Apart from exploration and production, all other steps of the energy chain such as refinement or enrichment, conversion and distribution can be moved physically closer to the final customer or are, like consumption, directly under the latter's control.

Geopolitical energy supply risks are thus a function of relations between producer and consumer countries for which both of them share responsibilities. However, even in the best of cases these relations are very difficult to predict. The issue is further complicated by the fact that the majority of the easily accessible stocks of hydrocarbons are located in potentially unstable regions.¹ There is thus only so much that can be done about the sources of geopolitical supply risk. On the demand side, the best-known strategy is the diversification of supply sources and of transport routes.

1. To some extent such instability is endogenous and not the result of a global geological lottery. Notions such as the "resource curse" or the "Dutch disease" highlight the increased economic and political instability that may affect overly resource-dependent economies. The resulting lack of diversification as well as the allocation of resources to rent capture, rather than productive investment, can thus hamper economic, social and political progress. There exist, of course, counterexamples. Norway is a frequently cited example, but by and large resource dependency does not correlate with geopolitical stability.

Given that the fundamental condition for geopolitical supply risks is the physical separation of the centres of production of primary energy and their consumption, it is tempting to address the issue by striving to bring production home (“energy independence”). Whether this is a good approach depends on a country’s geographical position, its own energy endowment, the state of its physical infrastructures for transport and storage, the diversification of its supplies, the willingness of its population to accept higher average long-term prices for lower volatility and a host of other issues.

In an ideal world, security of energy supply would not equate to energy independence or self-sufficiency. Free and global energy trade through smoothly functioning competitive markets would guarantee timely delivery of all necessary energy resources. Most countries are relying at least partially on the international trade of energy and will continue to do so. What is important in this case is not so much the security of the single shipment but rather the security of the system in which both producers and consumers have a stake.

The issue of self-sufficiency does assume though a particular significance in electricity markets, since due to the high costs of storage, electricity can be economically transported only over relatively short distances. In island countries such as Japan and Australia or *de facto* isolated countries such as the Republic of Korea, national electricity generation must be able to cover national demand.

E.4 The internal dimension: economic, financial and technical conditions for energy security

Energy security begins at home. The most important responsibility for OECD governments is setting appropriate framework conditions providing incentives for private actors to install domestically an adequate level of facilities for the production, transport, conversion and consumption of energy. Important elements in this strategy are regulatory stability, market organisation, fiscal coherence and predictability of environmental policy.

The challenge in the electricity sector is the creation of framework conditions that:

- do not discriminate against domestically producing, low-carbon energy sources such as nuclear and renewable energies; and
- allows for the construction of adequate transport, production and conversion capacity with appropriate long-term financial arrangements.

OECD governments thus have a responsibility to create market conditions that allow low-carbon technologies with lower supply risks to compete on a level playing field. Governments also have a role to play with regard to the provision of adequate levels of transport, distribution and conversion capacity. Partly, such capacity can be provided by markets themselves, but in other cases, it requires regulation and supervision. First, regulation must provide sufficiently attractive financial conditions for investment in transport and conversion infrastructure. Second, political backing must support projects that are necessary at the national level against blockage by repeated legal appeals, through appropriate technical regulations and zoning laws as well as adequate mechanisms of consultation, mediation and compensation.

E.5 Different approaches towards designing security of supply indicators

Approaches to assign numeric values to aspects of security of supply risks can be broadly categorised as follows:

- import dependency and diversification of fuel and energy supply;
- resource and carbon intensity; and
- system adequacy.

The first category of security of supply indicators covers primarily the external security of supply dimension, whilst the second and third ones broadly refer to the internal security of supply dimension.

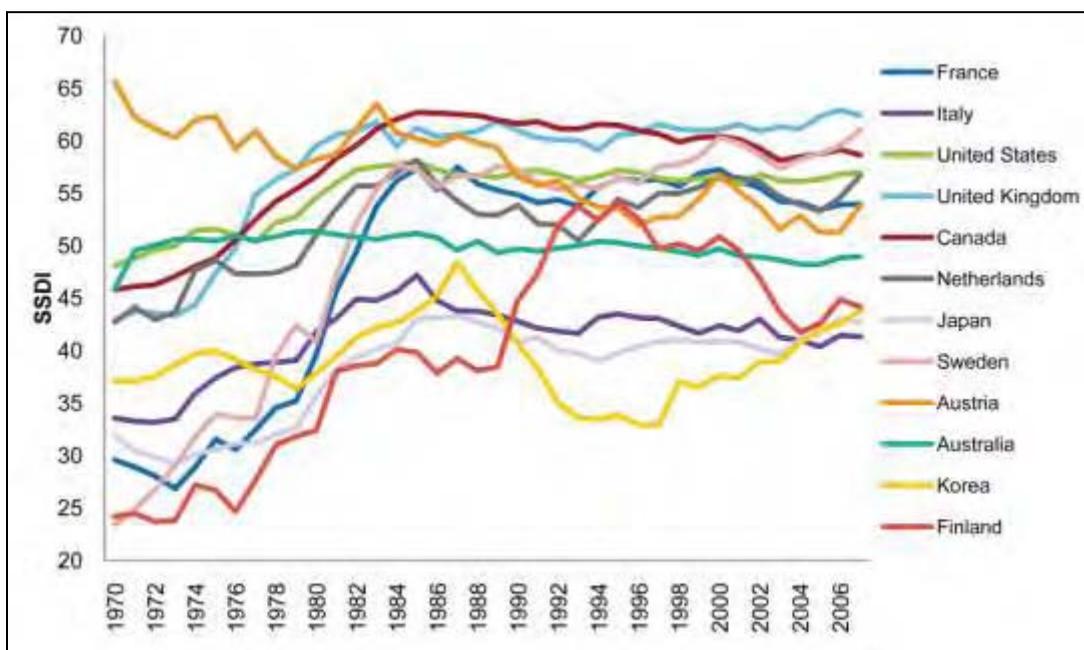
One indicator in particular seems to have substantial merits for the analysis in this report, capturing aspects of all three categories mentioned above. The generalised Simplified Supply and Demand Index (SSDI) is a composite security of supply indicator for a defined region in the medium and long run that includes major underlying supply-side and demand-side factors. This index is normalised to range from 0 (extremely low security) to 100 (extremely high security). It is based on the generalised SSDI but adapted here to be able to work with the only available consistent data set available for the past 40 years, the IEA *Energy Statistics*.

The SSDI is composed of three weighted contributions: demand, infrastructure and supply. These contributions take into account the degree of diversity and supply origin of different energy carriers, the efficiency of energy consumption by the main economic sectors, and the state of the electricity generation infrastructure.

The evolution of the SSDI through time (1970-2007) was analysed for several OECD countries: Australia, Austria, Canada, Finland, France, Italy, Japan, Korea, the Netherlands, Sweden, the United Kingdom and the United States (see Figure E.2). This allows one to track changes in the SSDI and provides an illustration of the security of energy supply of the selected countries for the last 40 years. It enables the identification of changes in the trend when important policy changes have been implemented, such as the United Kingdom's switch from coal to gas or the introduction of nuclear programmes in France and the United States.

One can see that the value of the SSDI has considerably increased between 1970 and 2007 in the case of most economies under study: Australia, Canada, Finland, France, Japan, the Netherlands, Sweden, the United Kingdom and the United States. On the contrary, the value of the SSDI is low or not increasing between 1970 and 2007 for Austria, Italy and Korea. Also, the gap among different countries has decreased. The improvement in the SSDI of a number of these countries coincides with the introduction of nuclear power, while decreases often relate to increases in imports.

Figure E.2: Evolution of the SSDI for selected OECD countries



In the United States, the value of the SSDI is generally high because of large domestic resources of fossil energy suppliers and an important share of reliable imports from Canada. An important increase in the SSDI may be noted in the second part of the 1970s because the energy intensity of the United States economy decreased, and nuclear power plants started to be widely deployed.

E.6 The role of nuclear energy in reducing security of supply risk

Nuclear energy has some distinct advantages in strengthening the external dimension of energy supply security. These include:

- Nuclear power plants produce electricity domestically. Their capital and labour inputs are also provided domestically. With more than 90% of its inputs in terms of value sourced domestically, it can be considered a largely domestic source of energy and electricity.
- Of course, a majority of OECD countries import part or all of their requirements of uranium. However, these imports frequently come from other OECD countries. Even where imports come from non-OECD countries, such supplies are well-distributed globally and have never given rise to security of supply issues in the past.
- Nuclear energy is capable of providing large amounts of baseload power at stable costs and would be unaffected by a sudden tightening of restrictions on the emission of greenhouse gases. Unsurprisingly, the great majority of long-term scenarios interested in the question of sustainable concentrations of greenhouse gas emissions include a large expansion of nuclear power.²

2. The influential Stern Report, for instance, advocates a doubling of global nuclear capacity by 2055 to 700 GW as one of the measures to stabilise greenhouse gas concentrations (Stern, 2006, p. 207).

For uranium, the majority of supplies are coming from politically stable OECD countries such as Australia and Canada. The only major geopolitical change in the supply of uranium is rapid mining development in Kazakhstan. According to *Uranium 2009: Resources, Production and Demand*, (NEA/IAEA, 2010), in 2008 Kazakhstan became the second world largest uranium producer (8 512 tU), between Canada (9 000 tU) and Australia (8 433 tU). Nevertheless, one can state that the uranium supplies used in nuclear energy production do not pose any major risk to energy security.

Overall, in the face of geopolitical supply risks, whether due to import dependence, resource exhaustion or changes in the global carbon regime, nuclear energy holds advantages that other fuels such as oil, coal and gas do not enjoy: wide availability of resources for a long time to come, modest impacts of increases in resource prices and resilience against carbon policy shifts.

In terms of internal risks, one needs to consider the investment costs and the functioning of the grid systems. With the first issue, the point is whether nuclear energy has specific characteristics which make it intrinsically a more attractive investment option than other generation technologies, in particular in liberalised power markets with uncertain prices. The joint IEA/NEA study on the *Projected Costs of Generating Electricity: 2010 Edition* provides some general information on the levelised cost of electricity (LCOE) per MWh for different technologies.³ The report shows that nuclear energy is a very attractive option at real interest rates that are below or only slightly above 5%.

The attractiveness of an investment in power generation, however, is not only defined by its LCOE that corresponds to the average discounted revenue, i.e. the price of a MWh of electricity that would allow the investment in question to break even. One key element is the uncertainty to which investors are exposed. The advantage of nuclear energy in this context is that its average cost remains very stable in the light of changes in the fuel or in the carbon price. In particular, it is protected against fuel price changes by the low proportion of fuel costs in the total lifetime costs of nuclear power generation.

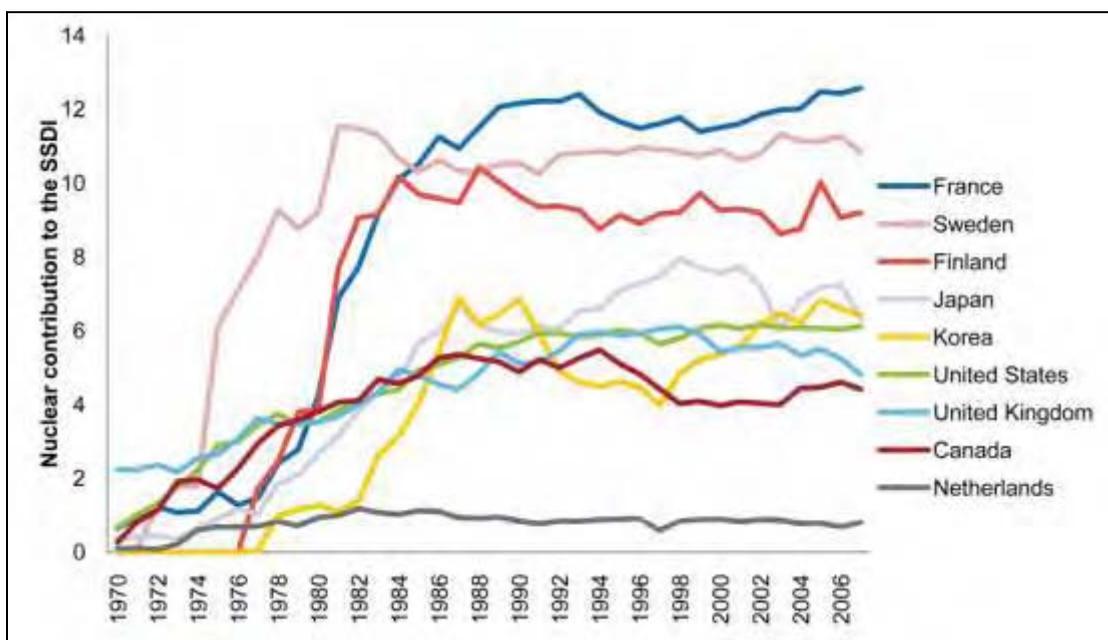
Investors in fossil fuel plants and, in particular, coal-fired power plants are also exposed to carbon price risk: the variation in the price of CO₂ permits, which constitutes a major source of uncertainty for coal-fired power production. Doubling the carbon price, for instance, from USD 30 per tonne of CO₂ to USD 60 per tonne would increase the total average cost of coal-produced power by 30%, more than doubling its variable cost in the process. This is not an unrealistic number. Given current commitments to reduce global carbon emissions by 2050 by 50% in order to limit the rise of global mean temperatures to 2°C, modelling results imply marginal costs for carbon abatement of at least USD 100 per tonne of CO₂ and perhaps much higher.⁴

Some countries in the world are currently showing interest in developing nuclear power to strengthen their level of security of supply. Particular examples are the countries that have decided to phase out nuclear power in the past: Belgium, Italy and Sweden. For countries like Finland, France, Japan and Korea, the increase of the SSDI is partly due to the introduction of nuclear power plants (Figure E.3).

3. The LCOE are calculated by discounting or compounding all costs to the date of commissioning and dividing them by the time value of total production. They thus indicate the discounted average (unit) cost of production. In the present case, the LCOE were calculated including a carbon price of USD 30 per tonne of CO₂.

4. Carbon capture and storage (CCS), on which the future of the coal industry will depend, is currently still a highly uncertain option that has yet to be deployed on an industrial scale.

Figure E.3: The contribution of nuclear power to progress in the SSDI



In the case of France, the contribution of nuclear power to the SSDI was more than 12 points in 2007 (about 30% of the SSDI score), followed by Sweden with 11 points (21%), Finland with 9 points (26%), and Japan and Korea with approximately 6 points (about 17% of the total SSDI score).

E.7 Public concerns over security of supply and the role of nuclear

It is of interest to know how the perceptions of consumers regarding security of energy supply correlate with the indicators of such security. To investigate this idea, *Eurobarometer* opinion polls, issued in 2007 and 2010, were analysed to see the correlation between public concerns and two main indicators:

- import dependency; and
- volatility of energy prices.

Citizens of the European Union (EU) are generally aware of the fact that energy dependency is one of today's most challenging energy questions. Overall, 61% of respondents believe that their country is entirely or very much dependent on energy coming from abroad. EU countries face different situations of energy dependency: Denmark is the only country where energy exports exceed energy imports, while the energy dependence rate is highest in small countries such as Cyprus, Luxembourg, Malta and Portugal. However, the level of awareness is not consistently high. For example, for Ireland, the energy dependency rate is approximately 90%, but only 64% of its citizens are aware of that.

When comparing the respondents' opinions and indicators, one finds that the results of the survey show better correlation between the values of the SSDI discussed previously than with the simple import dependency ratio. For example, the values of the SSDI for the United Kingdom are approximately at the same level as the perceived concern over energy dependency in public opinion polls. This suggests that the public implicitly has quite a good understanding of the complexity of the issue.

This is important for public acceptance of nuclear energy. A study of the correlation between the change in public support for nuclear energy between 2005 and 2008 with the respondents' answers to other questions in the Eurobarometer questionnaire in the same years suggests some insights into the factors that influence public acceptance. In particular, it becomes clear that the benefits of nuclear power in terms of diversification of the energy mix and alleviation of oil dependence were duly appreciated, and progressively more so by Europeans from 2005 to 2008. This in turn has contributed to greater overall support for nuclear power generation.

In Europe, the highest proportions of citizens who say that the share of nuclear energy should be maintained or increased are found in Bulgaria (90%) and Poland (88%), where the possibility of building a first nuclear power plant was recently discussed. Moreover, several countries that in the past shut down or put on hold their nuclear power programmes, but have recently changed their policy, like Italy or the United Kingdom, also display high shares of public support for nuclear energy with 73% and 75% respectively.

The main conclusion is that nuclear's political and social acceptability depends on a good understanding of its benefits to diversification, energy supply security and reductions in greenhouse gas emissions.

E.8 Conclusions

Due to its complexity and the dynamic evolution of the many parameters involved, as well as the public perception of "secure" supply, energy security remains an uninternalised externality or a public good that markets are unable to provide for at the appropriate level. Even in the presence of a globalised marketplace for most energy commodities, energy supply security thus remains a policy issue for which governments need to assume responsibility.

An external and an internal dimension of energy supply security are of importance, in both of which nuclear energy can play a constructive role. The external dimension is mainly defined by concerns about import dependence from potentially unstable countries. The internal dimension instead is about creating appropriate incentive mechanisms and frameworks to allow public and private actors to invest in adequate levels of production and transport capacity that provide continuous access to energy services at stable prices.

As an essentially carbon-free, largely domestic source of energy, nuclear power does indeed possess a number of attractive characteristics for improving the security of energy supply. It is a competitive power generation source with high energetic density and low sensitivity to the variations of the price of uranium, unlike fossil fuel technologies. Uranium resources are also well-distributed, with OECD countries such as Australia, Canada or the United States holding important shares.

This study shows empirically that nuclear energy has in effect contributed to improving energy supply security in OECD countries in a significant manner. It achieved this result by diversifying the energy mix, as well as by decreasing the overall share of fossil fuels, in particular natural gas imported from outside the OECD. The SSDI has been used to analyse energy supply security based on both supply and demand data. This shows that the security of supply situation in OECD countries has unequivocally improved since the early 1970s. This was due to three different factors:

- the introduction of nuclear power for electricity generation;
- a decrease in the energy intensity of OECD countries; and
- greater diversification of primary energy sources.

Quite naturally, the public at large remains unconcerned by the development of complex synthetic indicators. However, individual parameters such as import dependence and price volatility are consistently highlighted as issues of public concern, in particular in the regularly published *Eurobarometer* opinion polls. This suggests that nuclear is viewed more favourably if it is not pushed as an autonomous issue for its own sake but integrated into the context of broader policy objectives such as ensuring the security of energy supply or the reduction of greenhouse gas emissions. Nuclear energy is no longer a quasi-ideological “yes” or “no” issue. This insight holds both promises and challenges for nuclear energy. The promise is to become accepted as an essential element of broad energy policy strategies. The challenge is to bring about an evolution in its features and decision-making mechanisms to engage in real public debate on issues of concern to the general public as well as to energy investors.

Due to its large fixed costs (not only at the level of the individual plant but also at the level of education, regulatory infrastructures, fuel cycle strategies, etc.), nuclear energy will never be wholly an ordinary industry. Nevertheless, as a concrete response to real problems, nuclear is now being viewed more dispassionately and judged on its merits as a solution to questions of security of supply, cost stability and reductions in greenhouse gas emissions.

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Chapter 1

THE SECURITY OF ENERGY SUPPLY AND THE CONTRIBUTION OF NUCLEAR ENERGY – CONCEPTS AND ISSUES

1.1 Energy supply security: An introduction

The continuous availability and affordability of energy and, in particular, electricity supply is an indispensable condition for the working of modern society. This is especially true for advanced industrial or post-industrial societies, where electricity provides the essential services necessary for production, communication and exchange. Not surprisingly, governments of OECD countries are thus concerned with understanding the factors influencing the security of energy and electricity supplies and with developing policy frameworks and strategies to enhance them. Energy security here has two main dimensions: an external dimension that aims at ensuring a stable supply of imports and an internal dimension that is concerned with maintaining domestic infrastructures at adequate capacity levels and in good working conditions.

As a domestic producer of baseload electricity at stable cost, nuclear energy is well placed to play a constructive role in both dimensions. This report aims to examine the role that nuclear energy can play in enhancing the security of electricity supply of OECD member countries. However before doing so, the concept of “security of energy supply” must be defined and understood as it applies to the formulation of government policy.

This is less straightforward than it may seem. Energy supply security is a many-splendored notion that can mean very different things to different people. A foreign policy expert will look at the issue differently than a network engineer or an economist. Definitions of what is security of energy supply by different experts abound but they are often too abstract to come to grips with the concrete issues intrinsically linked to geopolitical preferences, strategic technology choices and fundamental orientations of social policy. Definitions also change from country to country. A country with limited access to cross-border energy infrastructures but a broad domestic resource base will thus think differently about the security of its energy supplies than a small, open economy closely interconnected with its neighbours but with few resources of its own. Not unlike the notion of “sustainability”, another key dimension of energy policy in OECD countries, the notion of security of energy supply is often being applied in different ways to support different policy objectives.

A basic straightforward engineering definition of energy supply security is provided by William D’haeseleer as “avoiding the interruption of energy delivery to whatever end-energy consumer” (D’haeseleer, 2009, p. 2). Evelyne Bertel broadens the definition slightly by including price aspects: “The notion of security of energy supply... may be defined in a broad sense as the lack of vulnerability of national economies to volatility in volume and price of imported energy” (Bertel, 2005, p. 4). Jean-Marie Chevalier even includes environmental aspects by stating that “... security of supply is a flow of energy supply to meet demand in a manner and at a price level that does not disrupt the course of the economy in an environmental sustainable manner” (Chevalier, 2006, p. 2).

Jaap Jansen and Ad Seebregts further enlarge the approach by focussing on the demand side and energy service security which is defined as “the... enduring, uninterrupted access of the population in a defined region to affordably and competitively priced, environmentally acceptable energy end-use services” (Jansen and Seebregts, 2010, p. 1655). This very broad approach includes also non-energy products of fossil fuels such as plastics or fertilisers. A rather legalistic definition of the security of supply, in the electricity sector this time, is instead provided by Eurelectric (Eurelectric, 2006, p. 6), which states that:

Security of energy supply is the ability of the electric power system to provide electricity to end-users with a specified level of continuity and quality in a sustainable manner, relating to the existing standards and contractual agreements at the points of delivery.

Certain approaches to the security of energy supply aim at integrating part of the advocated solution into the definition of energy supply security. The Centre for Strategic and International Studies (CSIS) thus defines a secure energy system as one that is characterised by a diversification of sources, fuels, suppliers and supply routes as well as by a reduction of energy intensity (CSIS, 2010, p. 10). Jan Horst Keppler instead proposes a risk management approach to energy supply security going beyond traditional notions such as energy independence or even the avoidance of supply interruptions. A secure energy supply system is one that is capable of withstanding shocks and of adapting. The resilience (flexibility, elasticity) of the system thus becomes its key characteristic. The key policy task thus becomes to design a “framework for insurance and for allocating risk efficiently between private players (quantifiable risk) and public players (non-quantifiable risk or uncertainty)... given that markets cover risk very well and uncertainty very badly” (Keppler, 2007a, p. 22).

The most widely known definition of energy supply security is probably the one propagated by the IEA, which defines security of supply consisting of adequacy, reliability and affordability. Adequacy and reliability can be considered short-hand for the absence of physical supply interruptions mentioned in the proceeding definitions. The notion of “affordability” is more problematic as it indicates a normative notion of the price level. To the extent that energy supply security pertains to trade between different nation states, insisting on “affordable prices” and thus, implicitly, on certain distributional arrangements can undermine the very objective it is trying to achieve. However affordability can take the meaning, not of low prices, but also of effectively managed price changes.

While each definition thus brings its own focus to the issue, the different points of view mentioned above are united in their concern that energy consumers should be able to consume energy and energy services in an uninterrupted manner at costs that are stable and known in advance or manageable in the rate of adjustment needed. Based on the preceding definitions and others in the large and varied literature on the security of energy supply, this study proposes the following fairly straightforward and consensual definition:

Security of energy supply is the resilience of the energy system to unique and unforeseeable events that threaten the physical integrity of energy flows or that lead to discontinuous energy price rises, independent of economic fundamentals.

The two key dimensions of the security of energy supply

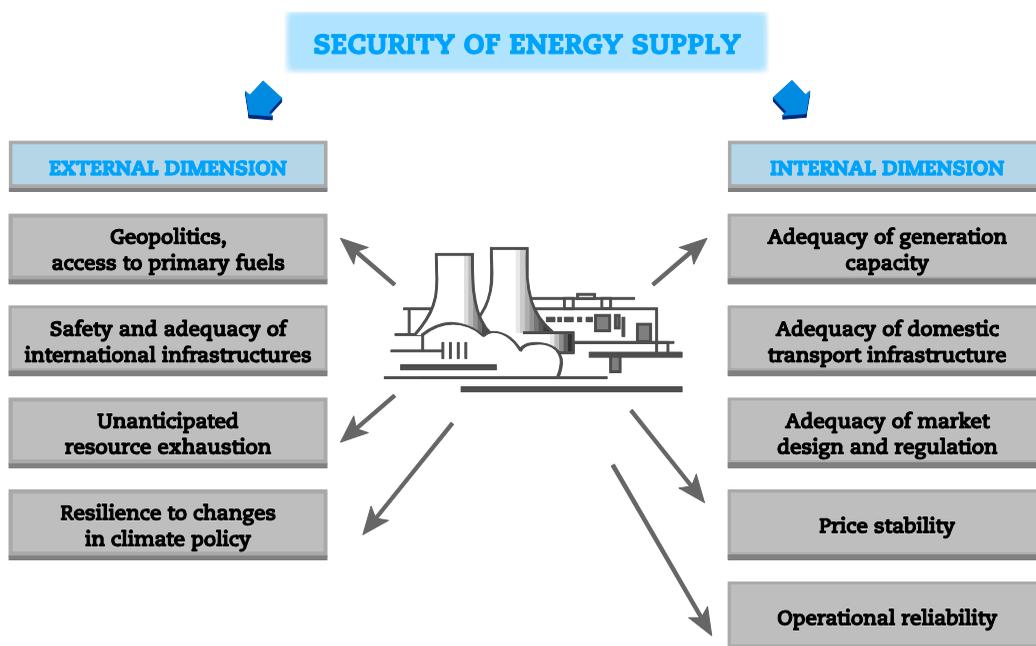
This study focuses on energy supply security in two dimensions, the external or geopolitical dimension and the internal dimension that includes technical, financial and economic issues. While the complex issue of energy supply security can be sub-divided in a number of different ways, this approach has the advantage of helping to identify areas where an international organisation such as the

OECD Nuclear Energy Agency (NEA) can best add value to the discussions about the security of energy supply.

The geopolitical dimension considers the risks of short-term or long-term interruption of physical energy flows or other deliberate uses of market power for political, military or strategic reasons. It is the aspect of energy supply security uppermost in the minds of policy-makers and the general public alike. Recent interruptions in European gas supplies, the OPEC’s increasing grip on global oil markets and the spectre of a “gas OPEC”, give particular relevance to this aspect.

The extent to which nuclear energy can contribute to addressing this aspect depends on the extent to which it is substitutable with imported fuels. Nuclear energy is a substitute for natural gas and, in particular, coal in electricity markets to the extent that gas is used for baseload power generation. In a medium-term perspective, when electric cars might gain some market share, it is also conceivable that nuclear energy could, indirectly, substitute for oil. For the time being, the substitutability with coal is the most interesting issue, in particular in the light of the “geopolitical” risk stemming from global actions to contain climate change and to reduce greenhouse gas emissions. A sudden tightening of global climate policy, say in response to unequivocal and dramatic consequences of climate change, might indeed expose vulnerabilities in countries with carbon-intensive energy and electricity systems.

Figure 1.1: Dimensions of energy supply security and the potential contributions of nuclear energy



Second, the economic, financial and technical dimension of the security of energy supply considers the adequacy of investment in generation capacity and the functioning of infrastructures for the transport, transformation and transmission of energy (ports, high-voltage power lines, distribution systems...) (see Figure 1.1). This is also the dimension in which an organisation such as the Nuclear Energy Agency might play a role by assisting in framing investment choices and developing financing models for the electricity sector. Energy market liberalisation, the increasing frequency of brownouts or blackouts, declining reserve margins, volatile electricity prices and increased environmental awareness are all posing security of supply issues in the power sector. As a stable, essentially carbon-free source for baseload power with a predictable cost profile, nuclear energy can play its part in

addressing these issues. Of course, this also requires the creation of conditions ensuring the safe and proliferation-proof application of nuclear technology for domestic power needs.

Nuclear energy, like renewable energy sources, has the advantage of producing energy domestically at stable costs. It remains, however, a high-fixed cost technology, which means that private investors in liberalised markets are concerned about the variability of their returns over the lifetime of the plants, usually several decades. There is thus a role for accompanying measures governments can take to reduce such variability, for instance through market design or by stipulating provisions permitting the conclusion of long-term supply contracts between suppliers and consumers in a form that avoids market foreclosure (for instance by standardising and rendering transparent such long-term supply contracts).¹ Effective government policy must strive for a market environment putting all technologies on a footing that allows them to realise their respective strengths.

The question of indicators

Any policy issue benefits from robust, transparent and policy-relevant indicators that frame the issue and provide benchmarks for improvement. However, when dealing with externalities such as the security of energy supply, the establishment of indicators is not straightforward. Externalities are incompletely internalised by private markets precisely because of the multitude of public interests all along supply-demand chains and their problematic informational nature. Indicators for the security of energy supply thus must seek a compromise between feasibility and policy-relevance. Given that data is limited, proxies for the security of supply such as import dependency or lack of diversification are required. Chapters 2 and 3 will provide an in-depth discussion of the possibilities for creating robust and transparent indicators of security of energy supply and the contribution of nuclear energy.

Certain aspects such as geopolitical processes largely escape easy quantification anyway. This is different for technical processes where quantification and measurement are part of everyday management. Issues pertaining to the security of supply can thus be internalised more easily. It is perhaps in the area of power generation and network capacity, with its interaction of economics, technology and energy policy, where sets of well thought-out indicators might be most useful to identify gaps that might endanger the security of energy, or more specifically, electricity supply. Once such gaps have been identified appropriate policy solutions can usefully be developed.

Given that the study is concerned with the contribution of nuclear energy to the security of energy supply, it is natural that particular attention will be paid to the security of electricity supplies. In fact, there exist a number of indicators covering different aspects of both energy and electricity supply security. Some of them are historic (number of blackouts or supply interruptions, sharpness of price movements for certain fuels, historic relations with key suppliers...) some of them are forward-looking (reserve margins, share of domestic resources, degree of upstream-downstream integration, diversification of fuels or suppliers and the adequacy of physical and regulatory infrastructures).

This study has tried to pay equal attention to both aspects and has thus developed for the first time indicators of energy supply that permit analysis of trends over 40 years for a broad range of OECD countries. Given the public nature of “energy supply security”, no single quantitative indicator can capture *all* aspects of energy supply security. However, a set of core indicators has been identified on the basis of the discussion in Chapter 2. Considering the evolution of security of supply indicators

1. While this study stays clear of a debate about the merits of liberalising electricity markets, a regulated environment has distinct advantages for high-fixed cost technologies. Long-term contracts can also forge stable long-term relationships between buyers and producers and thus constitute a form of insurance against risk.

over time and comparing it with the development of nuclear power over the same period is particularly helpful to assess the latter's contribution to energy supply security. Chapter 3 thus provides the results of a model specifically developed for this study that provides a synthetic indicator of the security of energy and electricity supply in a broad range of OECD countries over the past 40 years.² The same model also provides an indication of the relative contribution of nuclear energy to a country's security of supply.

The role of governments

Once meaningful indicators have been established, the question is what to do with them. To the extent that markets cannot ensure security of supply by themselves, governments need to implement policies that can improve the situation. First of all, this means, of course, paying attention to the external as well as internal dimension of energy supply security. In the external dimension, ensuring transparent global markets that enable a mutually beneficial division of labour and the realisation of the comparative advantage of each trading partner is of particular importance. In the internal dimension, the focus must be on creating appropriate market conditions and incentive systems that enable all technologies to deliver their potential contribution to the security of supply, in particular high fixed cost, low-carbon technologies.

However, it also means that governments need to pay attention, in both dimensions, to short-run crisis management mechanisms as well as to longer term structural determinants. The latter include once more the provision of adequate physical and regulatory infrastructures that will enable private market participants to work with the right incentives. Section 1.5 of this chapter identifies five distinct policy areas on which governments need to focus in order to respond effectively to security of energy supply challenges:

- diversification and flexibility;
- energy conservation and demand management;
- storage of energy carriers;
- regulatory, institutional and fiscal frameworks; and
- crisis management mechanisms.

Of course, no government will benchmark itself against quantitative indicators in all five areas simultaneously in order to improve energy supply security. The issue is too complex and too comprehensive for allowing such an approach. This study therefore does not at this point contain a set of detailed policy prescriptions. It does, however, offer a framework for the development of concrete policies in the five areas mentioned. The underlying idea is that public and private actors need to work together to improve the security of energy supply by concentrating on their respective strengths. In particular, governments need to provide private actors (both on the supply and the demand side) with the incentives and proper regulatory framework to contribute to the public good of energy supply security or to reduce the impacts by insisting on increased flexibility, for instance. The key role of this study in this context is to raise awareness of the issue, to define the different dimensions and to highlight the positive contribution that nuclear energy can make to each one of them.

2. The same indicator can also be used *ex ante* in a forward-looking way for scenario projections.

Plan of the study

This first chapter of this study on the security of energy supply and the role of nuclear energy will therefore attempt to examine the notion of security of energy supply in the two key dimensions, the external dimension and the internal one. This will allow a detailed discussion of the feasibility of transparent and policy-relevant indicators in Chapter 2. Chapter 3 provides empirical evidence for the contribution of nuclear energy to the security of energy and electricity supplies in a broad sample of OECD countries over the past 40 years. Chapter 4 will discuss the changing policy attitudes facing nuclear energy once it is discussed in a security of supply perspective. Chapter 5 will conclude.

1.2 Why security of energy supply remains a policy issue in OECD countries

Energy supply security is a classic example of an externality, i.e. of an issue that affects the well-being of individuals and society but which markets are not providing at adequate levels. The reason is that the issue depends on subjective value-judgements, which may vary across market actors, citizens and countries. Markets thus cannot develop the verifiable parameters over which private buyers and sellers could negotiate satisfactory outcomes at sufficiently low cost. This informational complexity – even though it is due to very different reasons – is something energy supply security has in common with certain types of environmental externalities such as greenhouse gas emissions, the other great example of a market failure in the energy field. In both cases, it is necessary that governments step up to develop criteria, analysis and policies forcing private actors to take the security of supply issue into account.

Being a negative “externality”, energy supply risk constitutes a policy issue. This means private individuals cannot cover themselves for such risks due to their informational complexity and unquantifiable nature. A simple example clarifies this. Imagine the interruption of the activity of a steel producer due to a blackout. If blackouts happened regularly, the steel producer will have a back-up system whose cost is passed on through the price mechanism. If no other issues were involved, this would be the solution. In other words, the security of supply risk would be “internalised” and there would be no need for policy action.

Imagine, however, instead, now that: (a) blackouts are a recent and unforeseeable phenomenon; (b) a price rise for steel production would hit less prepared customers; (c) the shortfall in electricity hits hospitals, fire stations and schools; (d) the shortfall affects private individuals unable to install back-up; or that (e) the mere possibility of supply interruptions creates a sense of unease and loss of confidence. In all these cases, private foresight is not sufficient to internalise the impacts of a supply interruption and public action is warranted. One can attribute this need for public intervention to the existence of informational asymmetries or transaction costs.

Quantifiable and non-quantifiable risks

Externalities, by definition, cannot be fully privatised due to their complex and multi-dimensional nature. One aspect of this is that, in technical terms, energy supply risks do not follow a well-defined probability distribution function that would let private insurance markets take care of the issue. Another aspect of the issue is that the action of one actor in an energy system impacts the well-being or profitability of another, without taking this impact into account. Frequently, this is unavoidable for technical reasons. Gas and electricity are grid-bound and even oil and coal use common infrastructures such as dedicated ports, shipping lanes etc. Externalities, even if they affect market participants rather than society as a whole (imagine a sudden gush of wind power overloading the electricity grid and depressing prices for all participants), thus again need to be dealt with at a central level.

The crucial question is always whether private actors are able to deal with certain risks or whether governments need to address them. Certain unpredictable events do constitute genuine externalities that justify government action to address security of supply challenges. From a technical point of view, the key distinction is the one between “risk” and “uncertainty”. According to the distinction introduced by Frank Knight (1921), “risk” exists if events form a well-defined probability distribution over known outcomes.³ Risk can thus be taken care of by private insurers. “Uncertainty” is prevalent if no such probability distribution exists since there is insufficient data to define one. In this case an insurer of last resort, which can only be government, needs to take on responsibility. “Insurance” here needs to be understood in the wide sense that government is acting to ensure that the energy mix is adequately structured in order to be able also deal with uncertain events. For instance, providing loan guarantees lowering the cost of financing to advance the deployment of low-carbon technologies might be a perfectly justified policy action from the point of view of reducing greenhouse gas emissions.

The role of governments is to take responsibility for energy supply security because either the threats are of an unpredictable nature or because decisions need to be taken at a central level as private actors do not include the system effects they cause into their cost-benefit calculations. This is not to say that markets do not also have a role to play. Liquid and transparent markets are an essential mechanism for pooling and redistributing supply risks, as long as they are quantifiable. Insurance and hedging can thus reduce supply risk for market participants. There remain, however, aspects of security of supply that markets struggle to take into account and where governments need to play an active role in the formulation and orientation of long-term strategic choices in the energy sector. This concerns nuclear energy, in particular, since stable political, social and regulatory framework conditions are critical for its viability.

Assuming such a responsibility does not necessarily mean that governments need to quantitatively measure the size of the security of supply externality. The proceedings of the *Joint IEA/NEA Workshop on Security of Energy Supply for Electricity Generation* (IEA/NEA, 2005) thus rightly rejected the notion of measuring “willingness to pay”. Attempts to monetise security of supply risk would suffer from the intrinsic drawbacks inherent in all monetisation of externalities. If pertinent data existed, markets would have already internalised the externality in question and the case for government intervention would have vanished. Government intervention is precisely reserved for those cases, where imperfect information prevents private behaviour from bringing about socially acceptable results.⁴ That said, different indicators can, of course, be helpful to formulate and communicate government policy.

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3. To be precise, one would need to speak in the terminology introduced by Frank Knight (1922) about uncertainty rather than about risk. The important point is that the expected utility hypothesis breaks down in the case of uncertainty when probability functions are unknown. This means that insurance markets will not be able to cover the risks in question, which in turn motivates a role for governments in ensuring the security of energy supply.
 4. It is preferable to talk about “acceptable” results rather than “optimal” results, since the notion of optimality is ill-defined outside the sphere of private goods, where it implies the equating of marginal costs (supply) and marginal benefits (demand). If neither costs nor benefits can be quantified, the notion loses much of its meaning. For an intergovernmental organisation such as the OECD interested in the maximisation of social welfare through the safeguarding of public goods such as energy supply security, it is important to keep in mind that trade-offs on such issues frequently need to be made on an implicit or qualitative basis. Nevertheless, even imperfect indicators can be helpful in highlighting the contribution of different energy choices and in framing policy choices.

Energy supply risks are thus characterised by vulnerability to unanticipated, and often unforeseeable, phenomena that are inadequately taken care of by private risk management. This does not mean that any inconvenience happening to energy consumers is an energy supply risk. For instance, high energy prices are frequently confused with energy supply risks. This is wrong as long as these high prices are stable and reflect economic fundamentals or policy choices such as gasoline taxation. High prices may be an economic problem but are not *per se* security of supply issues. But the speed and the magnitude of sudden price changes leading to economic disruptions are a security of supply issue (see also Chapter 4). One also needs to look at the causes for price rises: high economic growth, for instance, inevitably means higher energy prices but does not necessarily imply increasing supply risks.

Neither is vulnerability to energy supply risks identical to structural facts such as import dependency even though the two are frequently confused. Policy-makers thus need to address expectations and perceptions as well as facts. Individuals and enterprises need to be enabled to deal with structural facts such as long-term high energy prices. The focus of policies to secure energy supplies should not be on the absolute level of energy prices but the size and impact of changes (volatility) in energy prices, protecting risk-adverse energy consumers from unexpected changes. In this perspective, an energy system must be judged by its ability to withstand shocks and to adapt. The resilience or flexibility of the system thus becomes its key feature.

Social attitudes and affordability

The right policy response depends also on social risk preferences. The degree to which the security of energy supply should be managed by investing policy resources depends also on the risk-adverseness of consumers, a parameter that varies widely between countries. The vast differential in fuel price taxation between the United States and European OECD countries, for instance, can be attributed partly to the fact that American consumers are accustomed to live with lower prices and relatively higher volatility of prices and thus risk (since wholesale price changes translate into retail price changes almost one-to-one), whereas European customers are accustomed to live with higher prices and relatively lower volatility and risk.

Social preferences also strongly influence the relationship between the security of energy services and their affordability. It is an open question whether the continuous provision of energy and energy services at high prices can still be considered a secure energy supply. Energy and energy services (light, heat, refrigeration, entertainment, public lighting, certain kinds of public transport, etc.) are to some extent merit goods, i.e. goods a society wants its members to enjoy regardless of their ability to pay. The difficult question is where to draw the line between a commercial service and a merit good. Not being able to use your private car is not the same as freezing in winter. Notions of security of energy supply also vary from country to country. Avoiding “energy poverty”, for instance, is part of the notion of security of energy supply in the United Kingdom, while it is little discussed in other countries. Each society thus needs to define its own notion of security of energy supply before being able to design the policy framework in which effective action is possible.

Governments are called upon to decide on two issues in this context. The first issue is a social policy issue inasmuch government needs to determine the extent to which it wants to subsidise the consumption of energy for needy parts of the population above their willingness and ability to pay. From a standpoint of economic efficiency, there are no objections to the advancement of such social policy objectives as long as they are pursued in a market-compatible way, for instance through lump-sum transfers in the form of energy vouchers rather than through wholesale price reductions.

The second issue is to which extent governments want to invest in achieving security of supply. Theoretically, a marginal increase in the security of supply – a reduction of the risk that consumers will experience physical interruptions of energy flows or extreme price volatility – should be equated to the marginal cost of achieving this increase. Only with theoretically unlimited willingness to pay could all security of supply risks be avoided, for instance, by installing systematic storage and back-up. In practice, however, such perfect security of energy supply is too costly. All countries thus implicitly accept a certain level of energy insecurity by limiting their investments in insurance. In other words, some supply interruptions are acceptable as an inevitable inconvenience, if the cost and effort to avoid them is too high. The final trade-offs cannot be determined analytically but are the outcome of compromises established by political processes.

Risks to energy supply security: an overview

In the present context, ensuring energy supply security has been defined as “maintaining the physical integrity of energy flows and minimising discontinuous energy price increases even in the presence of unforeseen shocks.” What is important in this definition is the unforeseeable nature and disruptive nature of shocks constituting energy supply risks, each event being of a singular, incomparable nature. Time is important here. If time frames are sufficiently long and the chain of events sufficiently predictable, customers and producers are frequently able to internalise security of supply risks in the market place. For instance, risk-averse customers would be paying comparatively higher prices for fuels less exposed to either physical interruptions or price volatility.

The aspect of time, however, cuts both ways. It is not only the ability of markets to anticipate risks that is at stake but also their ability to respond to them in time. Energy infrastructures have very long lifetimes and today’s energy choices define the sector for decades due to the irreversibility and sunk costs of equipments that lock in particular production patterns. Markets also can be myopic. A case can thus be made for governments to plan ahead and to reduce security of supply risks also in the long-term.

A good example is constituted by the climate change debate. On current prices, availability and production patterns, coal-fired power generation is in many countries a competitive and in the short-term very reliable source. It is, however, not only possible but probable that there will be, in the next two decades, i.e. during the lifetime of most existing plants, significant constraints on global CO₂ emissions. This means that countries relying heavily on coal-based power production such as Australia or Poland have higher than average risks of price rises or production shortfalls.

Once a risk to the security of energy supply has been defined as vulnerability to unanticipated or unforeseeable events, it is possible to characterise a number of issues that do constitute genuine energy supply risks:⁵

1. Long- or medium-term physical interruptions of energy supplies due to:
 - a. political decisions such as embargoes (oil crisis of the early seventies...);
 - b. geopolitical tensions involving one or more supplier countries (wars, mid-east tensions...);
 - c. internal problems of a supplier country or region (civil war, political tensions, strikes...);
 - d. limitations of productive capacity due to a lack of investment (refusal of foreign direct investment, bad management...);
 - e. limitations of production capacity due to the “sustainable” long-term management of natural resources (Qatar, Norway...);

5. This is an adaptation of the list by Keppler and Lesourne in Keppler (2007b).

- f. restrictions of supplies due to the long-term exercise of monopoly power by a single entity or a cartel (OPEC...);
 - g. restrictions on the use of certain fuels (constraints on fossil-fuel use due to limits on CO₂ emissions to combat global warming...); and
 - h. the depletion of natural resources to the extent that it is not adequately taken into account of by private actors or that new information suddenly arrives.
2. Short-term physical interruptions of energy supplies due to isolated and non-predictable events such as:
- a. political and military reasons (Suez crisis...);
 - b. commercial disputes (Ukraine, Belarus...);
 - c. sabotage (Iraqi oil pipelines...);
 - d. non-state violence against energy infrastructures (pirate attacks in the straits of Malaga and Hormuz);
 - e. meteorological events (Hurricane Katrina...);
 - f. technical accidents (Breakdown of European high-voltage system, Macondo oil spill in the Gulf of Mexico...); and
 - g. inadequate domestic generation capacity (California 2002...).
3. Short-term spikes in the price of energy due to:
- a. the sudden exercise of monopoly power by a single entity or a cartel (OPEC quota revisions...);
 - b. speculative bubbles and herd behaviour (oil prices during 2008); and
 - c. new information concerning the reserves position of a major supplier or likely future demand.

While a good case can be made for each item on this list, there are clearly some that fit better with the notion of a “security of supply risk as an unanticipated event threatening the physical integrity of energy supplies” than others. To the extent that the phenomena repeat themselves, the near-permanent series of Middle Eastern crises comes to mind, they have by and large been priced in and thus internalised into the behaviour of customers (1.b). Repeated events can be anticipated and priced by markets, unforeseen events cannot. This goes back to the distinction between risk and uncertainty, as only the latter constitutes a genuine rationale for government interventions.

Upon inspection it might even be unclear whether Item 1.f, the long-term exercise of monopoly power of an entity such as OPEC, is relevant to our discussion. Of course, the initial OPEC decision of October 1973 – sudden, dramatic, loaded with political overtones and coupled with a largely ineffective threat to suspend physical supplies – remains the archetype of an energy supply risk. To some extent it marked the starting point of the modern debate on energy supply security. While the memories of the first “oil chock” still linger, OPEC’s behaviour today, however, is that of any profit-seeking monopoly interested in stable market conditions and the maximisation of its resource rents.⁶ In the absence of a global anti-cartel system – and there is scant evidence that cumbersome multilateral

6. A “resource rent” is the difference between the cost of extraction of a resource and the price that it fetches on global markets. In more general terms, a rent designates the difference between cost and revenue and is a form of income for which no commensurable effort has been forthcoming (think of patents, legal monopolies or rock stars). It is always due to the intrinsic scarcity of the underlying product and its magnitude is exclusively determined by demand.

processes will move into that direction any time soon – it is unclear on which legal, moral or political grounds such behaviour could be sanctioned. In other words, while such anti-competitive behaviour is clearly regrettable from the point of view of the economies of OECD countries, it is unclear whether it can be tackled directly.⁷

There exist, however, indirect options to address monopoly power on the supply side. The diversification of energy sources and suppliers, the development of substitutes such as renewables or nuclear power, the provision of incentives for improving energy efficiency are all effective responses to long-term monopolistic behaviour. Such policy measures fall, however, in the realm of standard commercial practice and do not constitute *per se* measures to reduce energy supply risk. Private actors concerned about high oil and gas prices should be able to deal with the exercise of monopoly power to the extent that it is predictable and that the commercial competition is being played out on a level playing field.

Historically, the items under Point 2 are the heart of the security of supply issue. Most public discussions turn around short-term physical interruptions of energy supplies due to isolated and non-predictable events such as political crises, commercial disputes, sabotage, meteorological events, technical accidents or inadequacy of power generation capacity. It is in this context that classic security of supply measures have been designed such as, for instance, the IEA emergency response system for oil supply disruptions, which has been used in cases as diverse as the first Iraq war or hurricane Katrina.

The items under Point 3, *sudden* prices rise due to cartel action, the sudden deflation of speculative bubbles or important new information about supply and demand, clearly also constitute risks to the security of energy supply in terms of price stability. They also require specific responses such as improved transparency, more effective regulation of increasingly volatile and complex commodity markets, better coordination between suppliers and consumers as well as improved informational infrastructures in terms of standardising, collecting and regularly publishing relevant data among all stakeholders.

The particular role of the electricity sector

The sector in which security of supply issues pose themselves with the greatest insistence is the power sector. Of course, the need to balance supply and demand in power markets where electricity is non-storable and demand inelastic has always demanded close coordination between suppliers and the operators of electricity transmission grids. However, with the double challenge in many OECD countries of market integration and energy market liberalisation such coordination has come under increasing strains. The reasons are: (a) the inadequacy of the transmission infrastructure; and (b) the insufficient capacity for power generation which leaves the system vulnerable to sudden spikes in demand or otherwise minor technical accidents. A third major source for uncertainty in the power sector is created: (c) by large amounts of intermittent renewable energy such as wind power. In response to volatile wind patterns, the supply of electricity as well as the price of electricity can fluctuate widely thus imposing added risks on consumers and producers.⁸ It is in the electricity sector

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7. While a larger share of the resource rents going to consuming countries would certainly be welcome, one should not overlook the less insidious side-effects of stable, high prices for imported fossil fuels such as reductions in consumption and energy-related emissions, incentives to improve energy efficiency and, last but not least, an improvement in the competitive position of nuclear power.
 8. It is no longer unusual in Germany, for instance, that electricity prices turn *negative* during periods of low demand (for instance at night and during weekends), when there is strong supply from wind turbines. Prices can turn negative due to the fact that certain baseload producers such nuclear or coal can shut down their

where the economies of OECD countries currently face their greatest security of supply issue. It is also here that nuclear energy as a stable provider of baseload electricity at predictable prices has the greatest potential to contribute to reinforcing the overall security of energy supply.

To the extent that markets struggle to adequately provide for security of energy supply due to its complex, unpredictable nature, there is a role for governments to address the issue both in a short-term as well as a long-term perspective. This does not mean that the private sector, both on the production and consumption side, should be left off the hook. Individual actors in the energy field, both on the supply and demand side, are not passive victims in the supply security equation but need to bear their own share in providing for energy security by making judicious long-term choices in an appropriate division of labour between the public and the private sector. The public sector would thus only bear responsibility for sudden, extreme events or for blatant information failures of private actors with respect to long-term trends.

In summary, the complex subject of security of energy supply can in this context structured best by concentrating on two distinct aspects or dimensions of the issue:

- The external dimension, which deals with strategic and geopolitical challenges issues as well as the adequate political framework conditions for an uninterrupted flow of primary energy. In this context, the relative importance of import dependency will also be assessed and the vulnerability of carbon-intensive economies to changes in global climate policies discussed.
- The internal dimension, which deals with the economic, financial and technical issues that ensure that sufficient high-quality investments are undertaken in production, transport and conversion as well as in end-use efficiency. It also includes the institutional and regulatory realities of a national or regional energy market. Together they determine the reliability of the energy system and its resilience in the presence of unanticipated technical or meteorological events.

In the following, these two key aspects will be presented separately in order to assess the contribution that nuclear energy can make in either dimension.

1.3 The external dimension: import dependence, resource exhaustion and carbon policy

The security of energy supply remains an issue for governments since it is linked to policy issues that are difficult to quantify and to externalities between market participants. As pointed out above, it can also be usefully subdivided into two broad dimensions, the external dimension, where geopolitical issues enjoy large coverage, and the internal dimension, that includes economic, financial and technical issues. The following two sections will discuss the two dimensions one by one and assess the contribution that nuclear energy can make to each of them.

The geopolitical or strategic dimension of energy supply security is still the aspect that attracts the most immediate attention from commentators. It is also an aspect that lends itself to hyperbole, the

plants only at high costs (ramp costs) and thus prefer to keep them running even when prices fall below variable costs or, most spectacularly, turn negative. Wind producers instead have guaranteed feed-in tariffs and thus have no incentive to reduce production. While the phenomenon of negative prices is thus the result of well understood rational behaviour in the short run, it nevertheless distorts incentives and, in particular, reduces incentives to invest in adequate production capacity based on non-wind technologies. In other words, current policies will lead to an ever greater share of wind production, with all the impacts on security of supply as well as the volatility of production and prices this may entail.

selective use of statistics and gratuitous predictions. In fact, it is nearly impossible to advance any meaningful quantification of geopolitical supply risk since it is so closely intertwined with strategic interests, popular perceptions and social risk preferences. This is not to say that these factors should not play any role in assessing security of supply risk, but they can both be highly subjective as well as quite unstable over time.

Geopolitical risk refers almost always to primary energy carriers (oil, gas, coal, uranium or renewables) since their location depends on the vagaries of geology and climate. Production and consumption are thus often physically far apart and take place in countries and regions with different histories, cultures and values. All other steps of the energy chain such as refinement, enrichment, conversion and distribution can be moved physically closer to the final customer or are, like consumption, directly under the latter's control. Geopolitical energy supply risk thus concentrates on energy producing countries.⁹ It concerns the availability of energy stocks under or above ground, as well as the ability of supplier countries to produce that energy, i.e. their technical skill to garner it in marketable form, their foresight to make adequate and timely investments and their political willingness to make the produced energy available to international markets in a predictable manner.

Underground resources relate to fossil fuels and uranium, which pose complex but relatively well studied questions in security of supply terms. Above-ground resources concern the generation of bio-fuels or electricity from renewable resources, for the time being mainly biomass, wind, hydro and solar. The growing importance of geopolitical concerns regarding renewables has recently been highlighted by the discussions surrounding the giant Desertec project that aims at importing vast amounts of solar power from the Sahara desert to Europe. Historic disputes over hydroelectricity production between Brazil and Paraguay or the Province of Quebec and the State of New York have also shown that renewable energies are not immune to political squabbling.

Last but not least geopolitical tensions are rising over the distribution of responsibilities for reducing global greenhouse gas emissions as well as over the realisation, timing and distribution of "carbon rents", the ability to earn income from selling relatively low-cost emission reductions to countries with significant obligations to reduce emissions but lacking low-cost reduction options.

Geopolitical energy supply risks are thus a function of relations between producer and consumer countries for which both of them share responsibilities. However, even in the best of cases these relations are very difficult to predict. The issue is made more difficult by the fact that the majority of the easily accessible stocks of hydrocarbons are located in potentially unstable region. There is thus only so much that can be done about the sources of geopolitical supply risk. On the demand side, the best-known strategy is the diversification of supply sources and of transport routes. It is a sensible and long-standing strategy. As early as 1913, when the British navy switched from coal to oil to power its ships, Winston Churchill remarked that "safety and certainty in oil lie in variety and variety alone". In economic terms this means increasing the elasticity of demand *vis-à-vis* any particular source of supply. Thus if a supplier suddenly raises prices or threatens the interruption of deliveries, consumers have elsewhere to go. The principle is general and can, of course, be applied at the level of the total consumption of any specific fuel or of total energy consumption. The higher the flexibility on the demand side and the more consumers are prepared to change behaviour if needed, the lower are the risks for the security of supply.

9. Although it is strictly speaking incorrect from the point of view of thermodynamics, since energy cannot be produced, the authors shall nevertheless use the conventional expression of "producing energy" as shorthand for "harvesting energy in usable form".

Box 1.1: Managing security of supply through market-based measures

Increasing diversification and flexibility (elasticity of demand) is also the basic philosophy of two studies published in 2002 and 2004 by the International Energy Agency (IEA) on the security of gas supplies in OECD countries: *Flexibility in Natural Gas Supply and Demand* (IEA, 2002a) and *Security of Gas Supplies in Open Markets: LNG and Power at a Turning Point* (IEA, 2004). Both studies argue in favour of adopting a number of concrete measures that strengthen the flexibility of the markets. Most of these measures are market-based or market compatible. Governments can (and should) play a role in facilitating the adoption of such practices in the market-place but not substitute themselves for the market process, for instance through bilateral bargaining with favoured supplier countries. The proposed measures include:

1. Shortening the terms for sales contracts (currently between 8 to 15 years in Europe and 15 to 20 years in Asia instead of the more traditional 20-25 years).
2. Enhancing market access by facilitating investment into LNG re-gasification terminals and import pipelines.
3. Developing adequate financial instruments for risk management.
4. Adoption of portfolio approaches by buyers.
5. Smaller volumes for new contracts or renewals of LNG contracts.
6. Greater flexibility in reviewed contractual terms (for instance, interruptible contracts).
7. Sufficient storage capacity.
8. Flexibility in production (dual-firing systems).

Is energy independence identical with energy security?

Given that the fundamental condition for geopolitical supply risks is the physical separation of the centres of production of primary energy and their consumption, it is tempting to address the issue by striving to bring production home. In other words, enhancing energy security is seen as equivalent to increasing the share of domestic production and to strive for “energy independence”. The question whether energy independence is the same thing as the security of energy supply is as old as the debate over energy security itself. The answer is, of course, “it depends”. It depends on a country’s geographical position, its own energy endowment, the state of its physical infrastructures for transport and storage, the diversification of its supplies, the willingness of its population to trade lower average long-term prices for higher volatility and a host of other issues.

In an ideal world, security of energy supply would not equate to energy independence or self sufficiency. Free and global energy trade through smoothly functioning competitive markets would guarantee timely delivery of all necessary energy resources. But then again in such an ideal world, energy supply security would not exist as an issue. But even while reality often diverges drastically from the ideal of a global world of competitive markets, the concept of security of energy supply very clearly includes not only the notion of energy independence but also the notion of energy interdependence. Most countries are relying at least partially on the international trade of energy and will continue to do so. What is important in this case is not so much the security of the single shipment but rather the security of the system in which both producers and consumers have a stake.

Energy security as a national policy issue arises where fears exist that free trade may not be assured, for instance due to geopolitical reasons. In these cases, it can be argued that countries should strive for a certain degree of energy self-sufficiency, in addition to establishing the conditions for the market to resume its role. In the 1974 oil crisis, which remains at the origin of the modern debate on

energy supply security, the original notion of energy security was built around the imperative to guarantee the continuity of energy flows.

OECD countries thus hastened to improve the level of domestic supplies, to diversify suppliers away from OPEC and to develop their own resources in order to replace imported oil. More recently, the interruptions in Russian gas supplies that repeatedly struck Europe since 2006 encouraged an orientation towards alternative suppliers, a different vector of delivery (substituting pipeline gas by LNG) and domestic resources such as renewable energy. In both cases, nuclear energy also played an important role. The 1970s saw the launch of large-scale nuclear programmes in many OECD countries and the stirrings of a “nuclear renaissance” in the first decade of the 21st century were, in addition to climate change concerns, also supported by worries about the reliability of gas supplies.

Geopolitical supply risks need not equate to political animosity, civil strife or full-blown embargoes. It frequently relates to the more mundane issues of competent management and sufficient investment in producer countries. Even if sufficient oil, gas, coal or uranium is available, it still requires important levels of technological competence and equipment to extract the primary energy and to make it available to the market. Timely investment in production capacity in producer countries to match demand is thus important. Typical examples concern oil production in the Middle East, gas extraction on the Jamal peninsula in Russia, investment in liquefaction facilities for LNG in Qatar and elsewhere, and for exploiting uranium mines in many different areas.

To ensure sufficient production investment, it is important that fuel prices are adequate and stable. Prices that are too low or too volatile discourage investment. Volatile prices also discourage consumers, particularly if their demand elasticity is low. It is a challenge to reach optimal investments levels. Liquid markets on the one side and long-term contracts on the other are important factors in providing investors in producer countries with the necessary visibility for investing in adequate capacity for production, storage and transport. Storage assumes a particular importance in this context, as it can provide a temporary buffer for variations in supply and demand.

In practice, each country must find the right balance between self-sufficiency and reliance on energy imports in the context of a global division of labour. Two issues have particular bearing on this trade-off. First, social preferences for either a low cost-high risk structure of supply or a high cost-low risk structure of supply need to be translated into policy action. Second, in order to enable international energy trade, it is necessary to have the logistic infrastructure available. Worldwide, transport infrastructures such as roads, rail tracks, ports, pipelines and re-gasification terminals for LNG are thus required.

The issue of self-sufficiency assumes a particular significance in electricity markets, since due to the high costs of storage, electricity can be economically transported only over relatively short distances. In far-off islands countries such as Japan and Australia or *de facto* isolated countries such as the Republic of Korea, national electricity generation must be able to cover national demand.¹⁰

Self-sufficiency in electricity supply is sometimes the only option. For certain of these geographically isolated countries, imports of primary energy may also be more awkward due to the reliance on few and far-away suppliers. For large interconnected regions, such as Europe or North America, self-sufficiency at the national level is evidently much less of an issue even in grid-bound markets for gas

10. Great Britain’s electricity grid is, of course, connected with France and continental Europe through the massive interconnector undersea cable. But the interconnector’s 2 GW of capacity constitute less than 5% of Great Britain’s total installed capacity of around 70 GW.

and electricity. It would even be counter-productive. The condition is, of course, that sufficient cross-border electric connections exist and that the region in question is sufficiently harmonised and coordinated – for instance, in terms of the operational procedures and technical procedures of different transport system operators (TSOs) – to keep transaction costs at a minimum. In short, the issue is the depth of market integration.¹¹ A frequently cited example in this context is, for instance, the high share of Canadian natural gas imports in US gas consumption. In security of supply terms, it is largely a non-issue since the exchanges taking place on the United States-Canadian border are part and parcel of an integrated market zone that spans the border.

There is a link between the security of energy supply and import dependence, but the two are not identical. Discussions about the security of energy supply also need to specify the geographic level at which security is thought. This level may reach from local security of supply to global security of supply including security of demand for suppliers as a natural *quid pro quo*. Determining the level of analysis determines the results. The same holds for diversification. France may have a high share of nuclear energy in power production at the national level. However, this very same nuclear production is a contribution to the diversification of power supplies at the European level.

Traditionally, the national level has received the most attention. It is, however, increasingly recognised that the national level may not be the appropriate level to deal with the issue. In Europe, for instance, the creation of a single market for goods and services as well as the creation of a European-wide market for carbon emissions is driving an evolution that sees energy and security of supply issues more and more as European issues. Examples are the EU-Russia dialogue, the European directives to further the integration of electricity markets, its famous 20-20-20 targets for 2020 or even the recent initiatives of the European Commission to harmonise the assessment and management of safety risks in the nuclear field.¹²

However, at any geographic level there exist difficulties to define “secure” options. Domestic sources can be insecure. British coal is an excellent example. Britain’s “dash for gas” was also a response to the political volatility surrounding coal production. From the standpoint of the private investor, the decisions on phasing out nuclear power in Germany or Sweden despite its intrinsic advantages constitute similar risks concerning the use of a “secure” domestic source of energy. Current initiatives in both countries to reverse the phase-out improve, of course, the medium-prospects of nuclear energy in both countries but further highlight the difficulties of ensuring stable, long-term policy frameworks.

Such concerns, however, should not lead governments to selectively subsidise energy sources to counter perceived or real geopolitical risk. More, not less competition is the answer. Markets offering choices between competing sources, fuels and suppliers can be an excellent hedge against supply security risks. It is important in this process to allow each source to bring its advantages to the marketplace. This means that innovative forms of financing (of which long-terms supply contracts must be part of) must be created to allow for nuclear and renewable energies to overcome the disadvantage of high fixed-cost technologies in volatile price environments.

11. Legal and technical details can matter in this context. For instance, even neighbouring countries that exchange electricity may install circuit breakers at their borders and many grid codes specify that the cross-border lines may be cut if necessary in case of a blackout. That is why it is important in assessing market integration not only to regard the state of technical infrastructures but also of the legal and institutional arrangements ruling the operations of such infrastructures.

12. The 20-20-20 targets oblige the countries of the European Union to reduce by 2020 their carbon emissions by 20% from 1990 levels, to increase their share of renewables in energy to 20% and to increase their energy efficiency by 20% also from 1990 levels.

Box 1.2: Pitfalls of the geopolitical approach

Geopolitics and import dependency certainly have a bearing on the security of energy supply. Yet, one needs to be careful not to privilege this dimension to the exclusion of all others. A cautionary example is provided by the otherwise interesting and well-informed presentation by Professor John Gittus, Lloyd's of London, with the title *Keep the Lights Burning*. Insisting heavily on future turmoil in the Middle East and future interruptions of Russian gas, he raises the spectre of a return to "three-day week" in absence of drastic action and predicts a blackout in the United Kingdom by 2025 with a 75% loss of electrical power lasting more than one day with "2 to 5% probability" (Gittus, 2004, p. 7).

The choice of terminology, however, requires a moment of thought. The infamous term "three-day week" was coined during the 1984 "winter of discontent" when the UK coal miners went on strike. Gittus thus unwittingly highlights that fact that domestic energy resources need not necessarily outperform imported energy resources in their contribution to the security of energy supply. His own statistics confirm that the longest significant energy supply interruption in the United Kingdom was precisely due to the 1984 strike (Gittus, 2004, p. 5). What counts is not so much the distinction between domestic and foreign sources but the absence of efficient market signals and the degree of politicisation. Distributional conflicts in the English countryside can be as detrimental to the security of energy supply as the Arab-Israeli conflict. A hurricane affecting (domestic) wind power production or drastic carbon cuts in the face of catastrophic climate change are nowadays sources of supply risk as likely as old-fashioned animosity between nation-states. The latter, of course, still makes for much better journalistic cover.

The role of nuclear energy in reducing geopolitical supply risk

It is quite obvious that nuclear energy has some distinct advantages in strengthening the external dimension of energy supply security. Evelyne Bertel (Bertel, 2005, p. 6) states, for instance:

...nuclear power plants provide a largely or entirely domestic supply of energy [...] The main advantages of nuclear energy in this regard are the limited importance of raw material – natural uranium – in the entire fuel chain producing nuclear electricity, the geopolitical distribution of uranium resources and production capabilities, and the easiness for users to maintain strategic stockpiles of fuel.

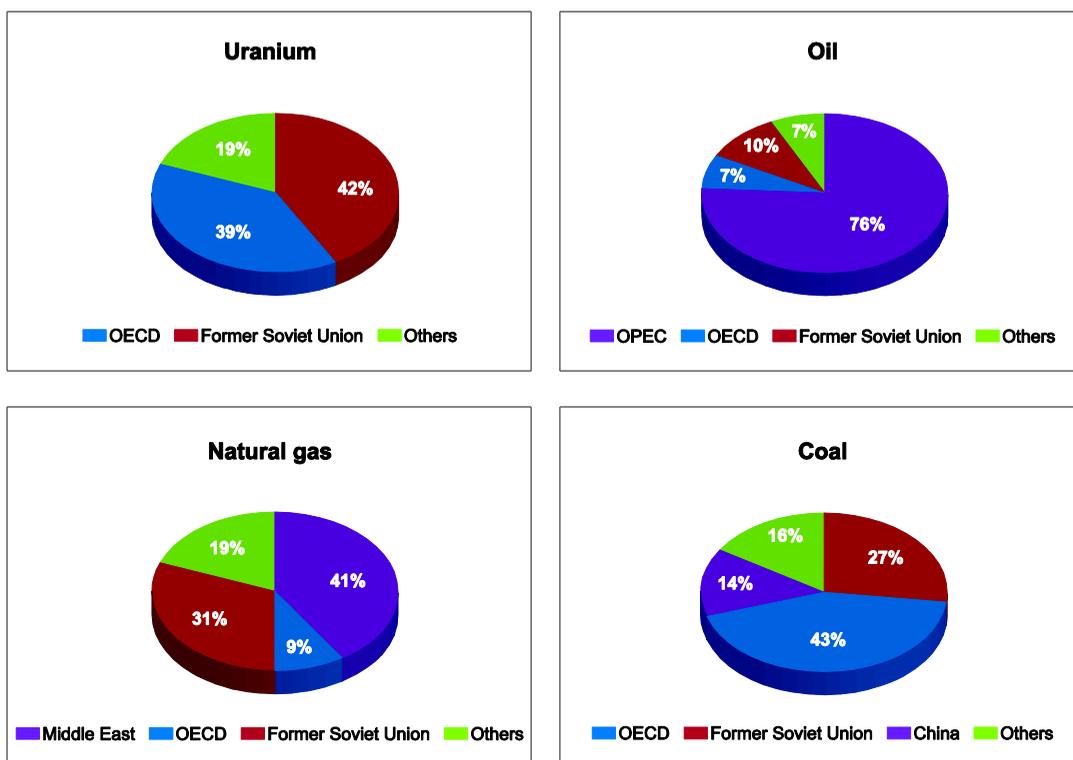
One might add that nuclear energy is capable of providing large amounts of baseload power at stable costs and would be unaffected by a sudden tightening of restrictions on the emission of greenhouse gases. Coming back to the issue of import dependency, the following table demonstrates that uranium resources and production are indeed well distributed. In addition, the majority of supplies are coming from politically stable OECD countries such as Australia and Canada. The only major geopolitical change in the uranium supply is rapid mining development in Kazakhstan. According to *Uranium 2009: Resources, Production and Demand*, in 2008 Kazakhstan became the second world largest uranium producer (8 512 tU), between Canada (9 000 tU) and Australia (8 433 tU). Nevertheless, one can state that the uranium supplies used in nuclear energy production do not pose any major risk to energy security.

The four pie charts below show the distribution of the relative shares of key energy resources between OECD countries and non-OECD countries (Figure 1.2). Under the assumption that import dependence from fellow OECD countries does not pose any security of supply issues, the graphs show that oil and gas pose the most critical questions concerning the security of supply. While the share of OECD countries of global uranium resources is 39%, their share of oil and gas resources amounts to only 7% and 9% respectively. In the case of coal, OECD countries hold again a very respectable 43% of global resources (mainly due to the United States, who hold almost a quarter of global resources).

Yet, while coal poses few issues with regard to physical security of supply, its high carbon intensity makes it vulnerable to future restrictions on greenhouse gas emissions.

A high share of global resources outside OECD countries, of course, does not mean that there will be major security of supply issues concerning oil or gas in the future. It just means that *ceteris paribus* nuclear energy, which relies on uranium, provides an added layer of protection against geopolitical supply risks.

Figure 1.2: Regional shares of key energy resources
(Global reserves in 2008, uranium in 2007)



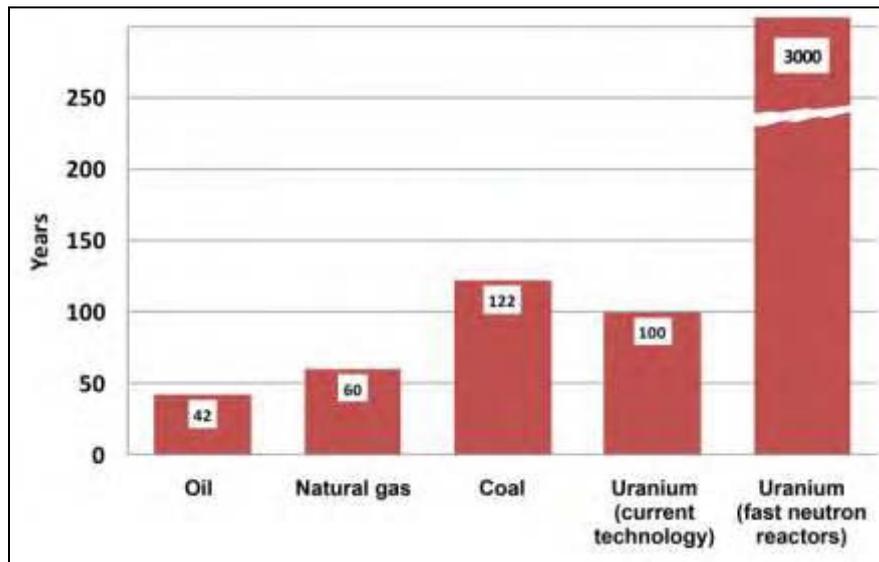
Sources: BP, 2009; NEA/IAEA, 2008.

Similar reasoning also holds for resource depletion. The following graph shows the reserve-production (R/P) ratios for key energy resources (Figure 1.3). The R/P ratios indicate the number of years that currently known (“proved”) reserves that can be recovered with reasonable certainty in the future under existing economic and technical conditions would last at current levels of consumption. This is, of course, a highly stylised number. While experts discuss intensely about likely, known or recoverable reserves, the moment at which production will peak, etc., static R/P ratios tend to structurally underestimate existing reserves. In reality, prices will rise as the point of exhaustion nears thus spurring both additional efforts in exploration and production as well as reductions of consumption.¹³ Technological progress will also increase reserves and the number of years that

13. Some analysts argue that an autonomous trend of increasing demand driven by higher incomes and growing populations would tend to increase also the denominator. The net result will depend on the classic problem of income vs. substitution effects. In early stages, the income effect that will *increase* demand will dominate; in later stages the substitution effect that will *decrease* demand will dominate. The net effect will be of second order.

consumption may continue (in the oil sector, for instance, R/P ratios have been steadily increasing over the past 40 years rather than decreasing as one would expect as time goes by).¹⁴ In other words, for each resource the R/P ratio indicates a lower bound of availability. Nevertheless, they remain a useful and readily available first indicator of the risk of resource exhaustion.

Figure 1.3: Reserve/production ratios of key energy resources
(Global proved reserves in 2008, uranium in 2007)



Sources: BP, 2009; NEA, 2008.

The graph above (Figure 1.3) shows that the risks for resource depletion are highest for oil and gas with R/P ratios of around 50 years. While this does not mean that the world will use no more oil in 50 years, it does mean that the pressure for massive price rises will be highest in the oil sector. The resource situation is less dramatic for coal and uranium with R/P ratios of around 100 years. Two things need to be underlined in this context. First, all the R/P ratios provided below refer to known or “proved” reserves. This is a restriction that underestimates, in particular, the availability of uranium resources where exploration and production have been sluggish in recent years due to the availability of enriched uranium from military sources after the end of the Cold War. Currently it is unclear to which extent the Russian Federation and the United States will continue to reduce their nuclear arsenal.

Second, currently known uranium reserves might last for a century only under the assumption that current fission technologies will not evolve over time. This is, however, again a rather restrictive assumption. If international research efforts into generation IV fast neutron reactors, such as the Generation IV International Forum (GIF) coordinated by the NEA or the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) coordinated by the IAEA bear fruit, this would allow the large-scale re-use of depleted fuel vastly improving fuel efficiency. In return, this would increase the availability of uranium by an estimated factor of 30.

14. A key issue in the availability of oil is the recovery factor, the proportion of a well’s reserves that are actually produced, that stands currently at 35%. If the recovery factor could be increased, say, to 50% this would double today’s proven reserves (*IEA World Energy Outlook 2008*, p. 212).

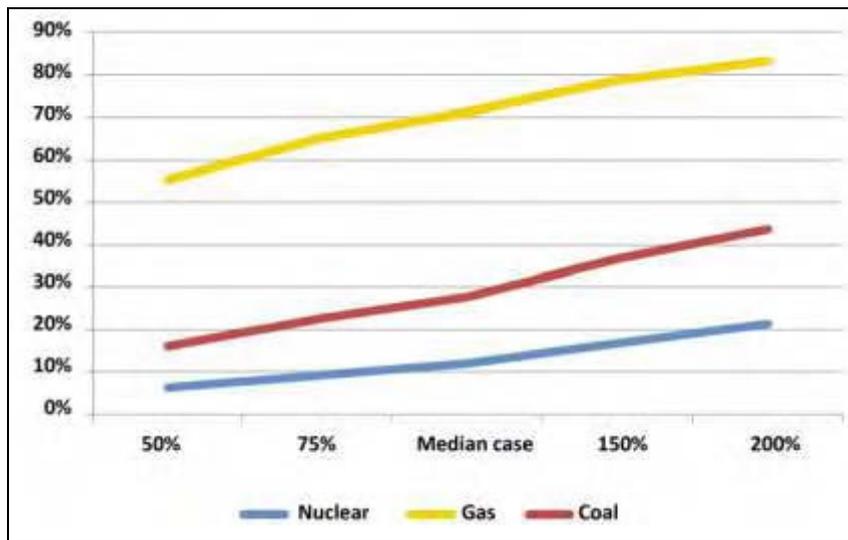
This is not to say that there are no resource issues pertaining to uranium. The NEA report *Forty Years of Uranium Resources Production and Demand in Perspective – The Red Book Retrospective* (NEA, 2006) points out that by 2020 secondary sources are expected to be depleted and that more exploration is required. This point of view is largely shared by the European Atomic Energy Community (Euratom) Task Force on Security of Supply in its *Analysis of the Nuclear Fuel Availability at EU Level from a Security of Supply Perspective* (2005). While the security of supply situation of uranium is judged favourable, it identifies a gap between the demand from reactor operators and the primary supply of uranium. While secondary sources (essentially stockpiles and re-enrichment for depleted uranium) could until now fill the gap, new supplies will be necessary in the future. Not unlike natural gas, uranium is mainly sold through bilateral long-term contracts, and only about 15-25% of it is sold on the spot market that is constituted of utilities, producers and the financial community. Even under the most restrictive assumptions, the situation of uranium, which has very high energy intensity and can be easily stored and transported, still looks very favourable when compared with the limited availability and geographic concentration of other fuels such as oil and gas.

Potentially greater issues, especially in the context of a potential expansion of nuclear power, are posed by the concentration of suppliers of vital components of the nuclear fuel cycle. One example is enrichment, where there are essentially only two international suppliers of enrichment services. Other, less pressing examples are constituted by the production of reactor pressure vessels, specific stainless steel tubes or high-quality graphite. In the case of enrichment services, their concentration in the hand of a limited group of suppliers under tight supervision is to some extent necessary given the sensitive proliferation issues connected with enrichment. In the other cases the question is – like in the oil or gas industry – whether equipment providers are sufficiently forward-looking to anticipate future demand.

Uranium, widely available and easily storable, clearly does not constitute a crucial energy supply risk. This regards both physical availability and the impact of price volatility. The impact of price volatility on the competitiveness and, ultimately, riskiness of different fuels is brought out starkly in the graph above. It shows the share of fuel costs in the LCOE for a nuclear, a coal and a gas plant depending on different price assumptions. These price assumptions vary around the “median” case of the joint IEA/NEA study on the *Projected Costs of Generating Electricity: 2010 Edition*¹⁵ (IEA/NEA, 2010). As the graph shows (Figure 1.4), even a doubling of the front-end costs of nuclear would only increase their share from 10% to about 20%, implying an increase of about 10% in the total cost of electricity produced by a nuclear plant. Doubling the costs of gas instead would increase the share of fuel costs from 70% to about 85% implying an increase of about 70% in the total cost of gas-fired electricity! The cost of a coal-fired power plant would increase by about 25% under the same assumption of a doubling of the coal price.

15. The “median case” refers to the median of the sample data in each category (nuclear, coal, gas, etc.) from a total pool of 190 power plants. Median fuel or front-end costs are thus 7 USD/MWh for nuclear, 18 USD/per MWh for coal and 61 USD/MWh for gas.

Figure 1.4: Fuel cost shares in the levelised cost of electricity with different fuel prices¹⁶
 (Median case refers to typical plants in OECD countries)



Source: IEA/NEA, 2010.

The cost of nuclear electricity generation is thus largely insensitive to price fluctuations of the primary fuel U_3O_8 . In addition, the cost of nuclear power is largely uncorrelated with either fossil fuel prices or with the economic business cycle.¹⁷ The stability of its variable cost and its independence from other energy costs is thus a distinct advantage of nuclear energy in a perspective of minimising security of supply risks that includes protecting consumers from sudden price shocks in the electricity market.¹⁸

The great advantage of nuclear power in the context of the security of supply debate remains its contribution of large amounts of essentially carbon-free baseload power whose variable costs through time are highly stable and little affected by geopolitical factors. The fuel with which nuclear energy is in direct competition is coal, which poses few security of supply issues but has due to its high CO_2 emissions of more than 0.8 tonnes per MWh [“median case” in the absence of carbon capture and storage (CCS) according to IEA/NEA, 2010] major problems of environmental acceptability. In terms of environmental performance, gas holds an intermediate position with 0.35 tonnes per MWh (*ibid.*).

16. The figure for nuclear makes reference to the complete cost of the front-end of the nuclear fuel-cycle, which includes uranium mining and milling, conversion, enrichment, fuel fabrication and waste management. Taking only the cost of yellow cake (U_3O_8), which contributes roughly one-third to front-end costs, would have produced an even lower ratio for nuclear energy.
17. In analogy with financial analysis one may refer to nuclear as a technology having a “low β ”, which indicates a low degree of correlation of the cost of nuclear with the cost of other energy technologies. Having a low β is a highly thought after property for portfolio risk diversification.
18. From a social point of view things are indeed obvious. However, things may not be quite as straightforward from the point of view of a private investor. Given that in a liberalised market the marginal fuel (the one with the highest variable cost, i.e. gas) sets the price of electricity, the electricity price in a liberalised market tends to fluctuate with the gas price thus preserving a rather stable profit margin for investors in gas. In a market with regulated prices instead, investors in nuclear would benefit from a stable profit margin and investors in gas would have to cope with the volatility of their cost base. Issues of market organisation are thus important in determining the relative competitiveness of different fuels. They can also drive a wedge between the private and the social benefits and costs of different fuels.

In the light of likely future restrictions on the emissions of greenhouse gases in OECD countries, the fact that nuclear energy does not emit any greenhouse gases is thus an added advantage. Abstracting for the moment from small amounts of emission during construction, nuclear-based electricity production is carbon-free during operations. This provides nuclear energy with enormous resilience against any changes in the global carbon regime, which may be considered a new form of geopolitical supply risk. Unsurprisingly, the great majority of long-term scenarios interested in the question of sustainable concentrations of greenhouse gas emissions – including the highly influential Stern Report or the *IEA Technology Perspectives* – include a massive expansion of nuclear power.¹⁹

Overall, in the face of geopolitical supply risks whether due to import dependence, resource exhaustion or changes in the global carbon regime, nuclear energy holds advantages that other fuels such as oil, coal and gas do not enjoy: wide availability of resources for a long time to come, modest impacts of increases in resource prices and resilience against carbon policy shifts. Of course, in the absence of widespread penetration of electric cars, the substitutability of oil with nuclear power is limited. It is also difficult to displace gas – and to a lesser extent coal – in peak-load generation due to their operational flexibility. Nevertheless, as far as baseload power generation is concerned, shifting from oil, coal and gas towards nuclear to the extent that renewable energy is not available at competitive cost is a sound policy option for governments interested in reducing geopolitical supply risks.

1.4 The internal dimension: economic, financial and technical conditions for energy supply security

Geopolitics and resource exhaustion are, of course, only the external side of the security of supply coin. Energy security begins at home. The most important responsibility for OECD governments is setting appropriate framework conditions providing incentives for private actors to install domestically an adequate level of facilities for the production, transport, conversion and consumption of energy. Important elements in this strategy are regulatory stability, market organisation, fiscal coherence and the predictability of environmental policy. Power generation is the key sector in this context.

The challenge in the electricity sector is the creation of framework conditions that (a) do not discriminate against domestically produced, low-carbon energy sources such as nuclear and renewable energies and (b) allow for the construction of adequate transport, production and conversion capacity under sufficiently attractive financial conditions. Concerning the first point, both nuclear energy and renewables have the great advantage of not being dependent on imported fossil fuels generating climate change-inducing greenhouse gas emissions. For the very same reason, both nuclear energy and renewables are technologies with a high fixed cost – variable cost ratio. High variable costs are, of course, precisely the result of using expensive imported fossil fuels. In the absence of an absolute cost advantage, however, technologies with a high fixed cost – variable cost ratio are a concern for risk-averse investors as much of the lifetime costs have to be disbursed before the first MWh is produced. This increases risk. Moreover, in liberalised markets prices follow the highest variable cost, which leaves technologies with lower variable costs exposed to price fluctuations. OECD governments have thus a responsibility to create market conditions that allow low carbon technologies with lower supply risks to compete on a level playing field.

19. The influential Stern Report, for instance, advocates a doubling of global nuclear capacity by 2055 to 700 GW as one of the measures to stabilise greenhouse gas concentrations (Stern, 2006, p. 207).

Governments also have a role to play with regards to the provision of adequate levels of transport, distribution and conversion capacity. The transformation of a primary energy carrier, such as oil or uranium, into a secondary one, such as gasoline or electricity, requires substantial capital investment in refineries, U-enrichment plants or LNG terminals. Sufficient transport and distribution capacity requires high- and low-voltage transport and distribution lines for electricity, high and low pressure pipelines as well as compressor stations for natural gas and oil. The domestic transport infrastructure needs to be complemented by sufficient cross-border pipeline connections and high-voltage lines to ensure more than one single delivery path. Last but not least, a complete energy system requires fleets of oil tankers, LNG tankers and freight ships and trains as well as the appropriate port infrastructures, for instance for coal transport.

Some elements of this can be provided by markets themselves, others require regulation and supervision. First, regulation must provide sufficiently attractive financial conditions for investment in transport and conversion infrastructure. If transport operators have operational independence, they will often determine technical requirements and submit them to their authorities of tutelage, usually the national regulator, for financing through regulated tariffs.²⁰ Policy issues are particularly challenging when transport and production are vertically integrated and the commercial interests of integrated incumbents are at odds with the public policy objectives of the regulator.

Second, political backing must support projects that are necessary at the national level against blockage by the not-in-my-backyard (NIMBY) syndrome through appropriate technical regulations and zoning laws as well as adequate mechanisms of mediation and compensation. When legitimate environmental concerns impede the construction of such installations, bilateral cooperation with neighbouring countries with more favourable conditions can yield mutual benefits. A special case, due to its intrinsic importance as well as due to the particular challenges that it poses, is constituted by power generation, which is discussed in the section below.

The case of power generation capacity

Power generation displays a number of peculiarities relating to the speed at which signals propagate and the difficulty to store electricity that both make it something of a special case. For instance, dispatchable capacity needs to be adequate at all time in order to ensure that sufficient active power is available in the system to meet demand, otherwise the frequency of the system would deviate from the desired 50Hz or 60Hz.²¹ Lack of sufficient active power capacity may also lead to “brownouts”, which is a reduction of the system voltage. This usually only occurs in regions with weak or isolated grids, where the lack of active power leads to reduced frequency, which in turn may lead to reduced generator voltages. To keep the voltage of an electric system at appropriate levels, sufficient generation of so-called reactive power is also necessary. This can be done by regulating the magnetic excitation of large synchronous generators in plants or through installing sufficient reactive power compensators.

-
20. There can, however, exist political issues concerning the specific regulation of such infrastructures, witness the European debate about the financing of trans-national interconnection capacity. Another “political” issue might be constituted by local resistance to new large-scale infrastructure projects. However such issues relate only indirectly to questions of security of supply as such.
 21. An alternative way of keeping the system functioning is “load shedding”. This can happen in two ways. Either the transmission system operator will take certain groups of customers off the grid, either spontaneously or as part of a prior contractual agreement, or he will resort to so called “rolling blackouts”, whereby power cuts are rotating from one district to another. The inconvenience and economic damage of such emergency measures in absence of adequate power capacity are self-evident.

Partly due to its technical peculiarities, the provision of adequate capacity for the production of electricity is the one area where the risks to energy supply security in OECD countries are the greatest. It also happens to be the area where nuclear energy can contribute most directly to the security of energy supply. The costs of an interruption of power supplies due to insufficient capacities on the economies of OECD countries far outweigh any real or imagined interruptions of physical supplies due to geopolitical reasons. Unfortunately, they are also much more likely and have been increasing lately. The simplest indicator for this risk is constituted by the major blackouts OECD countries have been experiencing in France (1999), California (2000), London (2003), Denmark and Sweden (2003), Italy (2003), Eastern Canada and the United States (2003), Greece (2004), Spain (2004), Germany (2004), the United States (2005), Western Europe (2006) and the United States (2008).²² Each blackout has its own history and context, which may be defined by technical accidents (Europe, 2006), high import dependency (Italy, 2003) or under-investment due to market imperfections (California, 2000). And yet, their increasing frequency points towards the common fact that electricity systems are less and less redundant, which means the N-1 rule is not respected.²³ If one element fails, the whole system fails.

The increasing tightness of electricity system is due to a combination of increased demand and stricter profitability requirements in the wake of market liberalisation in Europe and parts of the United States. One indicator of this process is that capacity margins are falling. The reserve margin or capacity margin is a standard measure for system adequacy and equals to the percentage difference between capacity and peak demand:

$$\text{Capacity margin} = (\text{Installed capacity} - \text{Peak demand}) / \text{Installed capacity}.$$

Ideally, gross figures for capacity margins would be adjusted for the age and composition of generation equipment. They would also need to take into account the need for outages for maintenance and the limited availability of resources due to climatic reasons such as the lack of water in hydroelectric reservoirs during the summer. On the other hand, provisions for interruptible contracts allowing customer-load shedding at the discretion of the energy provider permitting to cover peak load if needed, would improve security of supply at any given capacity margin. Last but not least, firm long-term import contracts are *de facto* part of a country's effective power supply but do not count towards its installed capacity. Of course, a simple capacity margin takes no such considerations into account. It nevertheless provides a useful, if crude, indication of the adequacy of an electricity system.

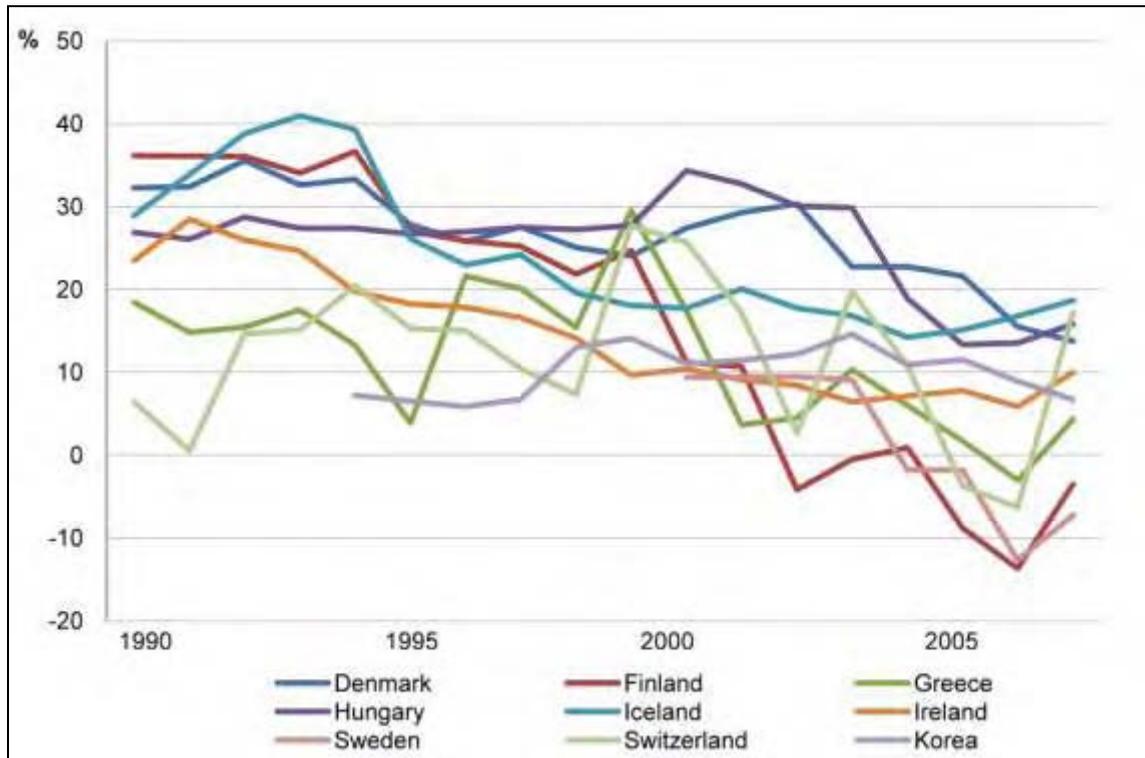
Capacity margins have come down considerably in OECD countries in recent years (see Figure 1.5).²⁴ The main cause for this development is in most countries the process of electricity market liberalisation. For European countries this happened in the wake of the first electricity market directive in 1996. In deregulated markets, private companies have no longer an interest in holding any spare capacity that would serve to mitigate costs and prices in the event of sudden demand peaks. On the contrary, such peaks are welcome opportunities to make additional profit and to finance the fixed costs of peak-load plants. Due to the inelasticity of electricity demand, some market power at peak time is almost inevitable and new entrants would have to tread a difficult path between profiting from high prices and causing sudden excess capacity and price decreases.

22. See Ladoucette, 2006, p. 5 and http://en.wikipedia.org/wiki/List_of_power_outages#2007) for details.

23. The so-called N-1 rule is a frequently used measure of redundancy. A system consisting of N elements must thus continue to function properly, even if the largest element in the system fails. True security of energy supply requires partial redundancy in the form of parallel paths or loop structures.

24. Negative reserve margins indicate that countries were required to cover at least part of the year a certain amount of their electricity consumption through imports.

Figure 1.5: Capacity margins in selected OECD countries
(1990-2007)



Source: IEA, 2010.

Adding to the security of supply risk in the electricity sector is the fact that the *quality* of capacity margins is declining. It matters whether a capacity margin is constituted by nuclear generation capacity, gas- or oil-fired capacity that can be brought on-stream at will or intermittent renewables. Renewable energy that constitutes a growing share of generating capacity in OECD countries might instead not be available when needed. The intermittency of renewable energies (especially wind and solar) which are governed by the weather and not by the needs of electricity consumers creates serious stress for power generation infrastructures and has led to the distinction between gross capacity margins and “reliably available capacity”.

The strategy of substituting nuclear energy with renewables, for instance in Sweden or Germany, bears thus some distinct costs in terms of security of supply. A power system must provide stable amounts of baseload power and cover peak demand at all time. It must thus be able to deal with variable and unpredictable events, be they related to the weather or to technical accidents. In this regard, power plants that are not dispatchable (such as wind turbines and PV systems) cannot be compared on a one-to-one basis with other plants capable of continuous production and dispatch, i.e. instantaneous power delivery upon demand.²⁵ Of course, the supply risks created by non-dispatchable technologies can be mitigated by installing back-up capacity with conventional fuels for periods when renewable energy is not available, but this adds to their cost.

25. To some extent, a more intensive use of information technology in the context of future “smart grids” capable of coordinating large numbers of decentralised production units, limited storage and demand management might be able to accommodate a small share of intermittent renewable energy in the system. It should also be pointed out that not all renewable energies are intermittent. Geothermal energy, biomass and hydroelectricity, for instance, are all capable of continuous production.

Why lower reserve margins do not lead to investment and increased security of supply

In general, a supply risk due to inadequate capacity and tight supply would lead to increasing prices and more investment. The market mechanism would thus provide an automatic stabiliser for the risk of interruptions of power provision. Unfortunately this is not the case in electricity markets, where tight margins and high prices do not automatically generate investment. This is due to the inelasticity of demand for electricity, itself due to the inability to store electricity and its character of an essential commodity. Even slight overcapacity will thus lead to very low prices, whereas under-capacity can lead to very high prices limited only by what is called the value-of-lost-load (VOLL), the cost of a shortfall of electricity to consumers, measured in the 1 000s of dollars. These asymmetric incentives create a tendency for private investors to under-provide capacity. When in doubt, private operators will err on the side of caution preferring to risk having too little capacity rather than having too much.²⁶

This may not be the end of the story. The future might hold even greater challenges for power sector investment at least in Europe (UCTE, 2005, p. 7). The drivers behind the trend of declining capacity margins and deteriorating security of supply in the electricity sector of OECD countries are according to Paun (2004):

- Plant retirements (half of current plants will probably be retired by 2030 which means between 500 and 600 GW of new capacity will be needed by then).
- Increased stringency of environmental and other regulations.
- Competition (maintaining reserve capacity which most of the time unused is costly).
- Local resistance, the NIMBY.
- Volatility of electricity and CO₂ prices.
- Volatility of costs, partly due to high feed-in tariffs for renewable energies.

The high price volatility and uncertainty in the electricity sector deterring investment are intrinsic features of power supply and demand. However, in recent years they were further increased by the following two factors: market liberalisation and unstable regulatory framework conditions. Market liberalisation has led investors to demand higher rates of return on their investments. Sometimes this can mean that the rate of return is several percentage points higher than in regulated markets. Especially capital-intensive investments such as nuclear power and renewables may suffer from this market risk factor.

In recent years, investors have thus tended to opt for combined cycle gas turbines (CCGTs), partly because they are cheap to build and thus require a lower amount of capital at risk. This allows exiting the market at relatively low cost if conditions should change. Per kW of installed capacity CCGTs cost roughly one quarter of a nuclear plant and one third of a coal-fired plant. Of course, gas is expensive and on a per-kWh basis, gas-fired generation is more expensive than either coal or nuclear (IEA/NEA, 2010).

26. These considerations abstract from deliberate attempts to restrict existing capacities in order to maintain higher prices. There is in recent years some evidence of “mothballing”, i.e. putting existing categories out of use which has the double effect of: (a) maintaining structural under-capacity; and (b) deterring new entrants with a threat of massive overcapacity if they should venture to enter.

The resulting “dash for gas”, however, has obviously negative impacts on the security of supply of importing countries. There exist only a handful of supplier countries for each one of the three regional gas markets in Europe, North America and East Asia as most imports are still traded by pipeline. A growing LNG market is improving the security of supply situation at the margin but holds with respectively 9% and 12% still a relatively small share of total imports in the United States and Europe respectively (IEA, 2009, pp. 18 and 38). For obvious reasons the situation is different in Asia where, due to Japan’s island geography, the share of LNG reaches 96% of total natural gas imports (*ibid*, p. 28).

A second important factor that hampers investment in the power sector is constituted by regulatory uncertainty. Many of these regulations concern environmental regulations. Investors can live with strict emission limits or safety standards, as long as they are stable and predictable. A case in point are the regulations governing greenhouse gas emissions under the Kyoto Protocol or the European Union Emission Trading Scheme (EU ETS), which have the potential to massively affect the relative competitiveness of different fuels. The early decision by the European Union to aim for a 20% reduction of greenhouse gas emissions (GHG) by 2020 compared to 1990 and the clear rules of the EU ETS are encouraging precedents in this regard and should promote investment. Price uncertainty in the carbon market remains an issue, but increasing maturity allows the use of conventional financial hedging instruments.

A potentially greater barrier to investments is constituted by the unpredictability of construction permits and licensing processes, such as the separation of construction and operation permits into a two-step process. In this regard, the decision of the United States Nuclear Regulatory Commission (US NRC) to perform all necessary investigations upfront and then to grant the construction and operation licenses simultaneously (“one-stop licensing”) should be welcomed by investors. On the other hand, threats of price caps or phase-outs act as deterrents to investors. This holds, in particular for nuclear power, which as a supplier of baseload power for long periods of time is dependent on the predictability of its future revenue. It is not even necessary that the threat is realised, a positive probability suffices to have investors look elsewhere. Regulatory uncertainty can also affect investments in transmission and distribution infrastructure. Since they also last for long periods of time, changing the rules of the game concerning financing and remuneration too frequently, unsettles both investors and users.

In order to guarantee adequate investment, governments thus have a responsibility to ensure stable framework conditions. This includes, of course, regulation itself. In particular, support for volatility-reducing market arrangements such as long-term supply contracts eliminating volatility, the abolition of price caps and the facilitation of interruptible contracts all have the potential to decrease uncertainty. This would foster investment, increase capacity margins and thus improve the security of energy supply in the electricity sector. Last but not least, governments must guide and educate public opinion in these matters. This does not mean that governments have to prod public opinion in one direction or another. However, they have an obligation to present the advantages and drawbacks of energy policy choices in an unbiased manner and then to strive for a long-run consensus providing sufficient visibility for private investors to step in.

Energy systems and transmission infrastructure: the technical dimension

In addition to adequate generation capacity, security of energy supply in the power sector also requires a well-performing transmission system. This performance depends on both the financial

framework conditioning the adequacy of grid capacity as well as the technical and operational procedures ensuring that this capacity is available and functioning at all times.

In a wider sense, adequate capacity is required not only for transmission but also for transformation. In the energy process, primary energy sources such as crude oil or natural uranium are converted to secondary media (for instance refined oil products, fabricated nuclear fuel) for transportation and further transformation into final energy carriers (for instance gasoline, electricity) which are then utilised by end-users to obtain energy services (for instance transportation, lighting). End-users do not consume crude oil, but a range of refined products such as gasoline, diesel, jet fuel, heating oil. In the case of nuclear energy, at the beginning of the chain stand raw fissile material such as yellow cake (U_3O_8), but production requires enriched UO_2 in the form of pellets integrated in fuel rods. Some energy forms are more crucial than others. Some need to be utilised immediately upon delivery such as electricity. Others can conveniently be stored.

Raw capacity is not everything. It is important to recognise in this context the distinction between “energy” as an amount available somewhere in the system and “energy delivery” at the point of the end-user. For the security of energy supply, the issue is *energy delivery* in the form of a useful energy service. There is thus no automatic link between *instantaneous delivery* and *installed capacity*. The installed capacity refers to the maximal energy flow per unit time that a certain installation can potentially deliver in standard (often optimal) circumstances. A wind turbine, for instance, is a case in point: a 1 MW wind turbine delivers zero instantaneous electric power when there is no wind. Similarly, even a power plant that is in principle dispatchable delivers no electric power when shut down for maintenance.

On the operational side, energy systems must also be capable to deal with system dynamics and mishaps, i.e., able to absorb or ride through unexpected events. At this level, one must guarantee that the overall electricity or gas system continues to operate reliably at the level of the end customer even in case of unexpected events. In case of electric systems, this level refers to avoiding blackouts. In the case of gas systems, it refers to avoiding sudden gas-delivery cuts. In order to guarantee that systems continue to function under extraordinary circumstances they require sufficient *back up* and *redundancy* beyond the requirements of normal operations.

This is why in the case of electricity systems the question of reserve capacity plays such an important role. In fact, a well-run system requires adequate primary, secondary and tertiary reserves (the different reserve levels refer to the different time frames at which operators need to inject or withdraw load into or from the system in order to balance electricity demand at all times). In addition, good control strategies are required. For electricity this means constant frequency and voltage controls and for natural gas constant pressure and flow-rate control.

The avoidance of blackouts also demands appropriate control strategies, including minimising the response time of certain components such as switches or valves, or organising that certain components (power plants, wind turbines, high-voltage lines) go automatically into “island operation” in the case of system failure, thereby isolating themselves from the rest of the system. While not very glamorous, equally vital are well designed maintenance strategies, encompassing preventive, predictive and corrective interventions, including the scheduling and coordination of planned outages.

A growing literature on the management of power transport infrastructures is couched in terms of ensuring “security of supply”. While indeed the adequacy and competent management of power transport systems are essential for ensuring the security of power supplies, they should, in principle, not be an issue for policy making. To the extent that energy transport systems are publicly regulated monopolies, their technical and financial requirements should be determined on the basis of

engineering criteria and passed on to the competent authorities. Remaining interruptions would then be due to bad luck, incompetence or extreme weather events, none of which is very responsive to policy changes.

However, in recent years the power sector and the technical infrastructures that are part of it have been undergoing rapid institutional and technical change in many OECD countries. Liberalisation and an increasing share of renewables created more volatile production patterns and have made load management a greater challenge. Vertical separation has brought new responsibilities and financial constraints. New technologies such as real time metering and “smart grids” offer new opportunities for clients but their integration and financing creates put the managers of transport infrastructures to the test.

Operators of power transport systems are thus affected indirectly by policy issues such as the liberalisation of electricity markets. Three particular channels can be identified in this context:

1. There are technical synergies between production and transport, not only in the provision of network services such as load balancing but also in the localisation of production and/or transport facilities.
2. The debate about ownership un-bundling (severing not only the managerial but also the financial link between producers and transporters) has destabilised transport operators who no longer know how investment decisions will be coordinated between owners and regulators.
3. The progressive integration of national electricity markets poses the question of investment in transnational interconnection capacity and its’ financing. This is particularly important for energy security, since in the case of a breakdown the availability of alternative routes in a pan-national network can be of crucial importance.

In order to deal with these challenges, Martin Fuchs, President of the Union for the Co-ordination of Transmission of Electricity (UCTE, today Entso-E), the European power transport coordinator, pointed out as early as 2004 the key challenges for “Security of Supply and Infrastructure Investment” (UCTE, 2005). His starting point was the decomposition of security of supply in the power sector into generation and network adequacy. The latter was sub-divided into long-term adequacy (availability of interconnections, infrastructure investments) and short-term adequacy (operational security).

One of the challenges is that ensuring “generation adequacy”, depending on location, fuel choice and overall capacity, is outside of the remit of TSOs. There is thus little scope to internalise synergies between transmission and production. The issue has become more prominent in recent years due to the large-scale installation of renewable energy sources. Germany alone had an installed 27 GW of wind powered capacity at the end of 2009. Location choices for renewable energy sources are made with regard to natural characteristics (availability of wind, water, geothermic sources or sunshine) and not with regard to the need of balancing existing network infrastructures. A sudden surge in wind force, for instance, can thus lead to unintended loop-flows through neighbouring networks reducing stability and security margins.

A second source for sub-optimal location choices by power generators is the miss-pricing of transmission services. Given that on a full-cost basis transporting fossil fuels is cheaper than transmitting electricity grid-planning should have priority over choices concerning the location of production units. However, when electricity transmission is free or not priced at marginal cost, operators will choose location so as to minimise their own private costs of transporting fuels and not the social costs of transporting electricity. The correct pricing of transmission and infrastructure costs (such as network services) is thus an important part of reducing risks to the security of supplies. In the case of nuclear energy and renewables, the argument is not about proximity to fuel transportation infrastructures such as ports or pipelines but about the environmental characteristics of their locations

– the availability of water for cooling, wind patterns and sunshine. Of course, the amount of grid externalities caused by nuclear energy and renewable energies respectively differs significantly due to the latter's intermittency. A new NEA report on the *System Effects of Nuclear Power*, to be published in early 2012, will study these issues in detail.

A recent publication by the IEA, *Learning from the Blackouts: Transmission System Security in Competitive Electricity Markets* (2005), equally focuses on the challenge to maintain the contribution of power transmission systems to the security of supply and highlights the risks that have come with rapid reform (IEA, 2005, p. 12):

Decentralised decision-making has fundamentally changed utilisation of transmission networks. Previously stable and relatively predictable patterns of network use have in many cases been replaced with less predictable usage, more volatile flows and greater use of long-distance transportation, reflecting growing inter-regional trade. [...] New patterns of transmission network use are creating a far more complex and dynamic operating environment, with real-time monitoring and management by system operators becoming more and more crucial for maintaining transmission system security.

The authors offer a number of suggestions to reduce the risk of future blackouts such as the clarification of individual responsibilities, better coordination, investment in the latest technologies and the best operators, emergency training, interruptible contracts and vegetation management since contact with trees is one of the most common causes of transmission line failure. These are, of course, perfectly sensible suggestions and one would hope that operators of well-run power transmission systems would not need prodding from policy-makers to adopt them.

The role of nuclear energy

In the following, the focus will be on the contribution that nuclear energy can make to the two security-of-supply challenges in the electricity sector developed above. This will allow providing at least preliminary answers to the two following questions:

1. To which extent does the choice of nuclear energy contribute to adequate investment in power generation capacity?
2. To which extent does the choice of nuclear energy improve the functioning of power systems and transmission infrastructures?

Concerning the first question, the point is whether nuclear energy has specific characteristics which make it intrinsically a more attractive investment option than other generation technologies, in particular in liberalised power markets with uncertain prices. The previously mentioned joint IEA/NEA (2010) study provides some general information on the LCOE per MWh for different technologies.²⁷ Table 1.1 shows that nuclear energy is a very attractive option at interest rates that are below or only slightly above 5% real.

The attractiveness of an investment in power generation, however, is not only defined by its LCOE that correspond to the average discounted revenue, i.e. the price of an MWh of electricity that would allow the investment in question to break even. One key element is the uncertainty to which

27. The LCOE are calculated by discounting or compounding all costs to the date of commissioning and dividing them by the time value of total production. They thus indicate the discounted average (unit) cost of production. In the present case, LCOE were calculated including a carbon price of USD 30 per tonne of CO₂.

investors are exposed. The advantage of nuclear energy in this context is that its average cost remains very stable in the light of changes in the fuel or in the carbon price. In particular, it is protected against fuel price changes by the low proportion of fuel costs in the total lifetime costs of nuclear power generation.

Table 1.1: Median case specifications summary

Median case specifications	Nuclear	CCGT	SC/USC coal	Coal w/90% CC(S)	Onshore wind	Solar PV	
Capacity (MW)	1 400.00	480.00	750.00	474.40	45.00	1.00	
Owner's and construction	3 681.07	1 018.07	1 915.65	3 336.96	2 236.80	5 759.35	
Overnight cost (\$/kW)	4 101.51	1 068.97	2 133.49	3 837.51	2 348.64	6 005.79	
O&M (\$/MWh)	14.74	4.48	6.02	13.61	21.92	29.95	
Fuel cost (\$/MWh)	9.33	61.12	18.21	13.04	0.00	0.00	
CO ₂ cost (\$/MWh)	0.00	10.54	23.96	3.22	0.00	0.00	
Efficiency (net, LHV)	33%	57%	41.1%	34.8%	-	-	
Load factor (%)	85%	85%	85%	85%	26%	13%	
Lead time (years)	7	2	4	4	1	1	
Expected lifetime (years)	60	30	40	40	25	25	
LCOE (\$/MWh)	5%	58.53	85.77	65.18	62.07	96.74	410.81
	10%	98.75	92.11	80.05	89.95	137.16	616.55

Notes:

Years refer to time of plant coming on line, i.e. duration of plant construction.

All costs are expressed in USD (2008 average values 1 USD=0.684 EUR).

Construction costs include owner's cost as well as engineering, procurement and construction (EPC) costs but exclude contingency and interest during construction (IDC). Overnight costs include construction and contingency costs but exclude IDC. Capital costs then include overnight costs plus IDC.

Thermal plant efficiencies are net (sent-out basis), lower heating value (LHV). The difference between lower and higher heating value, based on IEA conventions, is 5% for coal and 10% for gas.

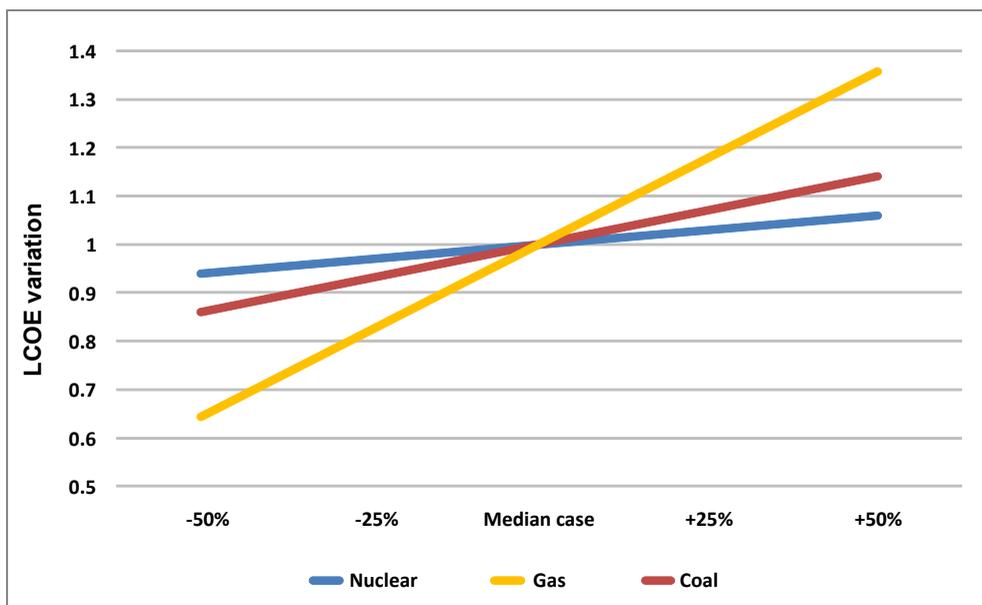
Source: IEA/NEA, 2010, p. 103.

Figure 1.6 shows that a 50% rise or decline in the price of uranium would only raise or lower the cost electricity produced by a nuclear power plant by about 5%. A change in the gas price in similar proportions would instead have the price of electricity produced by a gas-fired power plant by about 35%. The impact on the cost of electricity produced by coal would vary in the range of 15% if the price of coal varied by 50%. Once a nuclear plant is up and running, it reliably produces electricity at foreseeable cost, clearly an attractive feature for investors.

Investors in fossil fuel plants and, in particular, coal-fired power plants are also exposed to carbon price risk, the variation in the price of CO₂ permits, which constitutes a major source of uncertainty for coal-fired power production. Doubling the carbon price, for instance, from USD 30 per tonne of CO₂ to USD 60 per tonne would increase the total average cost of coal-produced power by 30%, more than doubling its variable cost in the process. This is not an unrealistic number. If current commitments to reduce global carbon emissions by 2050 by 50% in order to limit the rise of global mean temperatures to 2°, modelling results imply marginal costs for carbon abatement of at least USD 100 per tonne of CO₂ and perhaps much higher. Given that operators in liberalised energy markets will cease production when carbon prices are too high, nuclear capacity is a more stable

contribution to the overall power generation capacity than coal-fired capacity in the context of current efforts to introduce significant carbon emission reductions.²⁸

Figure 1.6: Changes in the LCOE of different technologies in response to changes in the fuel price
(Typical plants in OECD countries at a 5% discount rate)



Source: Adapted from IEA/NEA, 2010, Figure 6.9, p. 115.

While the impact of fuel and carbon price changes on the LCOE of different power generation technologies is obvious enough, the overall impact for investors may be less clear-cut, in particular in liberalised markets with volatile electricity prices. Although gas prices can be very volatile, investors in gas-fired power plants are to some extent protected against such price swings given that gas-fired power generation is the fuel with the highest variable cost and thus frequently sets the electricity price. In other words, if gas prices go up or down, so will electricity prices and the stream of net profits for the investor – his only true risk – stays the same. Investors in nuclear energy instead would be exposed to more volatility in profits precisely because their costs remain stable while their revenue in terms of electricity prices varies.

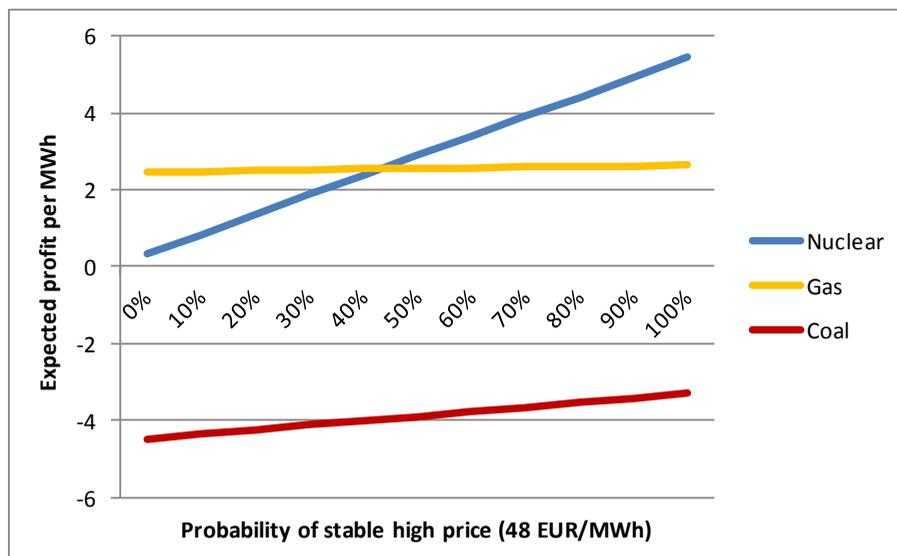
There is thus a mismatch between private and social incentives. From a social point of view, stable variable costs and stable electricity prices as provided by nuclear energy would, of course, be an advantage for investment, industrial consumers and households. Due to the peculiar price setting mechanism in the electricity market, however, only one technology (gas, the marginal fuel with the highest variable cost) profits from an automatic hedge through the alignment of its variable cost and electricity prices. In order to fully exploit its potential to contribute to adequate capacity and to the security of energy supply, nuclear energy would thus benefit from stable pricing arrangements either through regulated prices or through long-term contracts. Long-term hedging provisions locking in stable power prices would be an alternative but are hampered by limited liquidity in markets for multiyear forward contracts and would also carry additional financing costs.

28. Carbon capture and storage (CCS), on which the future of the coal industry will depend, is currently still a highly uncertain option that has yet to be deployed on an industrial scale.

Electricity price volatility has an impact on the relative profits of gas and nuclear works also through another, more indirect, channel. Depending on whether working with interest rates of 5% or 10%, the fixed investment costs of gas-fired power plants vary between 11% and 17% of total lifetime costs. For a nuclear power plant, fixed investment costs can vary between 59% and 76% of total lifetime costs depending on the interest rate (IEA/NEA, 2010). This means that investors have different incentives to continue production or to exit an industry in the case that electricity prices fall permanently below average lifetime costs. As soon as prices fall below the variable costs of gas-fired production, gas-fired production will stop, but production of nuclear energy will continue. What looks at first sight like a comparative disadvantage of gas-fired production is in fact a comparative strength in adversity. The investor in gas-fired capacity will exit the industry at a relatively small cost (his capital cost). The investor in nuclear capacity will lose proportionately more as he will have to abandon all hope to recover his massive capital cost, even though he will continue to make small profits over the lifetime of the plant on the basis of the difference between its low marginal costs and the electricity price.

Figure 1.7 renders this relationship graphically. It shows the profitability profile for power from nuclear (blue line) and from gas (yellow line) as a function of different levels of price risk. If there is no price risk – that is there is a 100% chance that stable prices will prevail – nuclear energy is the more profitable technology. However, with increasing price risk (higher volatility) the profitability of nuclear declines faster than that of gas. This is because, if prices drop very low, the operator of a gas-fired plant can exit the market. He will lose his (small) initial investment, but otherwise save on expensive gas. The operator of a nuclear power plant does not have this option. Having invested two-thirds of his lifetime costs on day one, he might as well stay in the market, even if his total losses over the lifetime of the plant are greater than the losses of the operator of the gas-fired power plant.

Figure 1.7: Expected profitability per MWh in function of the probability of a high-price scenario
 (The higher the probability of a high-price scenario, the greater the relative advantage of nuclear.)



Note: The calculations are based on the electricity and carbon prices prevailing in the European Emission Trading System (EU ETS) during 2005-2010. Capital cost (at a 5% real interest rate), fuel cost and O&M cost assumptions are taken from IEA/NEA (2010).

Source: NEA (2011 forthcoming).

Again it is imperative that nuclear operators are capable of insuring themselves against price risk either through long-term contracts or regulated prices. There is also some evidence that innovative

solutions for the financing of new nuclear power plants will enable new nuclear energy to establish itself also in fully liberalised markets (see Keppler, 2005). The picture changes further if carbon pricing is introduced. In this example, even with a relatively modest price for a tonne of carbon of EUR 15 per tonne, the profitability of nuclear is *always* above the profitability of a gas-fired power plant over the relevant range, assuming that the probability of a dramatic low-price scenario is less than 50%.

The question of system effects

Stable electricity prices and carbon pricing can thus leverage the positive contribution of nuclear energy to adequate capacity margins and cost stability in the electricity sector. In addition, nuclear energy also has overall relative benign characteristics for the functioning of electricity systems and thus the security of power supplies. All electricity generation connected to electricity system imposes both technical and pecuniary external effects on the grid operator, other producers and consumers. Such system effects cause impacts at least three different levels: (1) siting; (2) load management; and (3) electricity prices.

Concerning the siting of plants the advantage of nuclear energy is its great energy density, i.e., the very small space requirements per unit of capacity and output. Building the equivalent of a 1 500 MW nuclear plant would require 3 coal fired-plants with 500 MW or 5 gas-fired CCGTs with a capacity of 300 MW. For renewables the space requirements are even more daunting. Wind power would require 1 500 standard 1 MW turbines or 500 large 3 MW turbines. At 300 W per m², one would need to install 5 km² of solar panels.²⁹ Neither number takes into account the intermittency effect, where solar panels can be assumed following IEA/NEA (2010) to have an average load factor of 13% and wind power an average load factor of 26%, whereas nuclear energy has an average load factor of 85%. In order to compare like with like, the space requirement for solar power would thus need to be multiplied by 6.5 and for wind by 3.3. That said nuclear plants just as coal-fired power plants require water cooling. They are therefore best built close to large rivers or to the sea which may pose siting issues of its own.

Intermittency is, however, not only a capacity issue but also an issue for load management. In an electricity grid, supply and demand need to be balanced continuously. Intermittent sources thus need to be complemented by costly back-up technologies. Usually this function is assumed by gas-fired turbines that can be ignited and shut down quickly and that due to their low fixed costs are able to deal to some extent with lesser load factors. The geographical spread of renewable sources or mixing different renewable technologies such as wind and solar can, in combination with advanced technologies for the management of decentralised resources (“smart grids”), contribute to alleviating the intermittency problem at the margin.

While advanced electronics can considerably facilitate the balancing decentralised production and consumption this leads to a very stiff and nervous system. Large producers with a certain amount of inertia contribute best to maintaining stable frequencies. The continuous provision of stable amounts of baseload power as provided by nuclear energy thus considerably facilitates the management of electricity grids and the dispatch of electric power. Again there are some grid management issues specific to nuclear energy such as the need for organising availability during periodic shutdowns for maintenance (an issue that affects also coal-fired plants) and the construction of dedicated high-voltage transmission networks. They are, however, quite easily addressed since – contrary to the vagaries of the weather – they can be planned in advanced.

29. See http://us.sunpowercorp.com/downloads/product_pdfs/Panels/sp_315ewh_en_ltr_p_ds.pdf for industry information on the capacity per m².

Finally, system effects do not only pertain to technical issues. Different technologies also impose pecuniary externalities on their competitors. Imagine the wind blowing strongly at 3 a.m. Given that wind power has essentially zero short-run marginal costs, this can push power prices in liberalised electricity markets very low indeed. This effect is due to the fact that: (a) demand is very low at certain hours of the day; and (b) that other installations such as nuclear or coal cannot be shut down at a moment's notice (ramp costs) and thus continue producing electricity. The effect is magnified by the fact that wind power producers are remunerated according to a fixed tariff and thus do not themselves experience the effects of their production decisions.

Germany has thus seen *negative* prices for electricity in at least two instances in the first six months of 2010. While the micro-economic mechanism is well understood, it is nevertheless disastrous for the profitability of baseload technologies such as nuclear that depend on a steady flow of income in order to finance their high fixed costs. It is evident that very low or even negative prices have the potential to destabilise the whole outlook for power sector investments and thus carry a social cost far beyond their immediate private impacts.

In conclusion, OECD countries, especially in Europe have a capacity issue in electricity markets, which is due to stronger competitive pressures and the increased price volatility in liberalised electricity markets. Fossil fuels (especially coal) will have increasing difficulties to contribute to the new capacity that is needed due to the new competitive pressures created by carbon pricing. Renewable energies pose challenges for the reliability of power systems due to their large space requirements, their intermittency and impacts on network stability as well as due to their impact on power price volatility.

In this context, nuclear energy has a number of advantages to bring to the issues of adequate power generation capacity, system management and security of electricity supply. This applies to both the external and the internal dimension of the security of energy supply. It does not raise any geopolitical security of supply concerns, has few system effects and promises great cost stability once built. As long as adequate framework conditions are provided, in particular low financing costs and stable electricity prices, nuclear energy is well-placed to contribute to the security of energy supply and the smooth working of electricity systems with adequate capacity margins in OECD countries.

1.5 Orientations for government policies to enhance the security of energy supply

The preceding sections have explored the two key dimensions of energy supply security and the contribution that nuclear energy can make supply risks. From this discussion can be drawn a number of broad policy conclusions.

The question of how to ensure timely energy delivery to a particular group of customers requires an analysis in different temporal and spatial dimensions. As far as the temporal dimension is concerned, one can distinguish periods reaching from a few seconds (for technical failures), a few days (for policy responses to supply interruption), to several years (the time to implement new policies) up to 100 years (the lifetime of certain energy structures). The list of security of supply risks presented above quite naturally reflects this distinction between a short-run and a long-run aspect of the security of energy supply. In the short term, governments or public institutions basically need to ensure effective crisis management. This can take the form of holding emergency stocks in oil and gas markets or ensuring the creation of protocols for effective cooperation in the management of power grids in the case of technical failures or sudden demand shocks. Of course, it also includes setting the regulatory framework for the operation of nuclear plants.

In the long term, governments need to pay attention to the evolution of supply, demand and prices by containing, wherever possible, steep price rises or high price volatilities. This includes a focus on adequate infrastructures for the production, transport, conversion and end-use of energy (including spare capacity to deal with sudden shocks). It also includes setting the rules of the game in a manner that provides private actors with a sufficiently stable perspective of the future in order to proceed with the necessary investments.

Wherever possible, decision-makers need to ensure a maximum amount of protection and flexibility in the energy system to mitigate impacts. Thus flexibility enhancing measures can take many forms. For instance, they can take the form of taxes on energy consumption or carbon emissions that reduce consumption and hence vulnerability. Flexibility can imply the use of dual use technologies or back-up systems. Diversification of technologies and sources at the geographically appropriate level is equally part of dealing with security of supply in a long-term perspective. Following Keppler (2007a), one can group different mitigation measures at the disposal of policy-makers into three categories differentiated according to their time horizon:

1. The short term requires the ability to respond sudden shocks to the energy system. Physical stockpiles and interruptible contracts for especially prepared consumers (that are rewarded by lower prices) can be useful in this context. This also regards the technical preparedness of physical infrastructures. As mentioned above, an often required level of redundancy is the so called N-1 rule: a system consisting of N elements must be able to function properly if only N-1 elements are available.
2. The medium term requires the management of consumer behaviour. Fiscal instruments can be useful here to reduce demand, either for energy in general or for particularly risky fuels, and to increase energy efficiency. Carbon taxes that constitute *de facto* a tax on fossil fuels are, of course, of particular relevance in this context.
3. The long term requires the creation of the physical infrastructures and long-term trading relations that define the structure of a country's energy system. A key point here is the technological and geographical diversification of energy imports in order to hedge against supply risks. This includes the development of domestic energy resources such as renewables and nuclear energy.

Organising government action according to these three time horizons should quite naturally structure policy responses to questions of energy supply security and should allow developing a systematic response to reducing supply risk.

Diversification and flexibility

Ceteris paribus, that means if there is no clear hierarchy between different energy options, the first intuitive strategy is clearly to diversify with respect to the type of fuels, their geographical origin and their transport route. This corresponds to the folk wisdom of “not putting all one's eggs into the same basket.” The fact that the future is unwritten applies to any number of dimensions – high and volatile fuel prices, the climate change challenge, the geographical concentration of fuels and geopolitical tensions to name just a few. Facing them requires a well balanced portfolio that spreads the risks and ensures that the system as a whole remains robust in the light of any sudden changes.

Of course not all fuels can be easily substituted in the near-term, think of refined petroleum products for transport, where it is difficult to opt for other fuels on a significant scale in the coming years. In such cases, the use of scarce resources must remain confined to applications where there are

no substitutes available. In the case mentioned, for instance, it makes little sense to utilise oil for electricity generation (unless for specific cases such as jet fuel in peak turbines, or heavy residues with no alternative uses). Fuel diversification must also consider the level at which diversification is measured. France's high share of nuclear energy can thus be considered a contribution to the diversification in fast integrating European power markets.

In addition to the diversification of fuels, the diversification of sources of origin, technologies and transport routes must be pursued. This concerns, in particular natural gas where storage is only possible at high costs. Importing gas from a single country only means running unnecessary risks and both transport by pipeline and transport by LNG tankers should be facilitated as complements. Ideally some redundancy in transmission infrastructure should be maintained in order to dispose of alternatives in times of crisis. The issue is, of course, that redundancy is costly and in practice governments have to decide how much they are willing to invest – or constrain their private operators to invest – in redundancy as form of insurance against security of supply risks.

As far as electricity generation is concerned, all reasonable possibilities must remain part of the portfolio even though the weighting must be determined by the specific security of supply characteristics of the different fuels: nuclear, coal (possibly equipped with CCS), gas, oil (as jet fuel for peak-load combustion turbines), biomass, wind, water, solar, geothermal, wave or tidal. The “right” mix will be determined by many factors, but there are analogies with profit maximisation in stock markets, where portfolio analysis determines the appropriate mix. Unfortunately, the applicability of standard portfolio analysis remains limited by the availability of good data on the volatilities of different parameters over time, which is one of the principal reasons why governments need to remain involved. For heat production, depending on the actual objective (such as space heating in buildings, sanitary hot water for domestic or professional needs, and industrial heat) diversification is also often less evident since one is dealing with specific services at the level of the final consumer.

Box 1.3: A common sense approach to the security of energy supply

Originally developed with a view to the security of oil supplies, Yergin and Frei (2006) provide a list of ten sensible proposals that transfer without difficulty to the security of energy supply at large. Their approach is characterised by the fundamental idea of enhancing the resilience and flexibility of the energy supply system:

1. Diversification of energy supply sources is the starting point for energy security.
2. There is only one... market.
3. A “security margin” consisting of spare capacity, emergency stocks and redundancy... is important.
4. Relying on flexible markets and avoiding the temptation to micromanage can facilitate speedy adjustment...
5. Understand the importance of mutual interdependence among companies and governments at all levels.
6. Foster relationships between suppliers and consumers in recognition of mutual interdependence.
7. Create a proactive physical security framework that involves both producers and consumers.
8. Provide good quality information to the public before, during and after a problem occurs.
9. Invest regularly in technological change within the industry.
10. Commit to research, development and innovation for longer-term energy balance and transitions.

Finally, the fundamental idea that security of supply depends on the flexibility of a power system when confronted with unforeseen events also extends to the technical level. The mix of baseload and flexible peak-load capacity is a classic example to deal with variable load. Back-up facilities can cope

with the intermittency of renewables. Fuel switching, storage (see below), physical exchange with other regions through cross-border interconnectors, liquid energy markets, parallel supply paths and sufficient redundancy through standby components are all part of this effort. As always, energy supply risk is not inevitable. However, avoiding it comes at a price.

Energy conservation and demand management

Another often cited strategy for OECD governments in the pursuit of energy supply security is energy conservation and energy demand management. Energy demand management has at least three different dimensions in this context:

- The management of energy demand at the macro-level mainly through taxes and subsidies by imposing security-of-supply adders on fuels representing particular risks.
- Enhancing the responsiveness of consumer demand to market signals, for instance through smart metering and peak-load pricing. This has two distinct variants:
 - Load shifting in order to smooth daily and seasonal demand variations. This allows to run baseload technologies for longer thus saving on expensive peak production.
 - The reduction of total energy demand by increasing overall efficiency in energy consumption.
- Rationing energy quantitatively in times of acute crisis.

The basic idea behind energy conservation and demand management is that every Joule, toe or BTU that is not consumed does need not be provided. The less energy is required, the less of it needs to be produced and imported, the less scope there is for any breakdown in supply. And yet, this intuitively appealing reasoning needs to be qualified. In some forms, inefficiency can provide a source of flexibility in times of crisis and supply interruptions – simply by eradicating its most blatant manifestations. One needs to recall that the redundancy required by energy systems to cope with unexpected shocks is in itself a form of inefficiency, at least in a short-term perspective. Of course not all forms of inefficiency are alike and yet care has to be taken not to define the notion of efficiency too narrowly. Inefficient consumers can cope with a reduction in supply partly simply by raising efficiency.

In a perspective of ensuring the security of energy supply, the focus needs to be not so much on reducing general energy demand but to reduce demand for the fuels or the forms of consumption that are most vulnerable to supply risks. Reductions during periods of peak demand are thus particularly valuable. Not only does high peak demand impose high marginal costs on the system (peak capacity needs to be available at all times but is only used for relatively short periods), but it also needs to be satisfied with the fuels that are exposed to the highest security of supply risks, namely gas and oil. Differentiated pricing (according to season or time of day), load shedding – the ability to take certain groups of consumers off the grid at critical moments, in exchange for more favourable prices the year round – are important options in this context.

Storage

Where demand cannot be managed in sufficiently precise manner to avoid security of supply issues, energy storage can be used to decouple temporarily physical demand and supply. Such buffers or temporary stocks can provide some protection against the immediate impacts of unforeseen and unforeseeable events. Storability of fuel is a valuable asset. Some fuels provide implicit storage. The

most energetically dense, commercially available fuel is uranium. Coal has a relatively high volume per unit of energy but is not too difficult to store. Liquid fuels are also reasonably well storable – hence the possibility to have strategic oil stocks.

Ease of transport and storage is, of course, one of the reasons for the popularity of liquid fuels. Natural gas storage is less evident, although there is some degree of seasonal and peak storage. Decreasing the pressure in pipelines may also be considered a form of stock draw-down, the stocks in this case being the gas that is “stored” in the pipeline (“linepack flexibility”). Commercial storage of gas to provide flexibility for arbitrage with coal also exists but is usually still considered too expensive. Storage finally is absent for wind or solar power since the latter manifest themselves naturally as variable fluxes. However, this does not mean that renewables are never storable. Hydropower, either in natural reservoirs or through pump storage is an excellent medium for storing energy and, implicitly, electricity that can be readily produced by releasing the water to drive a turbine.

Other than by such roundabout means of using the kinetic energy associated with elevated hydro reservoirs, it is exceedingly difficult to store electricity which precisely leads to the sort of load management issues alluded to above. Storage by chemical batteries is, of course, possible but currently still expensive and available only for small quantities of power. The continuous improvements in performance, most recently in the field of lithium-ion batteries for passenger cars, suggest however some hope for the future. Heat³⁰ can be stored through thermal buffers, either underground, in phase changing materials or just in certain materials (amongst which water). Heat pumps and passive solar heating are applications of this principal but the storage time for high-temperature thermal energy remains very limited.

Electric and hybrid cars are also an essential part of one of the more forward-looking visions of the electricity system. From a power generation point of view, electric cars are essentially batteries on wheels. A large fleet of electric cars coordinated by GPS, smart metres and real time incentives for charging and discharging power to the grid offers some exciting new possibilities for load management. The idea is that car owners can charge their vehicles at night – thus increasing baseload demand during the hours when electricity is cheap – and could be offered enticing incentives during the evening rush hour, which coincides with the daily peak of electricity demand, to reconnect their cars to the grid to discharge some of the power stored in their car batteries. The obvious advantage is that net power demand would much more stable around the clock.

In practice, however, the transaction costs for inducing drivers to return to the grid not only for charging but also for discharging might be high and the necessary incentives more costly than peak-time electricity production. That is why the future implication of electric cars into electricity systems will probably be organised by way of aggregators such as “Better Place”, which exchange empty batteries against full ones and then optimise recharging according to the incentives available. The service station of the future will thus not work by reloading but by exchanging the tank.

In either case, the stabilisation of demand through the optimised re-charging of car batteries would be of great interest for technologies producing baseload power such as nuclear energy. In other words, the possibility of widespread availability of storage would make a higher share of nuclear energy the efficient solution from a grid management point of view. Under the assumption that *ceteris paribus* nuclear energy has more favourable characteristics from a security of supply point of view than, say, coal or gas, this would also reduce energy supply risks.

30. More thermodynamically correct this should read “thermal energy”, since “heat” is an energy-transfer mode.

Of course, there are a number of uncertainties that need to be addressed before this option is realised. First and foremost, while battery technology is progressing and major manufacturers have announced the introduction of electric cars in coming years, their price and performance, and hence their uptake by the public is still uncertain. Second, the behaviour and price responsiveness of electric car drivers is an as of yet unexplored social science issue. Third, the financial and institutional framework conditions (fractional or total ownership, long-term leasing or short-term hire) still need to be defined and the physical infrastructure to be put in place. In other words, enhancing the security of electricity supplies through widespread electricity storage by means of coordinating the discharging and charging of electric car batteries is for the time being just a scenario but one that deserves further study and close attention.

Regulatory, institutional and fiscal frameworks

The security of energy supply is in itself an issue because consumers and producers are averse to risk and uncertainty. Uncertainty slows down economic activity and, in particular, impedes investment, in particular investment in energy production, conversion, transport and end-use, where installations often have lifetimes of several decades. The more capital-intensive is an investment, the more such uncertainty will impact total project costs through the interest rate. In the electricity sector, nuclear energy and renewable energies are thus most heavily affected.

It is thus only natural that governments do everything in their power to reduce uncertainty and provide stable legal and regulatory framework conditions for energy markets. The regulatory aspect includes smooth and transparent licensing procedures, in particular for technologically complex installations such as nuclear reactors. At least as important are, however, the regulations that organise the working of electricity and carbon markets.

A crucial question in this context concerns the conditions under which long-term contracts for gas and electricity supply are permitted or even encouraged. Long-term contracts on the one hand provide certainty and visibility (and are thus often crucial for accompanying capital-intensive long-term investments), on the other, however, they can act as a barrier to entry for new, potentially more efficient, competitors. On balance, their positive characteristics outweigh the negative ones, in particular because the market entry issue can be addressed by standardising long-term contracts and thus rendering them tradable. Similar considerations apply to the question of unbundling vertically integrated energy companies that operate the gas or electricity networks through which they transport their energy. From a pure security of supply point of view, rather than from a market efficiency point of view, some degree of vertical integration can provide stability and market power in negotiations with importers for domestic energy companies.

Another lever of government in this context is, of course, fiscal policy. Encouraging the consumption of certain forms of energy through subsidies, while discouraging others through excise taxes, is a widespread and effective form of internalising real or perceived external benefits and costs. In certain instances such fiscal instruments correctly reflect security of supply concerns in a qualitative manner (quantitative measures of security of supply risk are currently still too vague to command widespread acceptance by observers and market participants). Whether this is by design or by accident is often not easy to tell. Petroleum products are thus highly taxed, while renewable energies such as wind or solar receive substantial subsidies. The former imply, of course, a comparatively high security of supply risk in OECD countries, while the latter provide some security of supply benefits due to their domestic nature (at least in terms of overall energy consumption if not in terms of dispatchable power supply). On the other hand, the consumption of natural gas, which also carries some security of supply risks, is only taxed lightly, while the production of nuclear energy, which is also largely a domestic industry, receives no direct subsidies.

In the absence of firmer indicators on the security of supply risk of different fuels, diversification remains the basis of all government policy to ensure security of energy supply. The proceedings of the *Joint IEA/NEA Workshop on Security of Energy Supply for Electricity Generation* for instance thus include both aspects in their list of measures (IEA/NEA, 2005, p. 6):

- imposing a share of “secure” energy sources in new generation capacity;
- introducing taxes on “insecure” energy sources;
- subsidising “secure/domestic” energy sources; and
- implementing tradable permits or certificates for secure energy sources.

On occasion, policies which have been designed with other objectives in mind can also have a significant impact on the composition of the energy mix and thus the security of supply situation. The most noteworthy example of such a policy is the introduction of carbon pricing in the European OECD countries by means of the European Union Emissions Trading System (EU ETS). Pricing carbon means raising the comparative price of the fossil fuels coal, oil and gas. Given that the vast majority of OECD countries are net importers of the hydrocarbons oil and gas (exceptions are only Canada, Mexico and Norway), carbon pricing *ceteris paribus* increases security of supply by improving the competitiveness of low-carbon sources such as nuclear energy and renewables. While OECD countries outside Europe are still debating the terms of their own carbon pricing regimes, there is a very good chance that the majority of OECD countries will follow the European lead in coming years due to a shared concern about climate change. In the medium term carbon pricing thus has the potential to be a transformative force in the energy markets of OECD countries with overall positive impacts on the security of energy supply.

Another example is, of course, electricity market liberalisation whose impacts on price volatility have been discussed above. The more volatile are electricity prices, the higher is the penalty for low-carbon technologies such as nuclear and renewables. Since the latter have overall good performance in security of supply terms, electricity market liberalisation without measures to address price volatility such as long-term contracts cannot be considered *ceteris paribus* as contributing to improved energy market security.

Crisis management mechanisms

While the prevention of security of supply risks materialising must clearly be a priority, demanding that such policies must be able to avoid *all* risks would clearly be unreasonable. The cost of supply interruptions may be substantial but it is not infinite, so neither will be the price that countries are willing to pay for avoiding them. It is also part of the nature of risk that the unexpected can happen. It is thus safe to say that security of supply risks will continue to manifest themselves even in the context of the best-designed policies. This, however, means that governments need to put in place appropriate crisis management mechanisms for different supply risks, whether they pertain to political dissensions between trading partners or technical accidents.

A good example in this context is the obligation of IEA member countries to hold 90 days of their net import volume of both crude oil and refined products. Such reserves have a double function. They act as a buffer for physical supplies in case of crisis and they can be used to put additional supplies on the market in order to correct short-term speculative price spikes. Ideally, such obligations are coupled with commitments of mutual assistance in order to provide solidarity with the countries most heavily affected and to pool resources, which provides added flexibility.

Crisis cooperation protocols also need to be implemented *a fortiori* for grid-based energy carriers such as gas and electricity, since there is no escape from the grid in case of crisis. The Russo-Ukrainian gas crisis in winter 2008-2009 highlighted the lack of preparedness and solidarity even between members of the European Union. The situation is somewhat better in the electricity sector where grid operators, forced by necessity, have developed protocols for cooperation when confronted with network incidents.

1.6 Conclusions

The preceding discussion has highlighted different aspects of the role that nuclear energy can play in reducing both external and internal energy supply risks in OECD countries. On the external side, a key advantage of nuclear energy is its relative independence from imported fuels. While only a few OECD countries dispose of domestic uranium supplies, resources are widely diversified and traded on global markets. In addition, uranium is easily storable and constitutes only a small share of the overall costs of nuclear energy. In a security of energy supply perspective, nuclear energy thus possesses some distinct advantages over oil, gas and even coal, which in the face of fast-rising Chinese demand has lost some of its reputation as a “safe” fuel.

On the internal side, nuclear energy is a reliable producer of baseload electricity at stable variable cost which is an attractive property from a social point of view, although liberalised electricity markets do not translate this advantage into stable end-use prices, since nuclear is rarely the marginal technology. In principle, nuclear energy is also well-positioned to contribute to adequate capacity margins and stable loads. By providing stable baseload electricity it reduces the complications of integrating intermittent or distributed generation, since as a reliable baseload source of power it helps maintain frequency and voltage. Expressed differently, the massive use of intermittent sources will require a significant fraction of continuously operating and robust baseload electric power generation fuelled by more steady sources. While the technical parameters of nuclear energy set limits to the extent it can make up for sudden load changes itself, the development of smart grids and demand response should smooth load variations (and thus increase the share of baseload demand). This would considerably strengthen the case for nuclear energy in co-operation with both other supply-side and demand-side technologies. Price volatility in liberalised electricity markets (and reinforced by intermittent renewables) does remain a challenge and needs to be addressed by appropriate means such as long-term contracts.

Last but not least, as a low-carbon source of electricity, nuclear energy is fully supportive of one of the defining policy challenges of our time – the need to reduce climate change inducing greenhouse gas emissions. In a security of energy supply perspective, nuclear energy seems thus well-positioned to reduce import dependency and to stabilise cost as well as to contribute to the diversification of electricity generation technologies in a manner that overall improves the security of energy supply. The following chapter will explore the extent to which the preceding considerations can be quantified in the context of appropriate security of supply indicators.

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Chapter 2

INDICATORS AND MODELS FOR MEASURING SECURITY OF ENERGY SUPPLY RISKS

2.1 Introduction

Building on the conceptual framework of Chapter 1, this chapter provides a general introduction to approaches aiming to quantify aspects of energy supply security risks with policy-relevant indicators with special reference to the role of nuclear in the provision of energy security. It sets out to clarify the different approaches proposed in the recent literature to quantify aspects of energy supply security in order to set the stage for the empirical research undertaken in Chapter 3. In fact, the Simplified Supply and Demand Index (SSDI) employed in Chapter 3 builds on the Supply/Demand (S/D) Index presented below.

This chapter is organised as follows. Section 2.2 provides a broad taxonomy of approaches to quantifying security of supply risks and highlights possible uses of security of supply indicators in the design of energy policy and monitoring of its security of supply effects. A detailed review of selected security of supply indices is made in Section 2.3, which includes also a summary assessment of the indicators reviewed. Selected modelling approaches to weigh different supply security aspects and to arrive at a more comprehensive assessment of the energy supply security status of a country, with the emphasis on the country's public power system, are reviewed in Section 2.4. Section 2.5 concentrates on the S/D Index, designed by the Energy Research Centre of the Netherlands (ECN) and Clingendael Institute to integrate major supply side and demand side aspects into a comprehensive index. Section 2.6 presents concluding observations.

2.2 Different approaches towards designing the Supply/Demand Index

Approaches to assign numbers to aspects of security of supply risks can be broadly categorised as follows:

- simple quantitative indicators for separate risks;
- composite indicators, seeking to aggregate different risk parameters; and
- modelling approaches, seeking to determine the aggregate size of security of supply vulnerabilities and/or their aggregate impact on welfare.

Ideally, quantitative indicators yield security of supply scores on a normalised cardinal scale such as the $[0, 1]$ interval where equal differences in scores indicate equal differences in performance regarding the aspect considered. It is noted that certain relevant aspects for supply security risks, for instance those relating to political framework conditions, do not lend themselves to quantification. Hence, not all relevant aspects can be described with the help of indicator values. Security of energy supply indicators can enrich security of supply analysis, but cannot replace it.

Broadly speaking, an indicator is a quantitative or a qualitative measure derived from a series of observed facts that can reveal relative positions of, for instance, a country in a given area. Over time, they can serve as tools (OECD, 2008):

- to identify trends regarding the phenomenon captured by the indicator concerned across countries and over time;
- for benchmarking and monitoring performance; or
- to set policy priorities.

ECOFYS, for instance, categorises security of supply indicators into two main types (ECOFYS, *et al.*, 2009):

- *Vulnerability-based indicators*: indicators seeking to measure the potential risk and/or magnitude of a possible security of supply effect.
- *Outcome-based indicators*: indicators aiming to measure the actual outcome of supply insecurity. Ideally the actual or potential welfare impact would be measured. Yet given the innate difficulty to do so, indicators of the level of physical unavailability often are used instead, for instance the actual or expected cost of interruptions in electricity supply.

This is a useful categorisation. For policy design purposes, it is in order to consider also a third category of variables, i.e. *resilience-based indicators*. Such indicators seek to measure the capacity of the economy to absorb and mitigate the impact of supply insecurity, including notably the mitigation of negative actual or potential welfare impacts by increasing flexibility on the supply and the demand side (Jansen, 2009; Jansen and Seebregts, 2010; Jansen and van der Welle, forthcoming). Also the S/D Index approach proposed by Scheepers, *et al.* (2007) is predicated on both supply-side and demand-side vulnerability and flexibility aspects.

Simple indicators can be used to portray and explain single aspects of energy supply security. Many analysts of energy supply security prefer to describe and analyse energy supply security with the help of such simple indicators only. For example, ECOFYS deems that: “no aggregate indicator provides an adequate measure of all the relevant root causes of energy insecurity and current attempts to do so lead to a strong trade-off in transparency” (ECOFYS, *et al.*, 2009: 12) and “...there is an inherent trade-off in the construction of more aggregated indicators, which aim to be more comprehensive in their assessment, but which can introduce subjectivity in the weighting of the different components against each other, and reduce the meaningfulness and transparency of the final results” (ECOFYS, *et al.*, 2009, p. 38). In this regard, it should be noted that in quantifying certain security of supply aspects the application of subjective aggregation rules, that may introduce technology biases, is almost unavoidable. Take for instance energy intensity. The numerator of this indicator, “energy”, warrants an accounting unit to aggregate the energy content of different fuels. Should one use, for instance, fuel prices instead of primary energy supply per fuel unit, one may end up with quite distinct fuel shares in total energy use and different rankings of distinct energy intensity situations.

A *composite indicator* can be designed, compiling individual indicators into a single index on the basis of an underlying model. Ideally, the composite indicator measures multi-dimensional concepts which cannot be captured by a single indicator (OECD, 2008). Composite security of supply indicators can have several purposes. Composite indicators may synthesise the rather disjoint, fragmented and non-transparent overflow of information on simple indicators into some key numbers, the broad meaning of which is readily understood by external stakeholders. For instance, composite indicators

may “provide information to policy-makers and their constituencies on the seriousness of long-term overall supply risk. Moreover, political agreement may be reached that exceeding *a priori* agreed critical ...values will trigger implementation of an agreed set of emergency procedures to mitigate security of energy supply” (Jansen and Seebregts, 2010, p. 1655). An enumeration of the main advantages and drawbacks of using composite indicators in general is shown in Box 2.1 below.

Box 2.1: Advantages and drawbacks of composite indicators	
Advantages	Drawbacks
<ul style="list-style-type: none"> • Can summarise complex, multi-dimensional realities with a view to supporting decision-makers. • Are easier to interpret than a battery of many separate indicators. • Reduce the visible size of a set of indicators without dropping the underlying information base. • Enable to include more information in given size limitations. • Place issues of country performance and progress at the centre of the policy arena. • Facilitate communication with the general public and promote accountability. • Help to construct narratives for lay and literate audiences. • Enable users to compare complex dimensions effectively. 	<ul style="list-style-type: none"> • May send misleading policy messages if poorly constructed or misinterpreted. • May invite simplistic policy conclusions. • Can be misused if the construction is not transparent or if it is not based on sound statistics and conceptual principles. • The selection of indicators and weights could be the subject of debate. • May disguise serious failings in some dimensions and increase the difficulty of identifying proper remedial action, if the construction process is not transparent. • May lead to inappropriate policies if dimensions of performance that are difficult to measure are ignored.

Source: OECD, 2008, p. 13f, Box 1.

Most treatises on security of supply focus on the supply side of primary and secondary energy sources, including electricity. Recently approaches have been proposed which explicitly account for vulnerability enhancing or mitigating factors on the demand side (for instance, Scheepers, *et al.*, 2007; Jansen, 2009). As for supply-side vulnerabilities, notably when it regards imported energy carriers, they broadly relate to geopolitical security of supply risk, i.e. the *external dimension* of energy supply security identified in the previous chapter. Supply-side related vulnerabilities are in major part exogenous to the jurisdiction of importing countries of energy carriers. Demand-side vulnerabilities are instead mainly reflected in the internal, technical-economic risk dimension of security of supply risk. Last but not least, demand-side vulnerabilities as well as response options to both supply-side and demand-side vulnerabilities can be directly and indirectly influenced by legislation and policy measures in energy importing countries.

2.3 A detailed review of selected security of supply indicators

We have grouped the different security of supply aspects into three categories: import dependency and diversification of fuel and energy supply (Section 2.3.1), resource and carbon intensity which covers scarcity, use and emissions of energy use (Section 2.3.2) and system adequacy, which measures the extent to which generation and transport capabilities cover demand

(Section 2.3.3). The first category of security supply indicators covers primarily the external security of supply dimension, whilst the second and third one broadly refers to the internal security of supply dimension. Depending on the context, several indicators cover elements of both the external and internal dimension. For example, diversity of energy supply can refer to both overseas and domestic sourcing. The different sections will treat the following individual indicators:

Import dependency and diversification

- *Import dependency and vulnerability*: the extent to which a country depends on imports of energy carriers and its economy is vulnerable to related negative fluctuations in terms of trade or welfare.
- *Resource scarcity*: scarcity of energy resources and, optionally, rare mineral and other material resources used in electricity supply sector.
- *Price risk*: the extent to which buyers and society at large are exposed to price volatility with regard to an energy carrier or a related commodity, such as notably carbon emission rights.
- *Diversity*: the extent to which the supply system of energy resources or the one of a single energy resource or a related factor is diversified.
- *Market concentration*: the extent to which a market under consideration is unevenly shaped by market actors on the supply side.

Resource and carbon intensity

- *Resource intensity*: use of an energy resource per unit of output or per unit of demand.
- *Carbon intensity*: emissions of greenhouse gases (GHG) per unit of supply of an energy carrier or per unit of demand.

System adequacy, flexibility and supply security impact

- *Reliability*: the extent of reliability regarding the supply and transport of an energy carrier, notably power.
- *Flexibility*: the extent to which market participants in a country have leeway in replacing *ex ante* supply of energy carriers when unexpected supply constraints including demand-side and supply-side response.
- *Supply insecurity impact*: actual or potential impact of insecurity of energy carrier(s) supply.

A summary assessment at the end of this section will provide an overview of the strengths and weaknesses of the different indicators presented.

2.3.1 Import dependency, diversity and market concentration

Vulnerabilities of import dependency are positively related to (fuel) resource scarcity and fuel price risk. Resource scarcity and fuel price risk are factors primarily determined by global or at least regional market developments, and consequently refer primarily to the external dimension. Also import dependency and diversification are closely, if negatively, intertwined. In fact, diversification with respect to fuels (away from fossil fuels), external suppliers, transport routes and modes, etc.

might be an important response to overdependence on fossil fuels from just a few producer countries with political regimes, perceived as less stable.

A second sub-section will address the important subject of diversity indicators, which are playing a large and growing role in the security of supply debate.

Import dependency, resource scarcity and price volatility

Geopolitical risk remains to some extent associated with imports of energy carriers. This might be monitored by a variety of import dependency and vulnerability indicators. It constitutes a simple and intuitively appealing proxy indicator for energy supply risks (see Chapter 4). *Inter alia* the following two indicators are proposed in recent literature:

- *Import dependency*: the extent to which a country depends on imports of fossil fuels. Net import of fossil fuels and derivatives as a fraction of total consumption, by fuel or aggregated and expressed in primary energy supply terms. A focal fuel for many countries especially in the developing world is oil.
- *Ratio of net fuel import bill to GDP*: the net value of fuel and derivatives imports to GDP. It can be decomposed as follows (Percebois, 2006; WEC, 2008):

Fuel bill/GDP ratio = Import dependency x import energy intensity of GDP x net fuel import bill in USD weighted by energy content x exchange rate domestic currency per USD.

The energy sector and the electricity sub-sector are facing resource scarcity with regard to a wide range of energy and energy-related material resources, including prominently exhaustible fossil fuels. Focusing on fossil fuels, if international (world or regional) markets for fossil fuels were perfectly competitive with no dominant market shares for the largest market participants, fundamental fuel scarcity would be reflected in fuel prices. The supply side of these markets is fundamentally determined by the evolution of the aggregate volume exporters intend to offer under the given market conditions and supply flexibility, whilst on the demand side the evolution of the level as well as the flexibility of demand are the fundamental factors. In practice, many factors, both on the supply and the demand side, generate great uncertainties:

- The volume of energy stocks and flows under or above the ground is uncertain as is the ability of producer countries to harness that energy given technological and financial constraints.
- Access to reserves with relatively low extraction costs can be negatively affected by rising resource nationalism.
- On the other hand, change in exploration technology (seismic 3-D mapping, deep-water drilling, enhanced recovery technology, new technology to extract unconventional gas) can substantially improve access.¹
- Evolution of demand is affected by variations in economic growth and regulatory changes in importing countries, such as fuel taxes, carbon pricing or other climate change mitigation measures.

1. Enhanced recovery refers to the extraction of petroleum beyond primary recovery. With primary recovery only natural energy available in the reservoirs is used to move fluids through the reservoir rock or other points of recovery. Enhanced recovery technology includes water-flooding and CO₂ injection.

- High uncertainties may stimulate gaming on fuel price derivatives markets; even so, fuel prices, as for instance indicated by well-known benchmark price indices, provide valuable, if approximate, information on trends in fuel scarcity.

A key feature of fossil fuels is their ultimate exhaustibility. The ultimately recoverable conventional and unconventional *resources* are highly uncertain. Hence, statistics published by authoritative organisations such as the US Geological Survey (USGS) only give a necessarily very approximate picture of reality. *Reserves* are generally defined as identified resources that are economically recoverable at the time of assessment or that can be recovered with reasonable certainty in the future under existing economic and technical conditions. For many countries, reserves-to-production ratios for oil and gas have been constant over many years, despite increasing exploitation of these resources. This is *inter alia so* because when known reserves start to be depleted, greater effort typically is dedicated to identifying new reserves as a replacement. Furthermore, the quality of statistics on proven reserves as published e.g. by British Petroleum is substantially affected by the mismatch between private information and public information, as private information held by companies and government officials involved in exploration is only partially divulged for strategic economic and political reasons. Statistical information on extraction (production) and use (consumption) of primary fuels and products is much more reliable.

Indicators such as reserves-production (R/P) ratios provide very crude first indications with respect to depletion trends and potential supply constraints.² Both indicators provide an indication of the length of time that respectively proven reserves and ultimately recoverable resources would last if production would continue at current levels. End-of-year energy reserves (resources) are expressed as fraction of energy or fuel production in that year.

The aforementioned ratio indicators can represent different fuels including uranium.³ Their reliability is limited, especially the numerator for reasons already stated above as is their significance. The rate of use of energy reserves, for instance, depends on many factors, including economic conditions, prices, geological conditions, political framework conditions, technological progress and exploration efforts. Trends in reserves-to-production ratios may therefore underestimate the total resource available on the one hand, while on the other hand providing inaccurate information about the extent to which a finite resource is being exhausted. Still they contain useful information on the geopolitical dimension of security of supply. Any declining trends in these statistics regarding gas and coal may well improve the prospects for nuclear.

High fuel price volatility translates into high uncertainty, and consequently in high risk premiums perpetrating throughout the economy. Notable oil price volatility tends to be negatively correlated with macroeconomic growth. In a carbon-constrained world, the price of carbon is increasingly important for participants in energy markets and society at large. Carbon price changes affect the cost of fossil fuel deployment in power generation and, consequently, the fuel mix in the electricity sector. Higher carbon prices thus tend to trigger a substitution of high-carbon fuels such as coal by lower-carbon fuels such as gas. Expectations of structurally rising carbon prices would be expected to foster investment in nuclear and renewable power generation.

The price of carbon and its volatility are largely determined by evolving GHG emission abatement policies. The stringency of such policies is largely determined by developments regarding the climate change negotiations at regional and global levels. Hence, price volatility regarding carbon

2. The reserves-to-production ratios have already been discussed at some length in Chapter 1.

3. For uranium see NEA/IAEA, 2010.

lies primarily in the realm of the external dimension. The volatility of both energy and carbon prices can be measured *inter alia* by standard deviations with respect to historical time-series of price changes per period. As history is not a perfect predictor of the future, complementing statistical analysis of historical time-series with analysis of market fundamentals is very much warranted (see for instance Fabozzi, *et al.*, 2002).

Diversity – a key concept in the security of supply discussion

The concept of diversity is being applied in many sciences. In a generic way it broadly refers to the extent of diversification between categories of all system elements encompassed by a specified system. The essential strength of a well-diversified system is that – in the face of a high extent of uncertainty about known specific outcomes and even outright ignorance about the nature of future outcomes – diversity provides resilience to systems.⁴ One of the first scientific disciplines where this concept was studied was bio-ecology. Darwin thus already demonstrated that diversification of a species within an ecosystem was a “spontaneous” survival strategy in the face of changing biotope conditions. Yet diversity also has costs. For example, certain cost reduction advantages related with economics of scale and standardisation might be foregone. Given new information technology developments, the diversity optimum may also shift over time.

Andrew Stirling has put diversity analysis on the map in the domain of energy policy formulation in general and *inter alia* security of supply more specifically. Stirling has done more: he has meticulously and profoundly explored and elaborated the concept of diversity for energy policy applications (see Stirling, 1994, 1998 and 2008). The analysis below is mainly based on his work and on Jansen, *et al.* (2004). Diversity can be characterised by the three basic properties *variety*, *balance* and *disparity*:

- *Variety* is the number of diverse optional categories into which a system may be partitioned. The electricity mix might be partitioned into “coal”, “gas”, “nuclear” and “renewable”, but alternatively into “coal”, “gas”, “nuclear”, “hydro”, “geothermal”, “biomass”, “onshore wind”, “offshore wind” and “others. The latter system counts more categories. All else being equal, the more system categories, the greater the system diversity. The choices made in partitioning system elements into system categories have a certain inherent arbitrariness.
- *Balance* refers to the pattern in the apportionment (spread) of the volume of different elements across the relevant categories. All else being equal, the more even the balance among categories, the greater is the diversity. This requires a shared unit of account. For instance, in quantifying an energy system and its categories of energy sources one may express the quantity of energy in primary energy equivalents using e.g. the IEA primary energy supply method, the so-called fossil fuels substitution method, the final energy consumption method, etc. But for certain purposes one may just as well express the energy encompassed by the various categories of the energy system considered in monetary value terms. Hence, the choice of the unit of account to assess balance implies some inherent arbitrariness.
- *Disparity*, finally, refers to the nature and degree to which the categories themselves are different from each other. For example, it would appear that the categories “coal”, “gas”

4. Andrew Stirling recites suitable dictums ascribed to Pliny and Lao Tzu respectively: “The only certainty is that nothing is certain” and “knowing one’s ignorance is the best part of knowledge” (Stirling, 1998, pp. 17 and 19).

and “oil” are less disparate than “gas”, “nuclear” and “renewable”, considering the heterogeneity of the latter category and the disparate cost attributes among the three latter categories. All else being equal, the more disparate the categories of a system, the greater the system diversity. Disparity is a fundamentally subjective and context-dependent property of diversity with often distinct inherent aspects, typically most of which of a qualitative nature.

Stirling has addressed the question as to whether and how diversity can be captured in a simple and robust quantitative index. Ecologist Mark O. Hill has demonstrated that the two most prominent diversity indices, that relate *variety* to *balance* (evenness of distribution), are derivations of the common general form (Hill, 1973):

$$\Delta_a = [\sum_i (p_i^a)]^{1/(1-a)},$$

where:

p_i denotes the share of the i^{th} species or element in an ecosystem of “ n ” species; and Δ_a denotes a measure of diversity in function of parameter “ a ”.

The greater the value of parameter “ a ”, the smaller the relative sensitivity of the Hill index to the presence of lower-contributing options (Stirling, 1998, p. 49). In other words, the higher is “ a ”, the more importance is paid to the feature whether the different elements are evenly distributed. A low “ a ” puts more emphasis on sheer variety, even if, for instance, a given species would be represented by a single exemplar.

Letting parameter “ a ” in the above equation go towards one ($a \rightarrow 1$), allows in the limit to obtain in the limit an exponential expression of the well-known Shannon-Wiener Index (SWI):

$$\Delta_1 = \exp^{-\sum_i p_i \ln p_i} = \exp^{\text{SWI}},$$

where:

$\text{SWI} = -\sum_i p_i \ln p_i$ and Δ_1 is a measure of diversity with “ a ” = 1.⁵

The minimum diversity value occurs when the system of elements is encompassed by only one category. The maximum value is attained when all system elements are evenly spread among the system categories.

Setting parameter “ a ” of Hill’s general form instead equal to two, one obtains the reciprocal of the function, referred to in ecology as the Simpson diversity index and in economics as the Hirschman-Herfindahl Index (HHI), (see below):

$$\Delta_2 = 1/\sum_i p_i^2 = 1/\text{HHI},$$

where:

$\text{HHI} = \sum_i p_i^2$ and Δ_2 is a measure of diversity with “ a ” = 2.

5. The proof is provided in the mathematical annex of Hill, 1973, pp. 431-2 using the properties that for small values $\exp(x) \approx 1+x$ and $\ln x \approx x$ which allow the transformation of the exponential function.

Diversity indicators can be complicated at will. One of the most interesting extensions is the inclusion of disparity, the “distance” between different options. For instance in a gas-based electricity system, it is one thing to diversify into oil and another one to branch out into nuclear, as the second option could be considered more “diverse”. Capturing disparity adequately, however, is problematic. The way in which a system is disaggregated determines the results. Stirling proposes to deal with this issue by means of a *triple* indicator including variety, balance and disparity that was independently earlier proposed by Rao (1982), see textbox below. On the one hand, this approach is systematic. On the other, it still fails to measure variety, balance, and diversity in some unconditional objective fashion. As noted when explaining the three essential disparity properties above, measuring each of these aspects, above all disparity, has elements of inherent arbitrariness.

Box 2.2: Criteria for diversity indicators

Stirling has gone at great length to find the best indicator meeting a set of desirable criteria when measuring *variety*, *balance* and *diversity*, the exogenously determined difference or distance between the elements of a system (Stirling, 1998, p. 98; and 2008, p. 20, 1.2). These criteria are:

- *Completeness*: an indicator should address at the same time the variety, balance and disparity diversity of the elements of a system.
- *Parsimony*: an indicator should involve only the variables required in the appraisal of contending options.
- *Transparency*: an indicator should contain a minimal number of hidden assumptions concerning the nature and structure of the system under scrutiny.
- *Robustness*: the orderings obtained should not be sensitive to changes in the value of the included parameters.
- *Consistency* is composed of a number of additional criteria, which are:
 - With given balance and disparity, the index should increase monotonically with variety.
 - If variety is equal to one, the index should take a value of zero.
 - With given variety and disparity, the index should increase monotonically with the degree of balance in the spread of the different elements.
 - Given variety and balance, the index should increase monotonically with the distance between elements in the “disparity space”.
 - Where this distance is zero (i.e., where all elements are identical), the diversity index should take a value of zero.

One of the first attempts at designing composite indicators of energy supply security (Jansen, *et al.*, 2004), was also based on the SWI and inspired by Stirling (1994) and (1998). It was based on scenario information from 17 world regions and developed four composite SWI-based diversity indices of long-term energy security for different portfolios of fuel options. The four diversity-based indices allowed representing respectively:

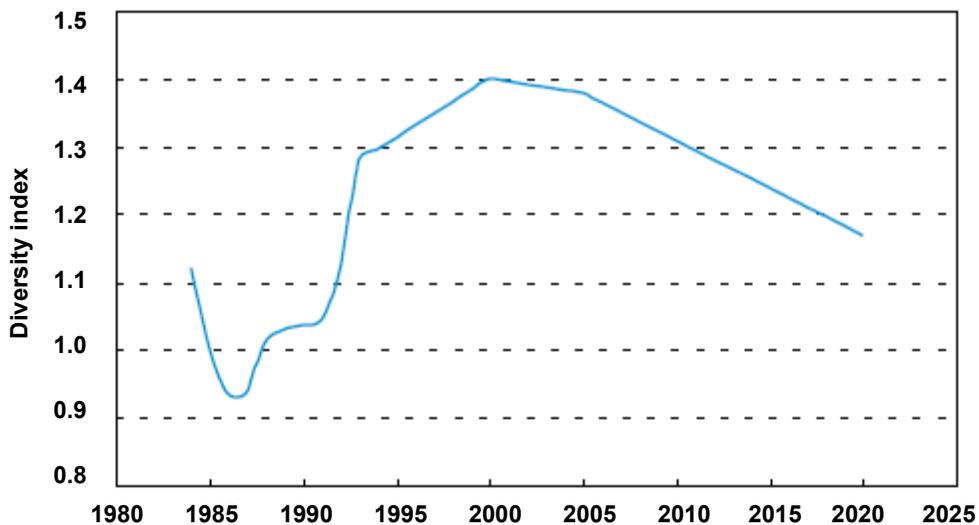
- diversification of energy sources in energy supply;
- diversification of imports with respect of imported energy sources;
- long-term political stability in regions of origin; and
- resource extraction relative to proven fuel reserves in regions of origin, including the home region.

When reliance has to be placed on pre-set sustainability scenarios and a long-term time horizon, in the face of huge uncertainties Stirling’s diversity approach has strong merits. Moreover, this approach is simple in principle and can be readily communicated. A weak point, though, of the pure diversity approach is the equal treatment of all sources, assuming ignorance about their specific security of supply characteristics. Yet for certain aspects one does have meaningful prior knowledge, for example, that certain sources are exhaustible whereas others are not.

A second weakness is the absence of any feedback mechanism on the demand side. It can be expected that once increasing supply risks are appropriately communicated and major supply vulnerabilities are manifest, actors in importing countries will enact public and private measures to respond.

Nonetheless, Stirling’s SWI was a pioneering attempt at designing security of supply indicators and was widely referred to in subsequent attempts. An early attempt to use Stirling’s SWI to assess security of supply by an international organisation was made by the IEA in *Towards a Sustainable Energy Future* (IEA, 2001).

Figure 2.1: A diversity index for UK power generation based on the SWI



Source: Stirling, 1994.

Figure 2.1 based on historical data from the United Kingdom as well as a forecast shows neatly how the “dash for gas” in the 1990s contributed first to energy diversification, while it subsequently reduced diversity and *ceteris paribus* the security of energy supply once it reached a disproportionately high share in power generation. The SWI remains a useful tool, but as has been pointed out above it must be complemented by qualitative information about different supply options.

Market concentration

Diversity indices can also be applied to markets. Well-diversified, liquid markets may provide a hedge against the exercise of market power. Competition authorities tend to focus on the related but opposite characterisation of markets: the extent of market concentration. The most common indicator used to measure market concentration is the HHI developed above. When applied to the supply side of a fuel or electricity market, it is defined as the sum of squares of the market shares of supply-side market participants. The general formula of the HHI is:

$$HHI = \sum_i p_i^2,$$

where p_i is the market share of company “i” expressed in decimals. The range of the HHI is thus $(1/N; 1)$, where N is the number of suppliers. The higher the number of suppliers and the better distributed their shares, the more competitive will be the market in question and the closer the HHI will be to zero. For economists, the HHI is particularly useful as it has the welcome property to indicate the relative mark-up of price above marginal cost under standard Cournot competition according to the formula:

$$(p - c)/p = HHI/\epsilon.^6$$

In this formula, p is price, c marginal cost and ϵ is the elasticity of demand. By convention, the HHI is expressed by competition authorities as:

$$HHI = \sum_i (p_i \times 100)^2.$$

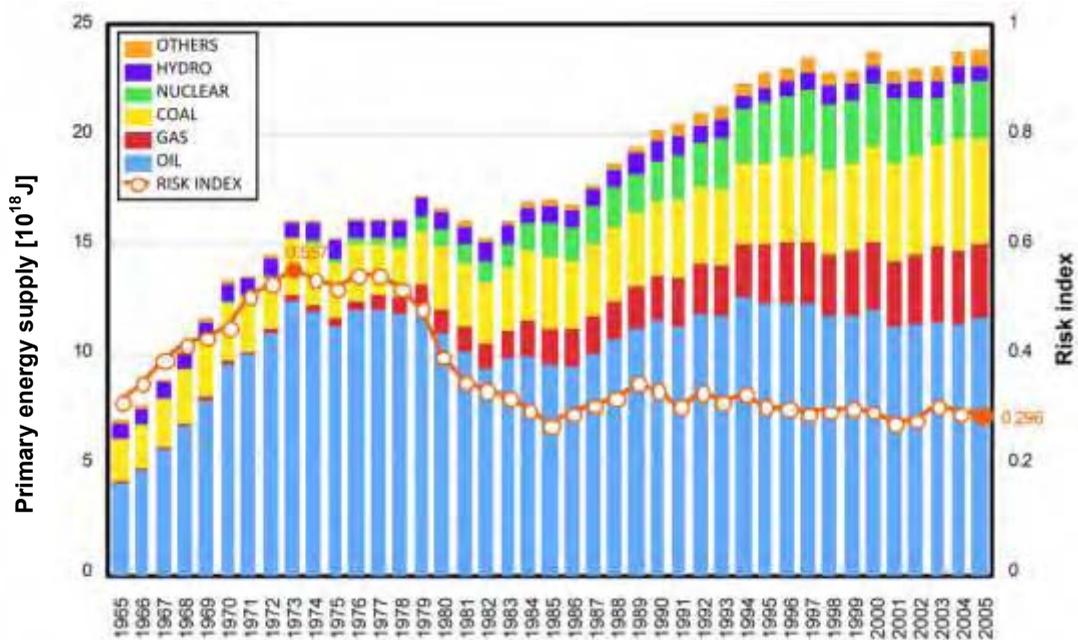
Then the range works out as $(10\,000/N; 10\,000)$. If the HHI is above 1 800 (the generally accepted norm), then a market is considered to be “strongly concentrated”. An HHI of between 1 200 and 1 800 indicates that a market is “moderately concentrated” (NMa, 2008). Of course, the grouping of actors that may or may not have collaborative strategies, such as export cartels like OPEC, has a huge influence on the determination of the HHI. In importing countries, the HHI is often applied to measure concentration of imports with exporting countries considered as a single entity while domestic supply is considered geo-politically secure.

Thomas Neff first used the HHI to measure supply security risk and diversification in world uranium supplies (Neff, 1997). The IEA also used the HHI for assessing the security of supply risk for fossil fuel imports in the interaction with climate change policies (IEA, 2007). Analogous to Jansen, *et al.* (2004), the IEA study introduced a composite parameter seeking to account for country-specific supply risk by including additional qualitative information even though assessing future levels of political stability is fraught with uncertainties. Special provisions were also taken to distinguish pipeline-based gas trade, which is governed by frequently undisclosed long-term contracts linked to the oil price, from the LNG-based spot gas market. Quite obviously, the two have very different security of supply implications, the former creating bilateral dependence, whereas the second offers multilateral flexibility. Projections to 2030 show how carbon reduction policy triggering a coal-to-gas switch may lead to a deterioration of energy supply security European countries, especially if mutual interdependence through long-term contracts remains the dominant pricing model.

The Central Research Institute of Electric Power Industry (CRIEPI) in Japan applied a similar methodology using the HHI for a case study on supply security in Japan showing how the diversification into nuclear energy improved energy supply security (Nagano, *et al.*, 2008). The risk index in Figure 2.2 is a procurement stability index that reflects the instability of an energy mix due to resource distribution, trade share, Japan’s import structure and the socio-political risks of exporting countries with resource deposits or exports. The risk index has its maximum value of 1, when all the primary energy needs are met solely by imported oil, while its minimum value is zero, when the whole energy supply is covered by risk-free domestic sources, such as hydro and other renewables.

6. Stirling is wrong to qualify the “comment by the economist Stigler to the effect that there exists a precise theoretical rationale for the use of Simpson (of which the HHI is a special case) as an index of concentration, but not for Shannon” as “curious, unsubstantiated (and apparently mistaken)” (Sterling, 1998, p. 51). Stigler was alluding precisely to the link, which is crucial for economists, indicated above.

Figure 2.2: A security of supply index for Japan integrating country and fuel risk
 (The lower the risk indicator the better is the security of supply situation.)



Source: Nagano, *et al.*, 2008.

Strengths and weaknesses of diversity indicators

The two import dependency and vulnerability indicators presented above are quite useful in illustrating geopolitical risk and how the diversification of fuel sources, for instance through the deployment of nuclear energy, can mitigate this risk. The resource scarcity indicators concerning fossil fuels may also attest to the potential benefits of more nuclear power. Yet transparency (reliability) and data availability (in the case of resources-to-production ratio) are moderate. High price risk regarding fossil fuels and carbon might emphasise the role of nuclear power in certain portfolios of generating assets to the extent that nuclear mitigates the volatility of the average generating cost for the whole portfolio.

Given the fact that unexpected future events abound, diversity in energy supply systems and indicators that measure diversity have supply security merits. A qualification is in order though. Even for longer term time frames not every aspect of supply insecurity is completely surrounded by ignorance. Diversity is certainly no panacea for all security issues, the more so because in the limit it comes at a cost, for instance in the form of benefits foregone of standardisation and economies of scale.

Overall the HHI has similar drawbacks and advantages as the SWI. Attractive for its transparency, elegance and mathematical tractability, it struggles to take qualitative information about different supply options into account. Nevertheless, both indicators are indispensable complements in any security of supply debate. As indicators of diversification in the wider sense – the HHI values evenness of distribution more than the SWI – they are particularly valuable if qualitative information on particular options is hard to come by or uncertain. They remain today’s equivalent of the folk wisdom “not to put all of one’s eggs into the same basket.” This is a criterion that needs to be carefully balanced against the increasing economies to scale that can be gained from doing precisely the opposite.

Regarding the nuclear option, diversity analysis might be fruitfully applied to gauge its role in diversifying away from fossil fuels. The nuclear option is especially attractive for diversification purposes in large power systems as there can be substantial economies of scale. Such economies of scale do not primarily pertain to the size of the individual reactor. More importantly, they apply to the possibility of spreading system-wide fixed costs such as appropriate institutional and regulatory infrastructures that oversee safety, security and waste disposal over a larger number of reactors. Only for very small, isolated systems can the lumpiness of the incremental investments in advanced nuclear reactors pose a bottleneck.⁷

In this regard, the dynamics of technology and institutional development work out in two directions. On the one hand, a strong drive towards power market integration, investments in robustly interconnected transmission networks, and a dash for (flexible) gas can be observed in several world regions, most ostensibly in Europe and North America. The same, if still to a lesser extent, goes for enhanced demand response. These factors will help to emphasise the role of nuclear in more diversified power systems. On the other hand, the large-scale penetration of distributed and intermittent renewable generation might present a challenge to nuclear. Widespread commercialisation of small-scale nuclear technology might be able to take on this challenge successfully.

For diversification as a hedge strategy against the (potential) exercise of market power, the HHI would seem more appropriate than the SWI. Stirling observes that the HHI does not properly reflect the diversity property *balance* as it gives a higher weight to producers with high market shares (Stirling, 1998). Yet, regulators overseeing the functioning of energy markets consider this bias as desirable as it is the market parties with the largest share that might potentially exercise market power.

In order to gauge sourcing geopolitical vulnerability risks associated with respect to a certain fuel, it is recommended to consider the international market for that particular fuel. A case in point is the market for hard coal. Many analysts stress the geographic spread of coal reserves, suggesting that geopolitical risk for hard coal is negligible. However, countries with major shares world reserves such as China, India and the United States do need their domestic reserves for own use. The supply-side concentration in the international market for hard coal as *for instance* measured by the HHI is in fact quite high (IEA, 2007). Due to a variety of facts such as Southern and South-Eastern China becoming more import dependent and Indonesia tightening exports, both, the correlation of hard coal benchmark prices for major import areas (such as the API#2 index for delivery to Amsterdam-Rotterdam-Antwerp) with world oil prices, as well as price volatility have increased over the last few years.

The usefulness of applying diversity and market concentration indicators depends *inter alia* on data availability. Often international trade flow data for fuels are hard to get by, amongst others for confidentiality reasons. Most trades, especially regarding uranium and gas, are done on the basis of long-term bilateral contracts instead of spot markets.

2.3.2 Energy and carbon intensity

The use of energy and carbon intensity indicators in order to assess security of supply risks is based on the assumption that every barrel, MWh or tonne of energy that is not consumed does not need to be imported or produced and thus does not pose a security of supply risk. By and large this is

7. Incremental investment in new nuclear build of currently available Generation III(+) technology, as offered by the three currently leading providers, relates to reactors between 1 000 and 1 650 MW. New small-scale nuclear technology could lower the capacity threshold and consequently expand the potential scope of nuclear to lower-volume markets (Kessides, 2010).

sound reasoning. Efficiency is good. And yet under some circumstances, inefficiency defined in terms of primary energy consumed per unit of energy service, provides a reservoir of flexibility in the face of sudden security of supply shocks (physical interruptions or price spikes) precisely by being able to improve efficiency.

An already efficient system no longer has this option as it is running a tighter ship. Improving vehicle fuel efficiency in the United States, for instance, is far easier than improving it in Japan. Improving carbon intensity in Poland is easier than doing so than in France. Of course, such considerations should not be used as excuse to let technical inefficiencies persist indefinitely. A secure energy system is a function of both, resilience (the ability to respond) *and* overall vulnerability as well as the importance of the respective sector in the whole economy, and in this latter perspective low resource and carbon intensity is clearly a desirable feature.

Energy intensity

Energy intensity on the supply side refers to the use of primary energy per unit of delivered end-use energy, such as notably electricity. On the demand side, the use of an energy resource per unit of output or per unit of demand matters. On the supply side, fossil fuels are extracted, transported, converted into secondary fuels and electricity and delivered to end-users. In general, high resource intensity is associated with high geopolitical risk. In all steps of the supply chain scarce resources can be saved by technological advances, adequate investments embodying technological advances, and improved operational procedures. This has both security of supply and environmental benefits. Useful supply-side indicators for monitoring and benchmarking progress on these scores include:

- the recovery factor indicating the fraction of original resources that are producible;⁸
- energy loss rate during transportation as a fraction of energy contained in fuels upon embarkation; for LNG this includes liquefaction and re-gasification, activities in which notable efficiency improvement has been achieved as a result of technological change;
- generation and conversion efficiency; and
- transmission and distribution loss rates in the power sector.

Demand-side actors also have a major role to play in reducing energy resources intensity levels in an economy under consideration. For *households and the services sector* it includes aspects such as energy performance of buildings/dwellings, the choice of consumption packages, the role of energy efficiency performance in choosing energy-using gadgets or the intensity of use behaviour regarding energy-using gadgets. Notably for households behavioural aspects are also very important.

For the *industrial sector* major relevant aspects are the trends in industrial sector composition and within-sector industrial activity composition, the energy intensity of specific industrial activities, investment in cutting-edge low-energy technology and “good housekeeping” in energy management. For the transportation sector relevant aspects include: composition of transport modes for passengers and freight transportation; energy efficiency of transport means per transport mode; intensity of use per transport mode; spatial planning and planning of public investment in transport infrastructure. It is beyond this study to elaborate on all these aspects. Generally, it can be concluded that resource intensity of final demand for goods and services has *a structural component, an efficiency component for specific energy-using equipment, and intensity of use component.*

8. For oil this is called *oil in place*: the total quantity of oil that is estimated to exist originally in natural occurring reservoirs.

A first impression of energy intensity for a country can be obtained by the *use of an energy resource per unit of GDP*. A somewhat more detailed picture can be obtained by the *use of an energy resource per unit of demand* in the main final energy use categories. The considerations presented above show that this indicator presents a very crude picture. Monetary values in the denominator blur the view on physical conversion processes and deflating time series in nominal terms presents a challenge.

Carbon intensity of energy supply and demand

In an increasingly carbon-constrained world, the carbon intensity of fuels and electricity generation and associated regulatory uncertainty is an aspect of growing importance to market participants in the energy sector and the wider society. In general, high carbon intensity is associated with high geopolitical risk. Not only the resource as such which embeds the carbon component is of relevance; in fact this risk is exacerbated by changes in global climate policies in the negotiations of which many individual countries may have a very limited role. If *ceteris paribus* the issue of climate change is to be embraced and to be transformed into stringent carbon reduction policy in the economically leading countries and regions across the world, this would be expected to boost the role of nuclear in securing power supply. The key supply-side indicators are:

- emissions of greenhouse gases per unit of supply and combustion of a fuel; and
- emissions of greenhouse gases per unit of electricity: per technology and aggregated, weighted by volume of electricity generation.

For an unbiased comprehensive picture it is in order to compile statistics on a *life cycle analysis* basis. This is particularly relevant for fair comparisons involving coal- and gas-based technology with application of carbon capture and storage (CCS). Numerous publications of CCS promoters and official statistics providers present estimates (or rather projections assuming deployment of cutting-edge technology and contestably high learning rates), comprising GHG emissions at the generating plant only. The business case for nuclear relative to fossil fuel power plants with CCS can be critically and negatively affected by these biases in the existing carbon intensity of energy supply statistics.

Strengths and weaknesses of indicators for resource and carbon intensity

For a good insight in *resource intensity* trends, quite detailed, disaggregated analysis of energy use is warranted, preferably at the level of specific energy use per unit of physical output and demand. Such detailed analysis is a prerequisite to arrive at good policy prescriptions on improving resilience of the economy by way of reducing energy intensities.

For the nuclear option it is relevant that energy savings options in many end-use applications entail substitution towards further electrification of the energy services. Two notable applications in this respect are electric vehicles in the transportation sector and electric heat pumps for indoor climate conditioning in office buildings and household dwellings. Heeding the life cycle analysis (LCA) caveat, the *carbon intensity indicators* above are quite useful and transparent. Unfortunately in many instances these indicators are not presented on a LCA basis, especially but not only regarding fossil-fuel based generation with CCS. The indicators can help substantiating the role nuclear can play in decarbonising the power sector in particular and the economy at large.

Rising carbon prices can have substantial welfare effects, contingent on the fossil-fuel intensity of the economy, including the fossil-fuel intensity of the import and export sectors. The same

considerations apply as presented in the previous sub-section on the *use of an energy resource per unit of demand* in the main final energy use categories. Further electrification of energy services provided to economic actors articulating their final demand for goods and services is broadly consistent with bringing down carbon intensity of demand. Again, *ceteris paribus* an enhanced role of electricity in the final energy demand mix is good news for nuclear.

2.3.3 Indicators for the adequacy of the energy system and technical infrastructures

System adequacy refers to technical capability of energy systems to maintain adequate supply and transport under a wide range of operational conditions. The breakdown of energy systems, in particular, electricity systems, frequently has significant economic and social impacts reaching from production losses and inconveniences to threats to human health and life.

However, the actual impact of supply and network interruptions on welfare is quite difficult to assess. Network security is usually measured by collecting information on the number and duration of interruptions. The number and duration of interruptions are weighted and normalised in different ways, leading to different security indicator types. Broadly, three classes of indicators can be discerned: first, customer-based indicators that relate security impacts to number of customers affected. The second class of indicators is known as load-based indicators since it relates security impacts to transformer capacity. Finally, energy-based indicators couple impacts to amount of energy not supplied (Ajodhia, 2006). There exist several indices for measuring electricity service quality such as SAIFI, SAIDI and CAIDI:

- *System Average Interruption Frequency Index (SAIFI)* measures the probability that a customer will experience an outage. It is calculated by dividing the number of customer interruptions by the total number of customers served. The number of customer interruptions is the total number of interrupted customers for each interruption. This is typically measured over the period of a calendar year.
- *System Average Interruption Duration Index (SAIDI)* provides a measure for the average time that customers are interrupted. It is calculated by dividing the total customer interruption duration by the total number of customers. The customer interruption duration is defined as the aggregated time that all customers were interrupted. SAIDI is also known as customer minutes lost (CML).
- *Customer Average Interruption Duration Index (CAIDI)* is defined as SAIDI divided by SAIFI and is a measure for the average time required restoring service to the average customer per interruption. It is calculated by dividing the total interruption duration by the total number of interruptions.

One further shortcoming is that customer based indicators do not distinguish between customers with different size, demand, interruption damage etc. Larger consumers, as approximated by the size of connected capacity or their volume of electricity demand, generally sustain higher costs per unit of unserved energy because of power interruptions than smaller consumers. By weighting interruptions on the basis of interrupted load or non-supplied energy (instead of customer numbers), security indicators can more closely reflect the impact of interruptions. One example of such an indicator is energy not supplied (ENS). This indicator considers the amount of energy not supplied because of interruptions, which is typically normalised by the number of connected customers. In other words, it provides a metric of system failure independent of the total size of consumption.

For policy reasons, since potential future outcomes are more relevant than past outcomes, the expectation value of the amount of electricity unserved can be used as a measure (BERR, 2007). In order to be able to differentiate between different situations, this requires probabilistic measures of supply and demand developments and options. This results in a probability weighted amount of energy unserved. In the case where the cost of interruptions per unit of energy is known (i.e. VOLL), multiplying the expected energy unserved by the interruption costs per unit, an estimate of the monetary, aggregated costs of energy insecurity can be derived (Van der Welle and Van der Zwaan, 2007).

On the basis of such assessment, the required benchmarks for the following technical indicators can be determined. Given the quite specific technical nature of the different indicators presented below, the assessment of the advantages and disadvantages of each indicator has been integrated in the presentation of each indicator.

Indicators for generation capacity margins

Both Chapters 1 and 3 use this important indicator, playing a central role in guiding electricity system expansion planning. The indicator provides insight into the extent to which the installed generation capacity exceeds peak electricity demand. In addition, the indicator could also be formulated with respect to fuels, for instance maximum gas supply capacity versus peak gas demand. It should not necessarily be considered as surplus capacity since this margin is required to cover the risk of generating plant unavailability (for instance due to a technical breakdown) or higher than predicted peak demand (for instance due to extreme weather events) (BERR, 2006). The indicator captures two effects on system adequacy: effects of (weather-related) extreme events as well as load balancing problems.

Indicators of generation capacity margin play a central role in guiding electricity system planning providing a good snapshot of system adequacy of generation, taking into account also potential impacts of (weather-related) extreme events on loss of largest plant. Nevertheless, some factors that influence system adequacy are not captured. Take for example the possibility of correlated forced outages (for example, a failure in a nuclear plant leading to a requirement for other similar plants to be taken offline) or fuel supply risks (Redpoint, 2008). Furthermore, the potential role of interconnections and demand response cannot be easily integrated in the indicator. Note that interconnections either can supply power to meet peak load or add additional demand to the existing peak load. Different definitions of peak generation and demand introduce some subjectivity in the determination of the indicator value. Besides, the large number of issues taken into account in some variants of the generation capacity margin might blur indicator results.

A variant of this indicator is the *de-rated* peak capacity margin, which adjusts the installed generation capacity by the expected availability of each plant at peak demand. The latter is effected by the probability of forced outages and expected output from intermittent renewable generation. The output from intermittent renewable generation is adjusted to account for its contribution to system reliability through the capacity credit. The capacity credit measures the percentage of maximum potential output that will be statistically available during times of peak load. Because of correlation in intermittent generation output profiles, the capacity credit decreases with the installed capacity of a technology and the penetration levels of other types of intermittent technology, while a better geographical distribution of plants (more dispersion) increases the capacity credit (Redpoint, 2008).

Dependent on the origin of the security of supply problem, further de-rating of the peak capacity margin can be a logical step in two kinds of situations. Firstly, if a gas shortage occurs, for safety reasons space heating and cooking obtain priority in gas use, implying that gas fired power plants will

lose gas. The same may hold for other fuels. Secondly, the loss of the largest plant, i.e. shutdown due to an extreme event, may decrease the peak capacity margin as well.

The de-rated peak capacity margin requires modelling of the capacity credit of intermittent generation, which is a complex exercise and, hence, detrimental to the indicator's transparency. Especially when intermittent generation is taken into account, the generation margin indicators do require much data. Concerning the prediction of future situations, any assumption about future generation decreases the robustness of the system adequacy prediction. The indicators can bring out the value of nuclear in that this generation option tends to make for high availability and stability. Cool water restrictions and flooding risks may currently hardly limit this value, but climate change might present a somewhat greater challenge on longer time scales in these respects.

Energy margins and the short-run availability of gas and oil

Like the generation capacity margin for electricity, it is possible to monitor whether energy supply in general provides solace under extreme (weather-related) events, i.e. the extent to which primary energy supply exceeds expected primary energy demand, for instance for gas. For a given source different supply options (for gas for instance inland production, import through pipelines or LNG regasification terminals, storage facilities) need to be summed up and related to energy demand (ECOFYS, *et al.*, 2009). As opposed to the (de-rated) generation capacity margin, the indicator accounts primarily for extreme and/or weather-related events. Load balancing failures are at most covered to a limited extent, since operators of facilities for gas and other energy sources have more storage capabilities (for gas for instance “linepack” in the network) or can establish these possibilities at lower costs than operators of electricity generation facilities.

The energy margin indicator covers all energy supply chain aspects, such as extraction, trade (import and export), conversion as well as storage. The indicator is therefore able to cover both the system adequacy and diversification aspects of security of supply. However, the indicator does not consider substitution possibilities with other energy sources. Also for this indicator, different definitions of peak generation and peak demand render the indicator slightly subjective. Energy margin forecasts require (in hindsight possibly less valid) assumptions about future supply developments. Infrastructure developments are surrounded with uncertainty. Hence, investment planning horizons are usually not longer than ten years.

Extreme weather events may directly impact peak demand for energy via increased heating and cooling demand, resulting in a temporary lack of available supply during peak demand periods. Likewise, extreme events (strikes, large-scale accidents and terrorist activities) may affect infrastructure and resources for the supply of energy. Both types of events decrease the short-run (SR) availability of both gas and oil (ECOFYS, *et al.*, 2009). This availability can be captured by constructing an indicator for short run availability of gas and oil in a number of steps. The first step consists of calculating the daily peak supply shortfall (DPSS) for oil and gas, where:

$$DPSS = \text{Peak daily demand for fuel (accounting for extreme weather)} - \text{daily supply (production + net imports) for fuel.}$$

Since production data for peak hours is not available for future years, average daily production is used as a proxy. Consequently, the daily peak supply shortfall is an average as well. Part of this shortfall could be met by existing storage given the scale of the shortfall.

Furthermore, extreme events such as strikes, large-scale accidents and terrorist activities may impact the level of concentration of resources and infrastructure and as a result DPSS. Reliance on a

single supplier, route or production plant increases the vulnerability of the system to extreme events. Therefore, daily supply is adjusted with the factor LSSPR to account for the loss of the largest supplier, route, or plant. LSSPR is defined as supply from the largest single supplier, plant or route (excluding storage). Hence,

$$DPSS = \text{Peak daily demand for fuel (accounting for extreme weather)} - \text{daily supply (production + net imports - LSSPR) for fuel.}$$

As a second step, when $DPSS > 0$, the short-run availability of gas in days is equal to the total storage capacity per DPSS. If extreme events are taken into account, total storage capacity should be corrected for the storage capacity of the largest supplier if this is storage. This availability can be corrected further for the energy dependency of gas in order to show the relative importance of gas as primary fuel. The energy dependency is based on the complement of the share in primary energy, instead of the share itself, because of the positive formulation of the indicator (short-run availability increases when a country is not fully dependent on gas). Hence,

$$\text{Short-run availability of gas} = \text{short-run availability in days} * \text{energy dependency factor.}$$

For oil, physical storage capacity is deemed not to be a limiting factor in the same manner as it is for gas. Therefore, in order to calculate the short-run availability of oil the required critical stocks of oil that would need to be kept to cover a benchmark period of time are considered. The benchmark period could be based on the length of the period IEA members are required to maintain stock: 90 days of average consumption. The availability is corrected for the energy dependency of oil, again by using the energy dependency factor explained for the gas case. Hence,

$$\text{Short-run availability of oil} = DPSS * \text{benchmark days required} * \text{energy dependency factor.}$$

Overall, indicators for the short-run availability of primary fuel are useful for assessing the risks of shortages given the availability of oil and gas as well as demand. The comprehensiveness of the indicator, however, is somewhat limited as likelihood and magnitude of a supply shortfall due to different types and locations of weather-related and extreme events are not considered. Yet, short-run availability of gas and oil may be overstated due to the usage of average daily production data, whilst the indicator loses track of the impact of specific supply issues. Since production data for peak hours is not available for future years, average daily production is used as a proxy. Short-run availability forecasts require assumptions about uncertain future supply developments.

Must-run baseload generation capacity

This capacity measure is usually defined as total capacity in GW of less flexible “full load” generating units for which part-loading or switching off, except for planned outages, has economic disadvantages or sheer technical limitations, notably nuclear and coal-fired power plants. If the fraction of total baseload capacity is relatively high compared to baseload demand, the ability of generation on the power system to match system demand may be affected. In this respect, it is the complement of the load balancing failure which is identified through the de-rated electricity peak capacity margin. However, whether the latter is mainly aimed at identifying supply shortages, the indicator at hand is aimed at discovering temporary oversupply. Whether or not this situation may occur, depends on the flexibility of the power system as a whole, i.e. flexibility on the supply side (shutdown and ramping capabilities of generation units) and demand side (interruptible contracts, variable pricing, smart metering, etc.). The flexibility of the demand side of the power system will be dealt with in more detail under demand-side security of supply indices.

The “must-run” baseload generation capacity accounts for the unevenness of supply and demand from the perspective of maintaining the system in balance. This is particularly relevant when extreme events occur, occasioning sudden decreases in demand or increases in supply from other sources. Therefore, this indicator brings out a supplementary aspect of system adequacy. Generally speaking, the indicator is transparent, apart from minor baseload classification issues and issues pertaining to the use of different criteria for load following capabilities of generation. The required detailed country-specific data is probably difficult to obtain for multi-country analysis. This indicator may highlight whether or not (additional) baseload generation, including nuclear, poses challenges to maintaining the short-term balance in the power system.

Indicators of adequate investment in supply and transport

As pointed out in Chapter 1, insufficient investments in new capacity may occur when investors face a high amount of uncertainty and/or are myopic, i.e. are too focused on short-term market developments instead of accounting for resource depletion or stricter environmental policies which impact on the potential for structural, long-term market developments.

These long-term market developments include security of supply and sustainability policy, which may affect investments in adequate supply in different ways (ECOFYS, *et al.*, 2009). Firstly, policy may steer investments to production technologies that are less dependent or independent of fossil fuel consumption like renewables and nuclear generation. Such technologies are more capital intensive than (other) fossil fuel generation technologies; construction costs constitute a large part of the investment, while fuel costs are limited or even nil. Hence, the part of the investment that has to be paid upfront is higher in case of renewable and nuclear production technologies. With an investment indicator like *capital intensity* it is possible to monitor changes in generation investment patterns due to the increase of non-fossil fuel based generation like (intermittent) renewables and nuclear. Capital intensity is defined as the sum of capital costs divided by the sum of total costs.

Secondly, more investments in renewable generation will affect the operational behaviour of other generation technologies. Since renewable generation disposes of the lowest marginal costs and generation follows demand, it replaces other baseload generation at times of high output. Consequently, the *average load factor* of baseload plants will decrease, which decreases income if they cannot compensate for this tendency with higher prices at times of low output. If income decreases, investments in new generation facilities will be postponed or cancelled. Therefore, the average load factor of baseload plants (= electricity generation/maximum possible generation) may be an important indicator for future investments. Thirdly, procedures, time and cost to obtain construction permits, inspections and network connections give an impression of the ability to realise new investments.

In order to guarantee reliability of supply, available network capacity has to exceed peak load, i.e. a certain amount of network capacity has to be kept as reserve in order to maintain transport under adverse contingencies. Up to now, in network planning reserves are usually determined on the basis of deterministic “n-1” and “n-2” requirements, which require network operators to transport the power along a different route in case a contingency occurs (even when certain network components are not available due to planned outages, i.e. “n-2”).

Indicators of investment in adequate supply give an important but ultimately limited indication of a country’s true security of supply situation. For instance, the generation mix is largely shaped by policies in the past, among others the availability of primary energy supply sources like gas in the Netherlands and the United Kingdom. Regarding more specific capital intensity indicators, allowance

has to be made for the fact that capital costs can be calculated according different accounting or economic rules. Collecting data about capital intensities and load factors thus would require country-specific analysis, but this is typically beyond the scope of a multi-country study. Concerning administrative barriers, the World Bank and Standard and Poor's provide some indices about the relative position of countries. Whether investments renewable generation may curtail future investments in nuclear is an important issue for the coming decades.

As far as transport is concerned, insufficient investments in new capacity can occur when energy regulators face a high amount of uncertainty and/or are myopic, i.e. are too focused on short-term developments instead of accounting for structural, long-term developments related to generation, demand and network investment and operation.

Such long-term developments include security of supply and sustainability policy, which may affect investments in adequate transport capacity in different ways. Firstly, policy may induce investments in intermittent production technologies which require more investments in transport capacity due to the generally larger distance between production and demand, the concentration of resources, and the necessity to transport excess intermittent production at times of low local demand to other areas. With an investment indicator like capital intensity it is possible to monitor changes in investment patterns. Capital intensity is defined as the sum of capital costs divided by the sum of total costs. Secondly, procedures, time and cost to obtain construction permits, inspections and network connections give an impression of the ability to realise new investments.

Indicators monitoring the adequacy of transport, transmission and distribution capacity provide important information of the network component of system reliability but need to be refined in an ongoing process. For instance, future critical indicator values may be influenced by a shift from deterministic to probabilistic network requirements. The latter are expected to lower network reserve requirements under non-extreme system conditions (Van der Welle, *et al.*, 2009). Also, since calculations of required network capacity usually are not made public, their transparency is often poor. Data is difficult to obtain for confidentiality reasons. On first sight, the indicator is indifferent to the type of generation capacity used. However, recent connection policies in certain areas, notably Europe, oblige network operators to offer firm connection capacity for the full rated output of (intermittent) generation. Especially in distribution networks which are passively managed, this implies that network utilisation will decrease substantially with increasing shares of intermittent generation. In contrast, nuclear as an alternative, essentially carbon-free generation source, tends to exhibit a stable production pattern and, consequently, high network utilisation rates.

Complementary indicators of system security

In the following, a number of second-tier indicators for the assessment of the stability, adequacy and flexibility of generation and transport systems are presented. None of them will be a comprehensive indicator for the security of an energy system. Taken together, however, they are useful complements in assessing the exposure of an energy system to security of supply risks.

Mandate of the energy regulator

In case the regulator disposes of a mandate to ensure adequate transport and distribution infrastructure capacity, the regulator will issue regulation to guarantee the availability of sufficient network capacity to network users and monitor the compliance by network operators. For example, the regulator may prescribe network operators to publish regularly (every two to five years) plans which contain well substantiated expectations about long-term network planning.

The mandate of the energy regulator is a soft type of indicator that may summarise useful if qualitative information which is not captured by other indicators. However, some analysts consider that network operators do already have an inherent incentive to make sufficient network capacity available and question whether this particular indicator provides any added value. Moreover, in some countries, the formal mandate of the energy regulator is a tedious matter because of strong informal government involvement in regulatory decisions. The European Commission publishes this annual benchmarking reports including information about the mandate of regulators in Europe. In some other world regions such information might be at hand less readily. The indicator may to some extent denote a safeguard for guaranteeing the availability of sufficient network investments. Indirectly, this may favourably affect the investment climate for nuclear.

Storage capacity and critical stocks of fuel (including oil, gas and uranium)

Storage capacity can be estimated by dividing stock of some critical fuels by the corresponding daily, monthly or annual fuel consumption. The indicator provides an indication of the length of time that stocks would last if supply were disrupted. Storage capacity and critical stocks of fuel (including oil, gas, uranium) as an indicator provides a useful indication of a strategic resilience aspect of energy systems. The indicator is transparent with respect to specific primary fuels. Typically, storage capacity data is available for oil and gas. Availability of data about storage of uranium is fairly limited (NEA/IAEA, 2008). Future storage capacity is closely linked to government policy concerning storage (planning, administrative and regulatory requirements). Nuclear may exhibit favourable score with respect to fossil-fuel options as a limited amount of uranium is enough to bridge a long period after a disruption.

Rate of contractually flexible demand: interruptible contracts

One indicator to assess the flexibility of demand is the fraction of consumption which is covered by interruptible contracts as fraction of total consumption. This demand flexibility is useful as resilience measure if supply were disrupted at peak demand. The rate of contractually flexible demand (interruptible contracts) again provides useful information on a major aspect regarding the resilience of a certain national/regional energy system. This indicator is transparent when final energy demand is considered. The total amount of interruptible contracts in a country, however, cannot be obtained from international statistics. A high level of demand response is favourable for the business case of a baseload technology such as notably nuclear.

Load duration of back-up fuel supplies

The indicator estimates the number of hours that back-up generation capacity can deliver full electricity output using alternative fuels, after a disruption of primary fuel supply. Where applicable, the alternative fuels to gas-based generation (such as diesel, fuel oil or coal) are mainly stored on the site of CCGTs. The period of load duration depends on a number of factors; including the ability to restock back-up fuels, generator characteristics, the type of gas supply contract – either firm or interruptible – and expectations about the variability of electricity prices as these determine the installation of back-up facilities (BERR, 2006).

Load duration of back-up fuel supplies provides an indication of the resilience of the generation part of the energy system. However, when information on this indicator remains disaggregated, the overall picture for the national energy system may be less clear. Data about back-up storage facilities is probably plant or company-specific and thus difficult to obtain at the national level.

Pipeline capacity and utilisation

Pipeline capacity may constrain the import and export of gas during normal operation as well as emergency conditions. Indicators to measure the availability of pipeline capacity can be related to import, peak gas demand, etc. Pipeline capacity and utilisation provides important information about restrictions that pipeline capacity may pose to import of gas or oil, and therefore to system resilience. However, it does not address the issue of contractual limitations to gas flows which often impedes full utilisation of physical pipeline capacity. Although system operators monitor data about capacity and utilisation, data availability may be limited for commercial reasons. Future estimates require decisions about the likelihood of realisation of new projects. For nuclear generation, the indicator is not relevant.

Refining capacity and utilisation

Refineries process crude oil in various petroleum products, such as gasoline, diesel or naphtha, before it can be used in industrial, transport and heating sectors. Refining capacity may therefore limit the availability of oil derivatives for final consumption. There exists a number of indicators to monitor refinery capacity and its utilisation (differentiated by product) (ECOFYS, *et al.*, 2009). This indicator applies, in particular, to the flexibility of oil refineries in the face of overall demand changes. It does not account for the possible flexibility of refineries to switch production. As such, the indicator is fully transparent and indicator data is regularly published. As with forward-looking applications of other indicators, future developments – for this indicator regarding refining capacity – are uncertain. It has no relevance for nuclear generation.

Load balancing failures: Flexibility margin

In order to respond to fast changes in wind energy production, system flexibility is required. The maximum flexibility required is equal to the coincidence of a maximum decrease of wind output with a maximum increase of demand. This flexibility measure has to be compared to the maximum flexibility available, which is determined by the maximum ramp rate of controllable technologies times their availability and capacity. The flexibility margin indicator compares the maximum flexibility available with the maximum flexibility required, in proportion to the maximum flexibility required (ECOFYS, *et al.*, 2009).

The flexibility margin to indicate the likelihood of load balancing failure aims to assess information about the capability of power systems to mitigate the effects of security of supply shocks. This measure does not account for alternative sources of system flexibility like interconnection capacity, demand response and storage. The indicator warrants the use of assumptions for maximum ramp rates of controllable technologies. The difficulty is to take into account differences in plant availability, i.e. whether the plant is already (partially) used in the system or not, and therefore whether the plant has to ramp from a cold or warm state with corresponding ramping times. Wind production capacity and demand profiles are readily available. The contribution of nuclear power plants to the flexibility margin and therefore to provide system flexibility is very limited as ramping of nuclear power plants comes at prohibitively high costs.

Energy and peak-time interconnector margins

High utilisation rates of existing interconnection capacities may also highlight the need for investments in additional interconnection capacities. Two indicators are available to measure utilisation rates: the *energy interconnector margin* and the *peak interconnector margin*. The energy interconnector margin shows the utilisation of the available capacity across the year and is defined as

total imports per interconnector capacity in a specific time period (ECOFYS, *et al.*, 2009). The peak interconnector margin indicates the “spare” interconnector capacity available at times of peak demand and is therefore defined as imports in peak period/interconnector capacity (ECOFYS, *et al.*, 2009).

Peak/energy interconnector margin indicators provide some helpful insights into the utilisation of network capacity of existing interconnections. Because this information can hardly if at all be linked to price differences between markets, the value of these indicators in indicating whether or not additional interconnection capacity is required is rather limited. In principle, indicator values are transparent, although a certain variation in definitions of peak demand exist, potentially influencing peak interconnector margin results. Furthermore, results may differ significantly to the extent that physical or commercial interconnection capacity is considered. At least in Europe, data is readily obtainable from public domain documents. Interconnector information may be important for nuclear generation as it provides possibilities to export electricity at times of low demand.

Minimum interconnection level

The interconnection capacity can be related to a benchmark that reflects a certain minimum required capacity to mitigate unexpected consequences of extreme, frequently weather-related, events on supply or demand, as well as large unevenness between supply and demand. In the European Union, at the Barcelona European Council in 2002 it was agreed to increase minimum interconnection levels between Member States to 10% of the production capacity at national level [EC, COM (2006) 846 final/2].

The minimum interconnection level indicator provides a raw but useful indication of the extent to which interconnections can level out the consequences of unexpected (weather-related) extreme events and load balancing failures. Measures of network capacities are not unambiguous: both physical and commercial capacities can be used. Data on both physical and commercial capacities is available through (inter)national organisations. As a baseload technology concentrating on one important segment of demand and thus particularly implicated in the international division of labour, high interconnection levels are particularly important for nuclear generation.

2.3.4 Assessment summary

This section presents an assessment summary table of security of supply indicators (Table 2.1) reviewed in the preceding section. The following four criteria have been applied:

- *Usefulness*: the indicator gives a fair reflection of the level of security of supply risk for the security of supply risk aspect considered.
- *Transparency*: the indicator scores are readily interpretable in terms of security of supply risk and are instrumental in ranking distinct country situations (one country for several time periods, or several countries for one period in time), indicator scores are reliable, and the indicator can be used for both historical analysis and forward looking analysis.
- *Data availability*: Information on at least historical performance with regard to the indicator is available from public sources.
- *Relevance for nuclear energy*: The indicator is instrumental in depicting/substantiating the role of nuclear in mitigating security of supply risk.

The assessment on these criteria is expressed in terms of high (H), moderate (M) and low (L).

Table 2.1: A summary assessment of security of supply indicators

Indicator	Usefulness	Transparency	Data availability	Relevance for nuclear energy
Import dependency and diversification				
Import dependency	H	H	H	H
Ratio of net fuel import bill to GDP	H	H	M	H
Reserves/production ratio	H	M	H	H
Resources/production ratio	H	L	M	M
Energy and carbon price volatility	H	H	H	H
SWI diversity index	H	H	L	H
HHI market concentration index	H	H	L	H
Resource and carbon intensity				
Recovery factor	H	M	M	M
Energy loss rate during transportation	M	M	M	M
Generation/conversion efficiency	M	H	H	M
Transmission and distribution losses	M	H	M	M
Fuel or power use per unit of GDP	M	L	H	H
GHG emission per unit of fuel	H	M	H	H
GHG emissions per unit of generation	H	L	M	H
System adequacy				
Power generation capacity margin	H	M	L	H
Energy margin	H	M	L	L
Peak supply shortfall (gas and oil)	H	M	L	L
Must-run baseload power capacity	H	M	L	H
Indicators of investment in supply	L	M	M	M
Adequate transport capacity	H	L	L	M
Storage capacity for fuels	M	M	M/L	M
Share of interruptible contracts	M	M	L	L
Flexibility margin for load balancing	H	M	L	M
Indicators of investment in transport	L	M	M	L
Peak interconnector margin	L	H	M	M/L
Interconnector capacity benchmark	M	M/L	H	M

2.4 Comprehensive models for assessing the security of energy supply

In this section, three modelling approaches of energy supply security are reviewed with special reference to the electricity supply sector. Broadly speaking, modelling approaches to the security of energy supply seek to represent the energy system considered in a more or less comprehensive way under distinct energy scenarios with assignment of subjective probabilities to price risks and/or physical supply disruptions. They thus derive synthetic or integrated security of supply indicators that provide a snapshot of overall security of supply. In the best of cases, such indicators are potentially able to cover the whole supply-demand chain and capture the resilience of the system to react to disruptions and interruptions. In the following, this section will focus on:

- the Markowitz portfolio theory applied to the electricity supply mix;
- power system reliability modelling; and
- other modelling approaches.

Within the current project, a variant of the S/D modelling approach is used for empirical analysis that will be presented in Chapter 3. For that reason, the S/D is presented separately in Section 2.5 of this chapter.

2.4.1 Markowitz portfolio theory

Some sixty years ago, Harry Markowitz laid the foundations of mean-variance portfolio (MVP) theory in his seminal paper on portfolio selection, applied to portfolios of financial assets (Markowitz, 1952). The essential idea of this theory is that, in a financial world full of unexpected positive and negative surprises, it is in order to *rebalance portfolios into well-diversified ones* to neutralise non-systemic risk, associated specifically with single assets. The neutralisation of non-systemic risk is the so-called *portfolio effect*. This would leave such re-balanced portfolios only exposed to (systemic) market risk, affecting – if to different degrees – all risky assets. In heeding this prescription, the *efficient frontier* can be reached. These are the points of efficient portfolios yielding highest expected returns for various levels of risk.

The choice of a particular efficient portfolio as represented by a particular point on the efficient frontier would then depend on the preferences of the investor regarding the trade-off between portfolio return and portfolio risk. Crucial parameters for MVP analysis are the expected returns on individual assets, the expected risk (standard deviation⁹) associated with each of these returns, and the expected pair-wise covariances for all pairs of these returns. Most analysts determine the values of these parameters on the basis of time series analysis of historical performance data, consistent with the dictum that “history is a good predictor of the future”. We note that Markowitz himself and associates do not exclude the setting of different values if analysts have good reasons to deviate from historical values (Fabozzi, *et al.*, 2002).

Dan Bar-Lev and Steven Katz were the first researchers that applied Markowitz portfolio theory to the fuel mix of the electricity supply industry in nine United States regions, with multi-fuel power plants dominating the electric utility industry. They published the results in an article published in the *Journal of Finance*, the most prestigious periodical of finance theory (Bar-Lev and Katz, 1976). Bar-Lev and Katz defined *the reciprocal of average fuel cost per unit of energy input per annum* as return indicator and the standard deviation of a 17-years period time series for this indicator as risk.

Independently, Shimon Awerbuch later pioneered a similar application of Markowitz portfolio theory in the form of a country’s portfolio of generating assets considered from a social (cost) perspective (Awerbuch, 2000; Awerbuch and Berger, 2003). Awerbuch’s pioneering work drew much attention and following. Awerbuch defined the reciprocal of the LCOE as return but conflated the risk definition with the one pertaining to portfolios of financial assets, so as to express it in percentage terms. Building on this work, Jansen, Beurskens and van Tilburg have used for a similar type of analysis the standard deviation of the reciprocal of LCOE as a risk indicator instead (Jansen, *et al.*, 2006).

Shimon Awerbuch developed some powerful ideas. First of all, the conventional procedure to consider the LCOE of different power generating technologies on a stand-alone basis in power system expansion planning leads to an inefficient portfolio of generating assets. This results from ignoring the risks surrounding the LCOE estimates of different generating technologies and how these risks are mutually correlated. This can lead to inefficient risk-return portfolios, as the maximum return for given levels of risk will as a rule not be realised.

9. At the time that Markowitz wrote his seminal paper that earned him the Nobel price, variance as an indicator of risk was in vogue. Evidently, standard deviation is a simple (square root) transformation of variance.

Second, when departing from a situation of an existing inefficient portfolio, investing in capital-intensive but low-recurrent-cost generating assets can help to achieve lower expected portfolio cost of electricity at given level of expected risk. This may even hold for high-LCOE low expense technology. Notably gas-based and to a lesser extent coal-based generating technology is high expense technology. Internalisation of the cost of carbon emissions will reinforce the high expense character of fossil-fuel based technologies. Both fossil fuel prices and the price of carbon are quite volatile and consequently high risk. Conversely, renewable energies and nuclear power are low expense technologies. From a social perspective, apart from risks during the construction period, the latter technologies tend to have low (LCOE) cost risk, unless they are technologically immature. In conclusion, Markowitz portfolio theory can be fruitfully applied to demonstrate the portfolio effect of adding nuclear to a given (large) portfolio of generating assets from a social perspective.

Fabien Roques *et al.* developed the application of Markowitz portfolio theory to optimisation of power generating portfolios from a private utility perspective (Roques, *et al.*, 2006a). This enables large utilities to duly allow for the portfolio effect benefits of generating portfolios which includes generating technology with quite different cost and cost risk characteristics such as nuclear in comparison with portfolios dominated by “the dash for gas”. The pervasive assumption of risk management officers that the gas price risk can be largely passed on to the customers on account of revealed strong correlation between the price of gas and the price of electricity might prove costly once the gas market turns from a buyers’ market to date into a sellers’ market.

Markowitz portfolio theory applied to energy-related portfolios is a promising research area in need of further elaboration. Aspects in need of further strengthening include the transformation from one-period analysis into multi-period analysis building on recent work in this regard, research to improve the credibility of covariance matrices used, and segmentation of baseload, mid-load and peak-load technology. As stated above, Markowitz portfolio theory can help to duly appreciate diversity benefits that nuclear can bring in to portfolios of generating assets.¹⁰

2.4.2 Power system reliability modelling

In general, power systems are oriented towards providing a reliable and affordable supply of electrical energy to their customers. For that aim, analysis of future system operation is performed by system operators. Since system operation is stochastic in nature, the assessment of power systems should be based on models and techniques that respond to this behaviour, i.e. probabilistic models and techniques (Billinton and Allan, 1996). Probabilistic assessments attempt to quantify the likelihood, frequency, duration and severity of system inadequacy or security breaches (Billinton and Li, 1994). This section concentrates on the decision analysis model for security of supply issues in such a probabilistic context developed by Henk C. Wels while at KEMA (Wels, 2008; and 2009).

Modelling framework

Wels interprets security of supply as the ability to prevent blackouts of the power system as a result of events in which electricity demand is not met by supply. Such an event may be caused either by a physical interruption or disruption of production and/or demand or by a network disturbance. Examples of the former include a problem with the fuel supply of power plants, or a high demand

10. See for instance (Roques, *et al.*, 2006b).

growth which is insufficiently accommodated for by increasing supply. A network disturbance may occur for instance due to failures of grid components or external events (weather, terrorism or other “force majeure” incidents). Special attention has been paid to physical interruptions which can be related to the deployment of different production technologies (nuclear, gas, coal). Comparison of the frequency and impact of these interruptions provides information of the relative position of nuclear energy with respect to reliability.

To account for the probabilistic nature of future system operation, the study analyses a wide range of possible security of supply situations with help of a decision analysis model.¹¹ This model builds upon a probabilistic analysis of different future situations concerning security of supply. Among others, the Monte Carlo method is applied to generate random numbers for different input data within a given uncertainty frame. Regarding the distribution of input data a triangular distribution is chosen. The basis of the model is the probability of a gap between electricity demand and supply which cumulates in a blackout of the power system.¹²

The analysis consists of three steps. First, influence diagrams are drawn together with energy sector experts. These diagrams show the gap between electricity demand and supply as a function of demand, grid related power curtailments and production capability respectively. The diagrams are summarised together in Figure 2.3. Figures 2.4 and 2.5 show the influence diagrams for the demand side and supply side respectively, including most important drivers and underlying input factors (for example, energy saving consists of both current and expected energy savings effects).

Second, output variation due to variation of a range of input factors is determined through programming the diagrams in an Excel spreadsheet. Inputs may be either certain (i.e. depending on assumptions taken), for instance a decision on the time window to apply, or uncertain (i.e. to be handled in probabilistic terms). Two categories of probabilistic input factors are taken into account. Firstly, the occurrence of problems related to fuel supply, generic production design problems and licensing problems are reflected in mean time between occurrences (MTBO). Likewise for the transport sector, grid problems are reflected in mean time between failures (MTBF).

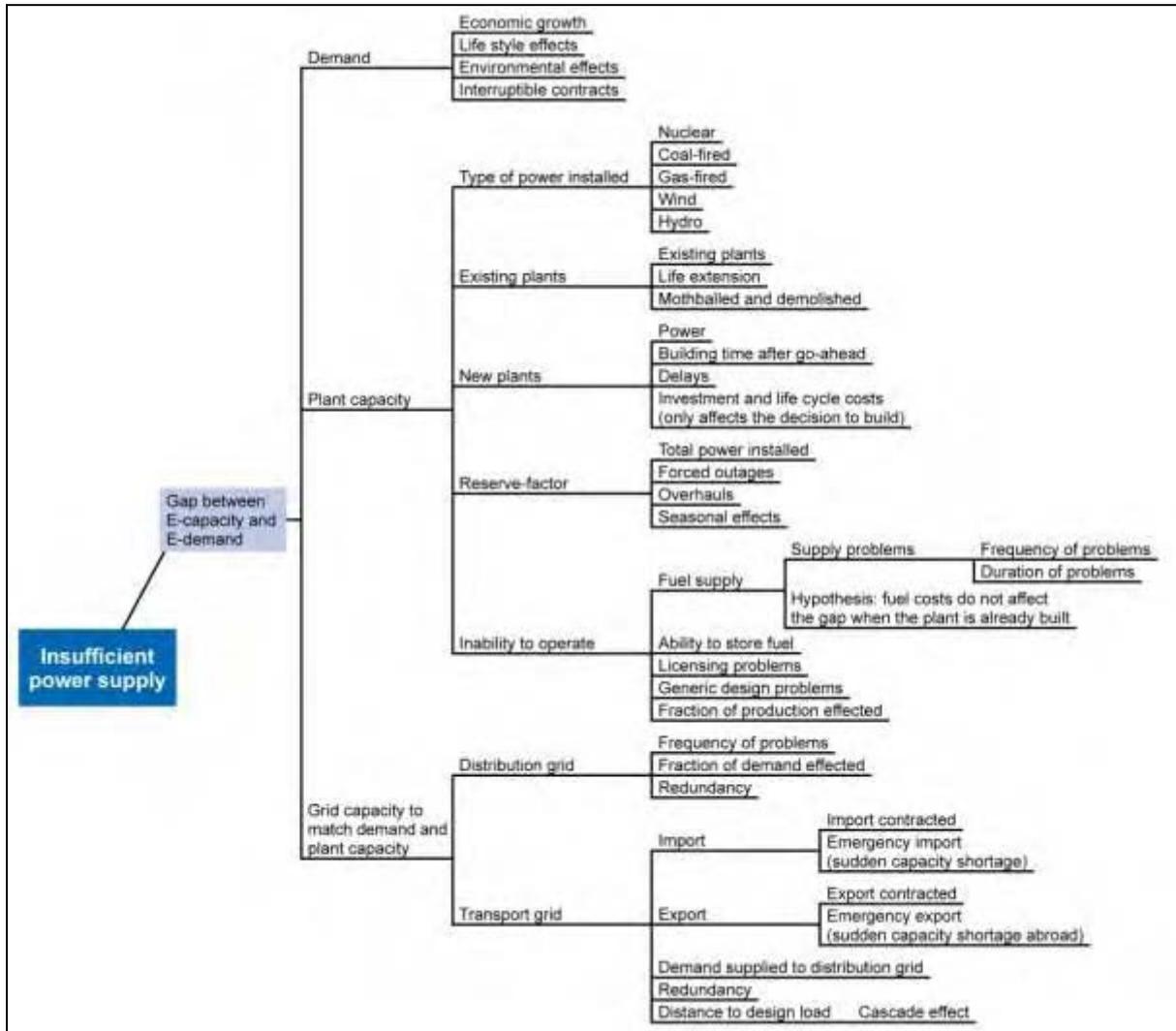
Third, the gap between production and demand, based on the analysis of the three influence diagrams, is combined with three factors: decisions on blackout factors, discount effect and time window considered.

These three elements determine together the blackout probability. In order to calculate the blackout probability for a huge number of different situations, probabilities have been attached to input factors in two ways, either deterministic or probabilistic. In a first step, a low, base or high value can be chosen for each input parameter. By using a special macro, one variable is changed at a time in a deterministic sense. This results in a Tornado diagram that ranks the results of the preceding single-factor sensitivity analysis. In a next step, using the Excel-based Palisades @RISK programme, a Monte Carlo value is drawn from a triangular distribution with low, base and high values having a 10%, 50% and 90% probability. Also with @RISK a Tornado diagram in a somewhat different form is generated.

11. The model was set up along the lines of the model of the Stanford University’s Strategic Decision Group.

12. It is assumed that plants that are commissioned at the time under question will be operated unconditionally in order to prevent a blackout or power cut regardless of costs.

Figure 2.3: An overview of factors susceptible to causing insufficient power supplies



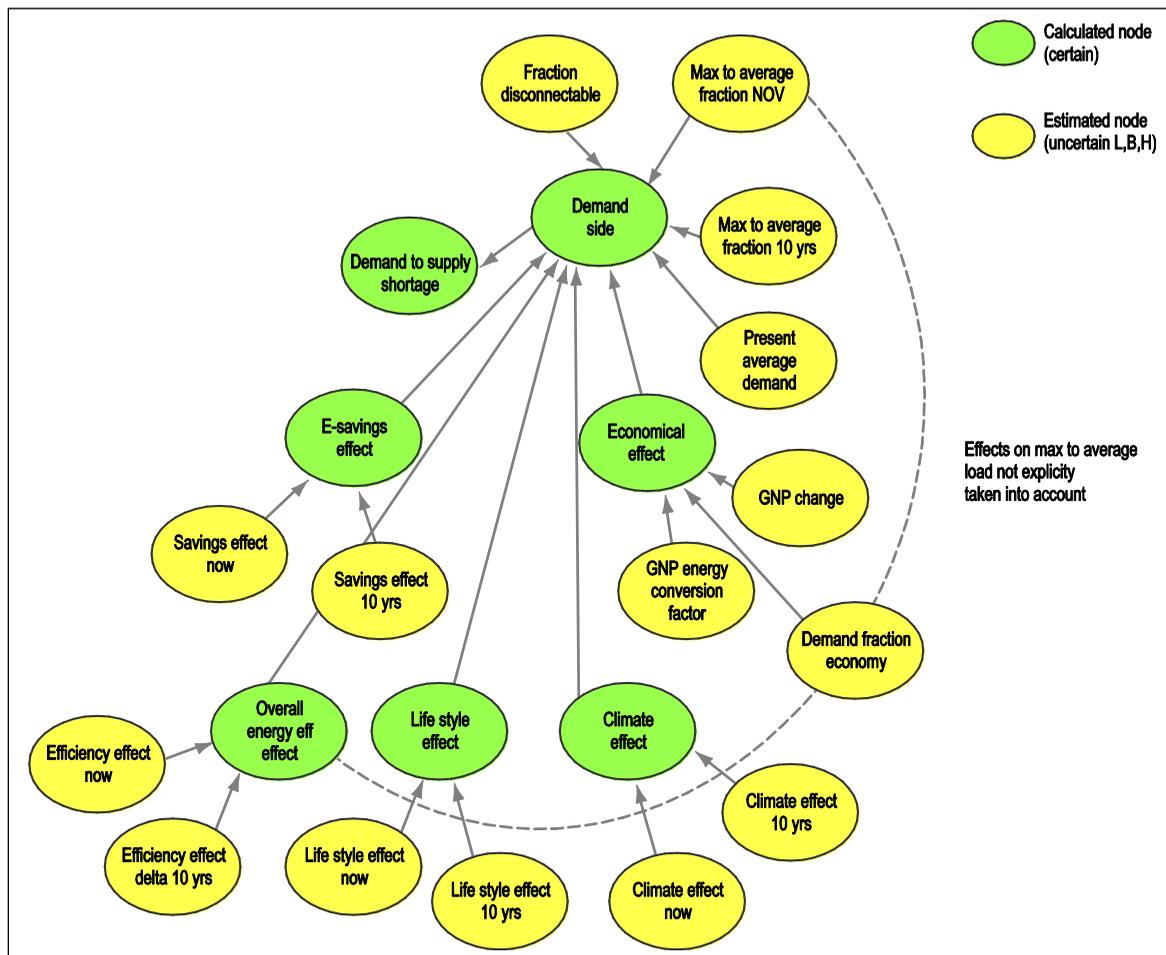
Source: Wels, 2009.

Reliability results for different production technologies

This section deals in more detail with the relation between reliability and different production technologies including nuclear generation. As a proxy for reliability, the difference between demand and available production capacity is analysed for different production technologies. Available production capacity differs between production technologies due to differences in fuel supply or input availability, generic plant design characteristics/problems, and licensing issues. With respect to fuel supply or other input availability, gas-fired generators may face fuel delivery problems, whereas wind turbines may face bad wind conditions, and nuclear power plants problems with waste removal and unavailability of enrichment services. However, nuclear plants have the inherent capability to be less vulnerable to fuel supply problems because of the storage duration of the fuel in the reactor core as

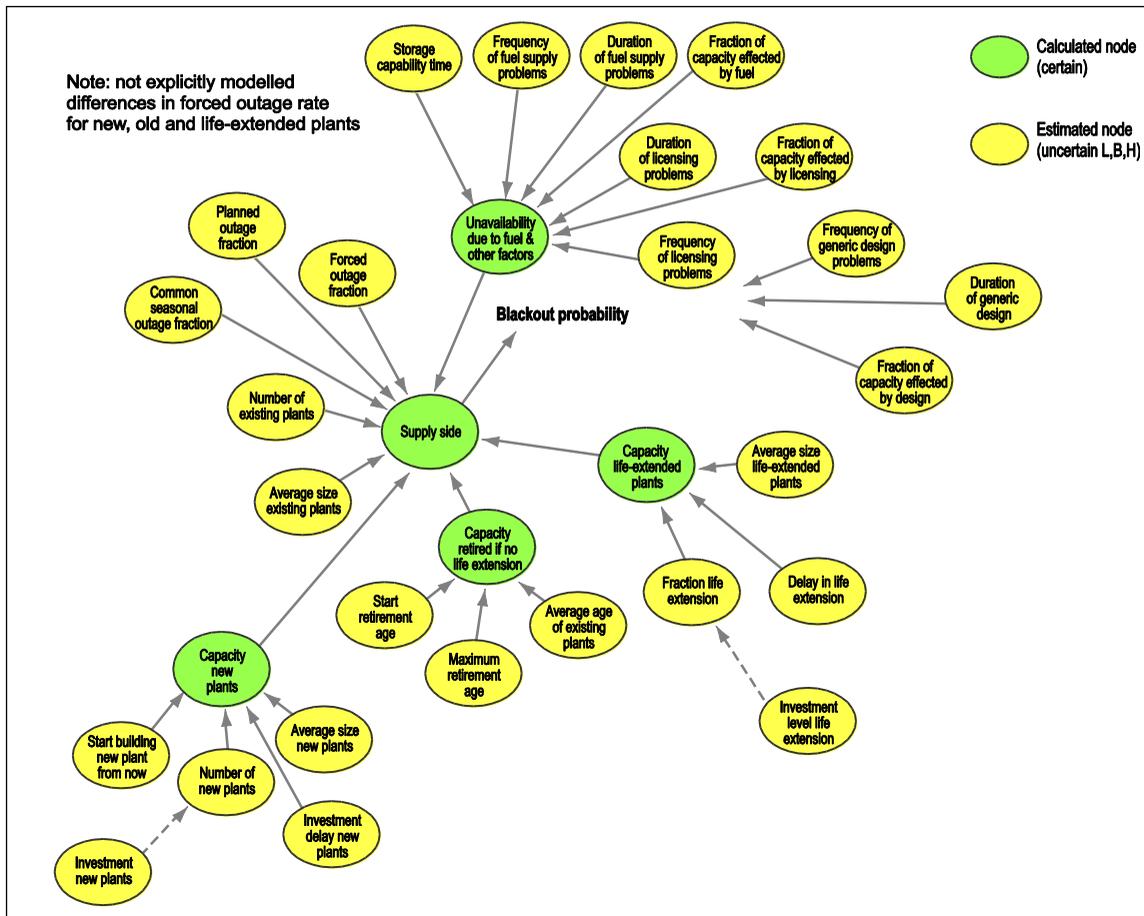
well as storability of fresh fuel and spent fuel capable to be recycled. Also, in the fuel manufacturing process, a considerable amount of fuel materials are stored as running stocks in the “pipeline”. Coal fired plants in general have storage capabilities either at the plant itself or in transportation basis.

Figure 2.4: Causal influences on the demand side



Source: Wels, 2009, adapted by the authors.

Figure 2.5: Causal influences on the supply side



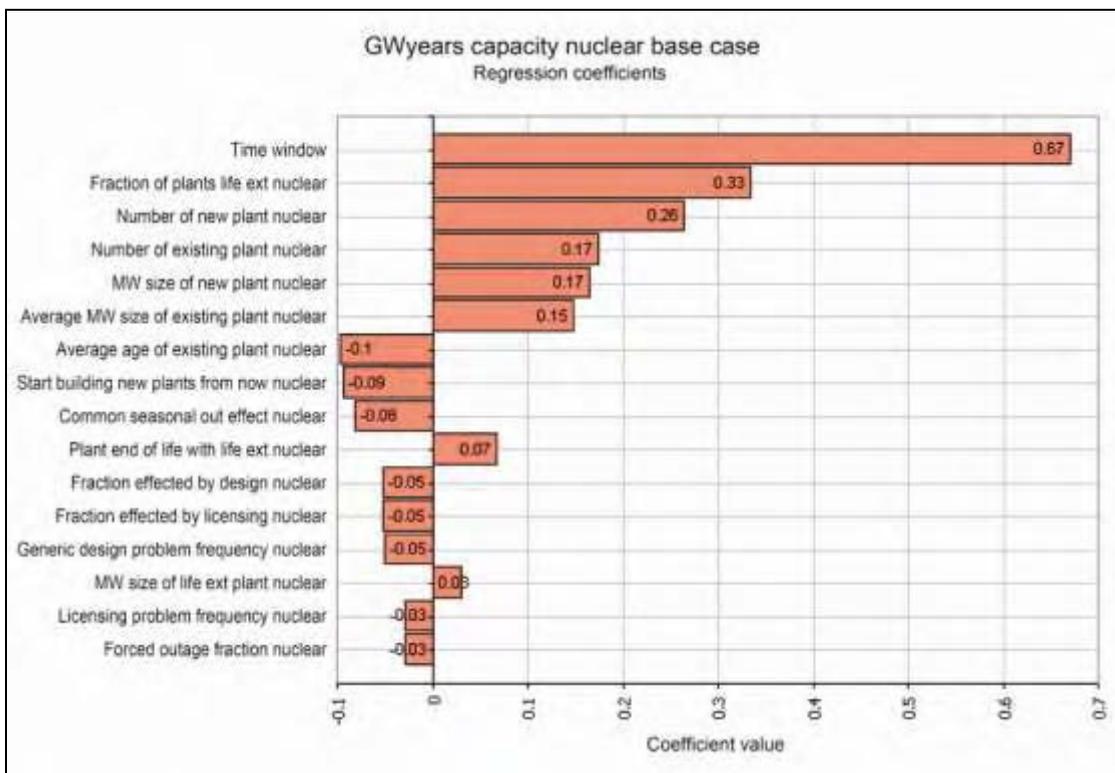
Source: Wels, 2009.

Most gas-fired plants have no storage capabilities at the plant itself, although storage in oil or gas fields may be present (only in some countries, limited storage capacities for LNG are installed at power plant sites). While many coal fired plants are able to fire gas or oil as well, the modern gas turbines in gas-fired combined cycle plants do not allow dual fuel capability (both gas and oil). However, they may be adapted (requiring additional system modifications like blade coating changes) if the frequency of occurrence and the duration of problems is large enough to justify such investments. Generic plant design problems may make a power system vulnerable when the type of generation plants is not very diversified; for instance in France two types of nuclear units form the majority of the production assets. Finally, some technologies (both coal-based and nuclear technologies) meet more public opposition during the licensing process than for instance gas-fired and/or combined heat and power (CHP) plants.

Fuel supply, generic plant design and licensing issues are technology-specific model inputs. Fuel supply effects were modelled by defining a fuel storage time (in weeks) in combination with an exponential distribution for problem frequency. This allows calculating the fraction of supply interruptions longer than a certain duration threshold. Likewise, for generic plant design issues and licensing issues, technology-specific problem frequencies, duration and fractions of generation effected were defined.

Concerning nuclear generation, based on Monte Carlo analysis a Tornado diagram for power production by nuclear plants is generated and shown in Figure 2.6. The diagram shows the correlation of the nuclear production capability with a number of potential explaining factors. Among others, it shows that capacity summed over the years is a function of the time window applied. The larger the time window, the larger is production capacity. A regression coefficient, similar to the often used correlation coefficient, shows the dependency of the results from the time window (0.67). The summed capacity is mainly defined by life time extension of existing plants, the number of new plants per year, the year that construction actually commences, etc. As is evident from the Tornado diagram, with the inputs used, fuel supply problems do not affect the nuclear production capability. Generic design problems and licensing problems are very small.

Figure 2.6: Nuclear power capacity as a function of different risk factors



Source: Wels, 2009.

These results are compared with the results for other production technologies (coal, gas, etc.). Based on three possible scenarios (base case, high nuclear and low nuclear) the correlation between the total number of failures due to a technology-specific incident and available production capacity (as proxy for the blackout frequency) has been calculated as shown in Table 2.2 below.

Table 2.2: Different factors cause failures for different power generation technologies
(Correlation coefficients)

	Nuclear part of generation			Gas-fuelled part of generation		
	Supply	Licensing	Generic design	Supply	Licensing	Generic design
Base	0.056	0.136	0.146	0.114	0.079	0.112
High nuclear	0.037	0.137	0.193	0.066	0.093	0.102
Low nuclear	0.056	0.123	0.165	0.098	0.081	0.162

Source: Wels, 2009.

Table 2.2, for instance, shows that for nuclear power plants blackouts are less related to supply problems than is the case with gas-fired power plants. However, nuclear generation faces more problems related to licensing and generic plant design issues than gas-fuelled generation. These results are subject to a number of qualifications.

For instance, it is unclear how input factors are selected and the bandwidth of values is determined, whereas assumptions for input factors shape the size of the contribution of each factor to the (intermediate) indicator results. There is also no calculation of the overall contribution of different sectors to the blackout probability and thus no real indication of the effect on security of supply. Only the contribution of factors to intermediate indicators was calculated. Finally, the analysis does not account for strategic behaviour of market participants since it is assumed that all power plants are available, i.e. no withholding of capacity.

The strongest limitation of power system reliability models, however, remains the assumption that power system can be stylised in a near complete probabilistic fashion. This renders these models unsuitable for forward-looking analysis with long-term time horizons. Nevertheless, by highlighting a number of stylised facts, decision analysis models as the one above can be useful inputs for starting broader discussions on the issue of energy supply security.

2.4.3 Other modelling approaches

This sub-section presents a number of idiosyncratic approaches to modelling security of supply risks, most of which have been developed in the context of the NEA Expert Group on Nuclear Energy and Security of Supply. Each one of them reflects the different national and institutional contexts in which they were developed. Naturally, they also reflect the methodological and policy priorities of their respective authors.

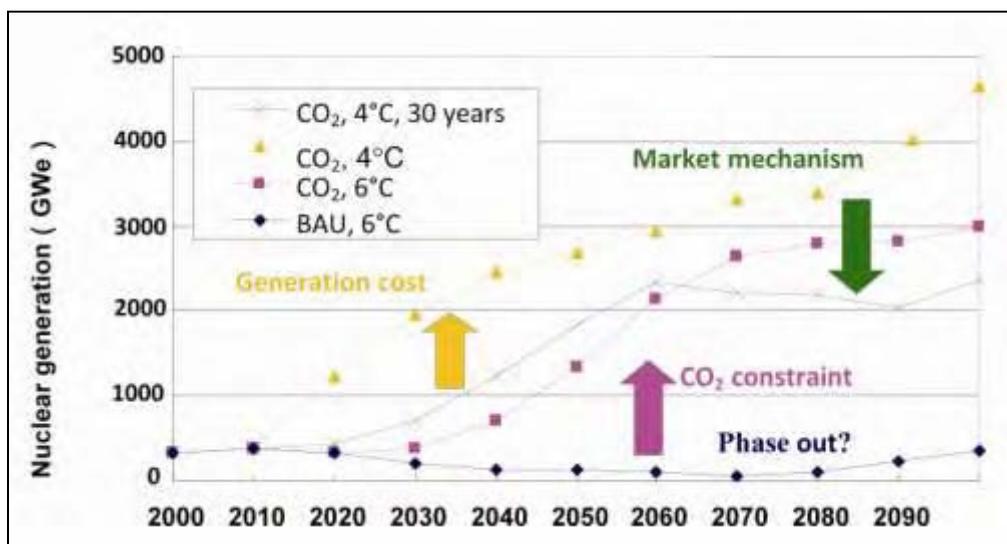
Modelling energy supply security in a carbon-constrained energy future

Hiroshi Ujita from the Tokyo Institute of Applied Energy discusses the *Role of Nuclear Energy in Environment, Economy, and Energy Issues of the 21st Century* from a global CO₂ emission reduction perspective (Ujita, 2007). In striving for CO₂ emission reduction, further constraints to the deployment of fossil-fuel-based, CO₂-emitting generation seem inevitable. Therefore the contribution of generation

sources able to contribute to both security of supply *and* climate change mitigation is key. The paper considers nuclear energy as indispensable to contribute to both climate change mitigation and effective use of limited fossil resources. The primary focus of the study is on the fuel diversity aspects of security of supply. In this respect, the potential contribution of nuclear energy in the generation mix of countries is taken into account both by the cost consequences of plutonium scarcity and the possible impact of terminating the non-proliferation treaty on the growth of nuclear power among regions. Termination of the treaty means abandoning interregional trade of plutonium, and as a consequence self-sufficiency of plutonium, which implies a change in the growth rate of nuclear power.

The study then models the development of global nuclear power under different scenarios with different assumptions about climate change policy with CO₂ constraints implied by different temperature increases, market structure and policy-making horizons of either 30 or 100 years (Figure 2.7).

Figure 2.7: Global nuclear development under different scenarios



Source: Ujita, 2007.

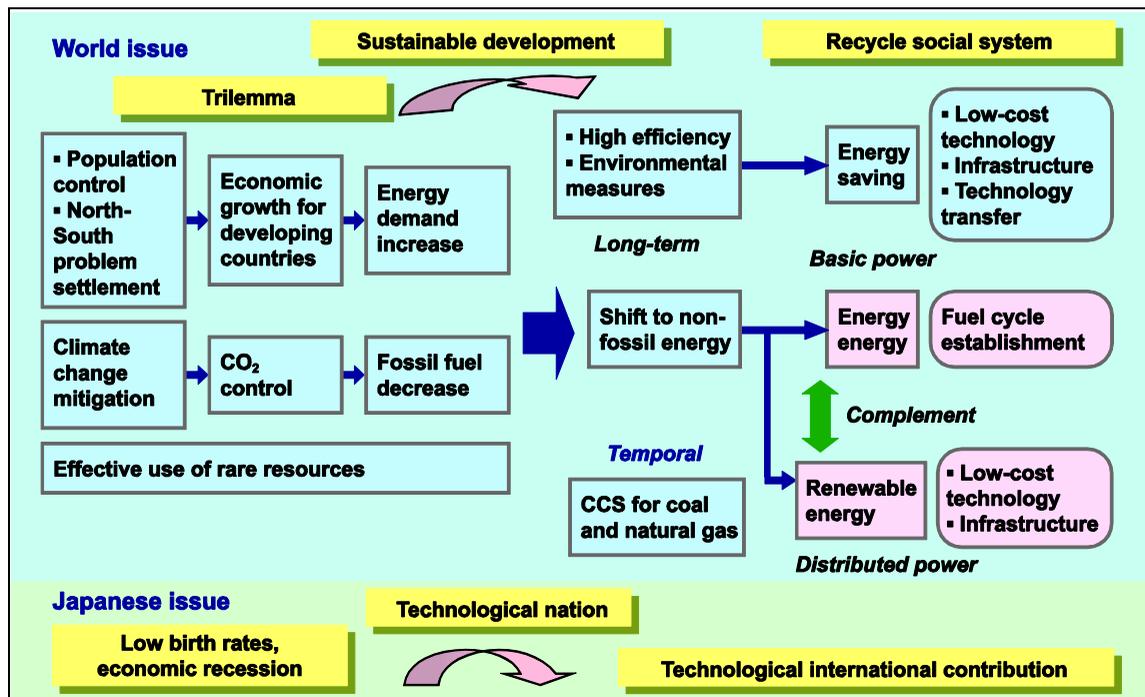
These different factors are included in the modelling framework. The model aims at long-term minimisation of total energy system costs from today to the year 2100 subject to a CO₂ constraint. Total energy system costs vary by region and year and are then optimised in order to attain global and long-term energy costs minimisation. Region and year-specific costs are summed up, accounting for the time-value of money by discounting future energy system costs.

Energy system costs are composed of production costs, transport costs, royalties, conversion costs, distribution costs, and a number of CO₂-related costs. All these costs depend on the kind of energy sources for each region and year. Energy sources are distinguished in exhaustible and renewable energy sources. Exhaustible energy sources are natural gas, oil, and coal; renewable energy sources are biomass, wind, hydropower, geothermal and photovoltaic.

These energy sources are deployed for three distinguished purposes; electricity, transportation, and heat. It is assumed that the costs of exhaustible energy increase linearly with the cumulative consumption, whereas the costs of renewable energy increase as the annual amount of renewable energy consumed grows. Special attention is paid to the possible role of nuclear energy under two different CO₂ emission constraints, and different nuclear cost conditions related to the available amount of plutonium and whether or not the nuclear non-proliferation treaty prevails. A concluding

figure highlights the great complexity of which long-term strategic energy choices need to take into account (see Figure 2.8).

Figure 2.8: Global environmental and resource issues and resulting energy perspectives



Source: Ujita, 2007.

The Hungarian fuzzy logic model

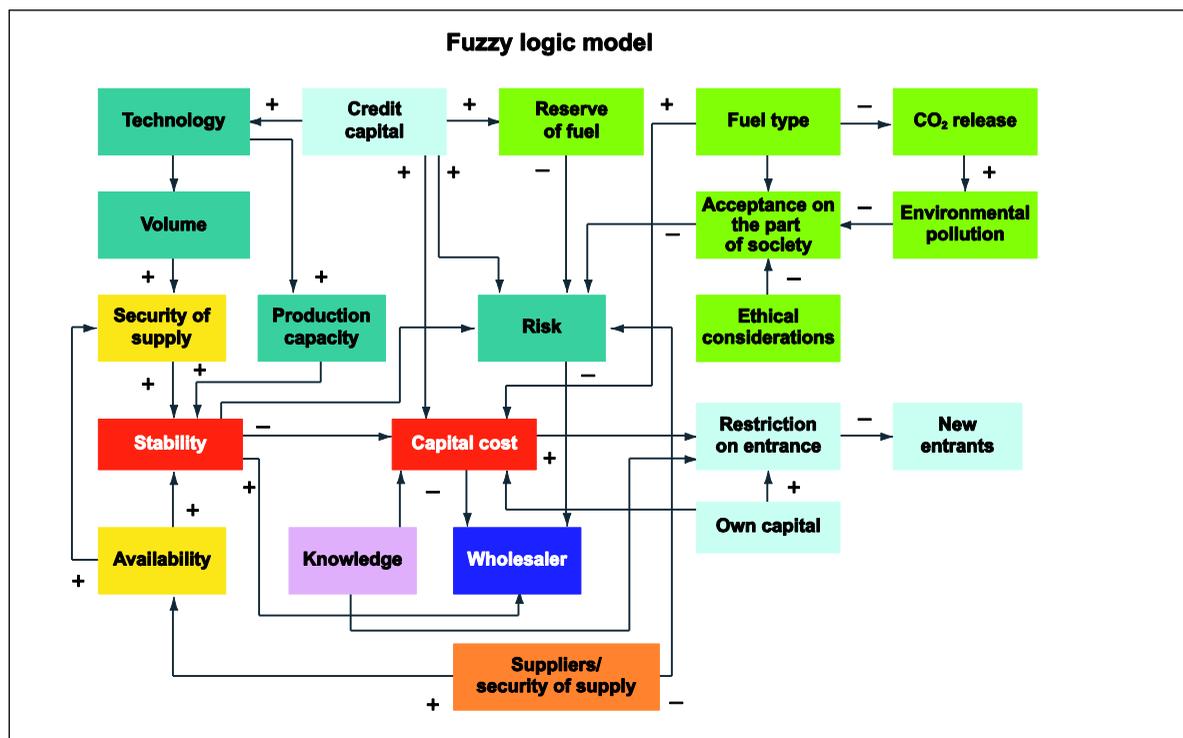
The energy system of a country is operated and developed under the influence of changes in the economic, societal, technological, environmental, political, legal and international environment. A large set of different factors contribute to the current level of security of energy supply. Supply security is mostly influenced by a set of these factors rather than by one single factor. Examples of factors include price fluctuations, energy policy debates, changes in country energy policies, market developments, bilateral or multilateral agreements for international energy transits, as well as system brownouts and blackouts. The fuzzy logic model tries to identify the extent to which these qualitative factors influence security of supply. The model combines information theory with argument mapping, fuzzy logic and neural networks to find the dominant explaining factors for the current level of security of supply in Hungary.

As a first step, logical relations between variables are derived using argument mapping, which is a visual representation of the structure of an argument in informal logic. The results of argument mapping are postulated in the logical model in Figure 2.9 below.

As a second step, information on all aspects contributing to security of supply is collected in a database, by using information of technical reports, journal articles and news from the mass media in Hungary for the period January 2005-December 2007. This concerns information about 600 events in the Hungarian electricity system. Dominant factors of these events can be derived by using fuzzy or approximate reasoning, i.e. qualitative information of past events are used to estimate uncertainties

(through probabilities) and tolerance (through spread). The number of system blackouts and brownouts are assessed through probabilities modelled by Monte Carlo simulations.

Figure 2.9: Underlying model of the Hungarian energy sector



Source: Hauszman, 2008.

In order to identify correlations between events and resulting actions by market players, primary events were grouped into categories corresponding to different aspects for supply security. All the events are linked to one or more boxes of the logical model showed above, and each box represents certain risk to the operation of the energy system. The extent to which an event influences the operation of the energy system is calculated, applying the SWI (see Section 2.3.1):

$$SWI = - \sum_i (p_i) \ln p_i$$

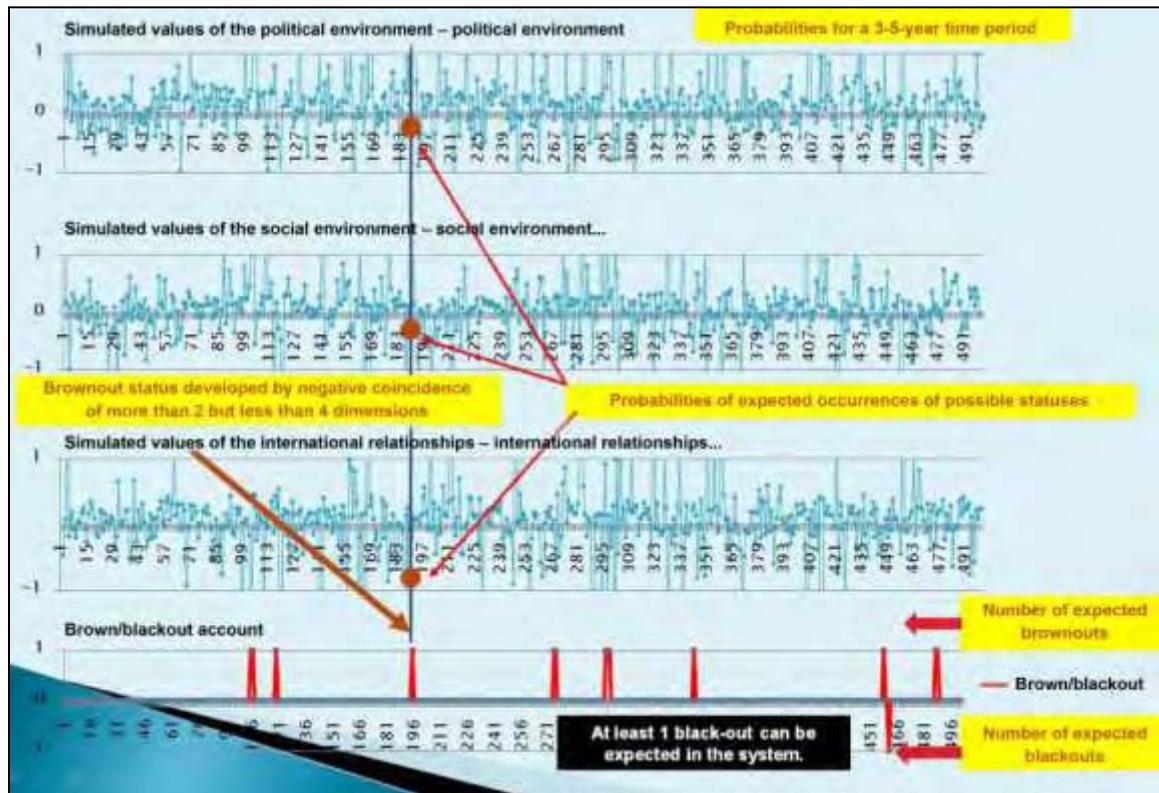
where p_i in the Fuzzy logic model context denotes the share of the influence group in the total database.

The registered events in the database, the groups formed from the initial set of events recorded and the dimensions (the economic, social, legal, technological, environmental, political and international environment) are finally structured in a three-layer neuron fuzzy model using Monte Carlo simulation to retrieve the probabilities of positive and negative outcomes in all dimensions as a function of time. Blackouts in the energy system are defined as simultaneous occurrence of negative influences for all dimensions as shown in Figure 2.10.

The Fuzzy logic model has a number of advantages and disadvantages. One advantage is that the model allows for better understanding of correlations of drivers of security of supply. Furthermore, the processing and evaluation of past events makes it possible to carry out simulations for the future at initially defined different risk levels. From these simulations, the frequency of blackouts and

brownouts can be derived. Another advantage is that the model is not a product of an engineering approach; it contains *a priori* no initial considerations, preconceptions or pre-defined probabilities. The model is constructed flexibly, based on the information on the relationship between the most influential factors captured throughout the data collection process.

Figure 2.10: Simulating brownouts and blackouts in the Hungarian electricity system



Source: Hauszman, 2008.

The advantage of a flexible modelling construction, however also means that the model only provides a general indication of security of supply, since it does not identify which part of the energy chain has the highest impact on blackout probabilities. Furthermore, there is a need for extensive data collection making comparisons between countries difficult. Next, events with dramatic consequences are hard to recognise in their initial phase, although manual intervention through re-coding the importance is possible. Another disadvantage is that the value of the model critically depends on the information gathered. Information of mass media may not cover the whole story, as mass media are geared to lay readers. Therefore, mass media provide an incomplete indication of correlations between events and resulting actions. Finally, human interpretation of specific events could influence data processing and the results of the assessment, although this can be reduced somewhat through expert participation.

The CRIEPI approach to security of supply modelling

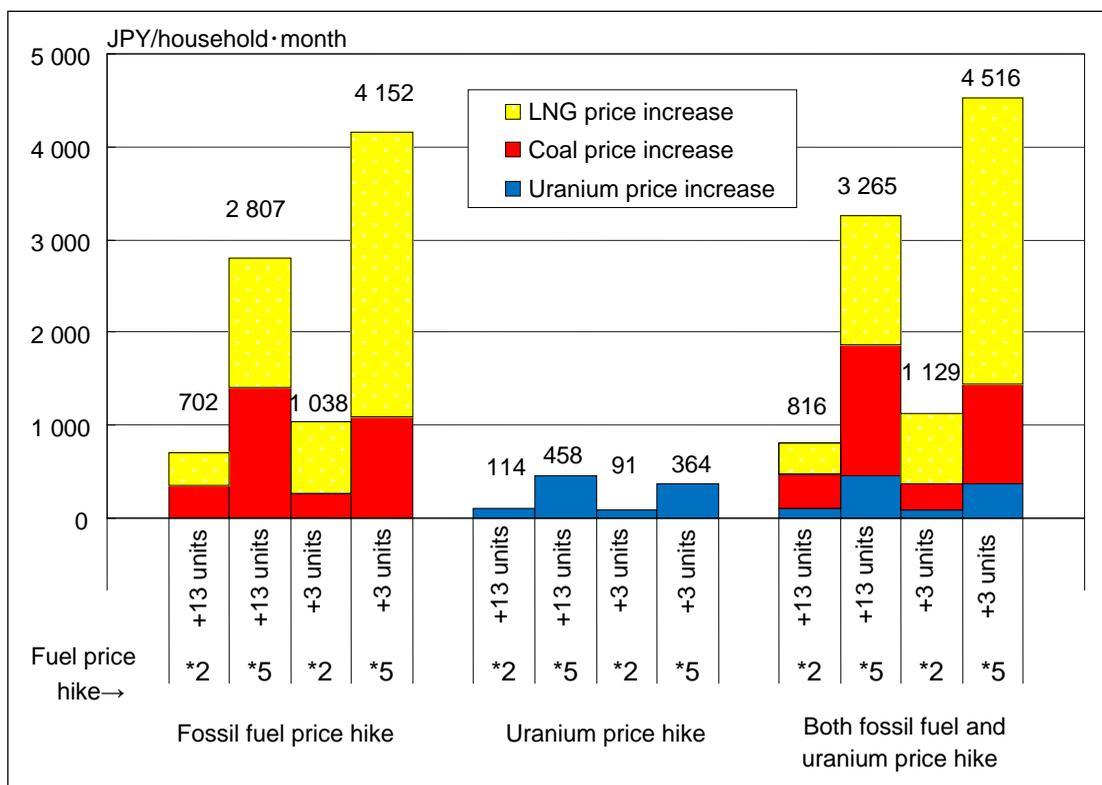
In the Japanese context, i.e. a fairly isolated island country with scarce primary energy resource endowments, the modelling of energy security naturally focuses mainly on issues like import dependence, the reliability of global trade patterns and energy markets as well as the socio-political stability of exporting countries. The CRIEPI presented a set of approaches to address those issues,

with special attention to the importance of nuclear energy in enhancing Japan’s energy security. Among the security of supply aspects evaluated were included cost effectiveness and fuel reserves, besides reducing national CO₂ emissions. Both aspects are described below (Figure 2.11).¹³

An economic model, either a power-system model encompassing power generation sector alone or a macro-economic model covering the whole national economic and industrial system, can illustrate the value of nuclear energy used at an order of magnitude by comparing results of the two cases with nuclear power and without. Nuclear energy in the Japanese situation decreases fossil fuel imports and total power generation costs, which consequently boosts national macro economy by stimulating consumption through increased investment and lower consumer electricity prices.

The simulation of Japan’s optimal power generation mix up to the year 2030 showed that, in the case of fossil fuel price doubling over the base case settings, the average generation cost in 2030 will rise by 2.3 JPY/kWh in the baseline case when 13 nuclear power reactor units are added as currently planned, and by 3.5 JPY/kWh if the addition is limited to the 3 units currently under construction or in preparation, respectively. When the price hike of fossil fuel is as much as 5 times, the magnitude of the generation cost increase goes up to 9.4 and 13.8 JPY/kWh respectively. Multiplying these figures with an average consumption of 300 kWh per month for a household shows that the addition of 10 nuclear power units results in a 30% lower increase of additional expenditures.

Figure 2.11: The impact of fuel price increases per average Japanese household in 2030



Source: Nagano, *et al.*, 2008.

13. One additional aspect, procurement stability, i.e. energy security market concentration has already been dealt with before in the description of market concentration indicators.

A comparison of the costs of fuel reserves between different generation technologies brings out the passive reserve effect of nuclear fuel. Since nuclear units can run for at least one year without refuelling, this buffering time can be understood as a passive fuel reserve. Primary fuels stored in the “pipeline” of fuel production processes, as well as spent fuel stored, may also correspond to a few years of fuel supply and thus gives additional years to the reserve effect. This reserve effect then may be evaluated in comparison with oil reserve or other forms of energy stockpile in terms of energy quantity stored and corresponding costs.

Economic model-based approaches require rather extensive efforts in model development as well as in data acquisition. The virtue of these models is their inter-temporal analytic capability as well as the ability to carry out sensitivity analyses, such as for instance the impact of fossil fuel price hikes. As long as the embedded numerical functions are kept transparent, the model results can be fairly related to the underlying model assumptions. These models can generate valuable information on the prospective cost-effectiveness of nuclear as well as its contribution to future supply security.

The Crisis Capability Index

The Crisis Capability Index (CCI) reflects the capability of a country or region to manage and mitigate sudden short-term energy supply interruptions. The indicator aims at identifying short-term actions that can obtain results within weeks rather than months. The indicator combines an assessment of a member country’s risk to be confronted with sudden supply interruptions and its potential impacts, the risk assessment (RA), and the capability of that country to mitigate these impacts, the mitigation assessment (MA). If the risk is high, more emphasis should be put on effective crisis capabilities than when this risk is low.

For assessing risks of sudden and unforeseen supply interruptions the main elements of the energy system are considered. Table 2.3 shows a checklist for risk assessment for sudden supply interruptions. The different elements of the energy system are grouped into five categories covering energy production, import, conversion and transport. For each element of a specific category three types of risks are distinguished: (1) technical and organisational factors; (2) human and political factors (including human failures and deliberate actions such as terrorist attacks); and (3) natural events. Each individual cause for a sudden supply interruption risk listed in the checklist should be assessed on the basis of the probability of such a risk and the impact of this risk on the energy system and on society. The risk can be valued with a figure indicating: no (0); low (1); medium (2); or high risk (3). Not all energy system elements are of equal importance in a country’s energy supply. Therefore, for each element the risk assessment score is multiplied, dependent on the category, by the relative share in primary energy sources (PES), final energy demand (FED) or total energy import. Adding the individual values together and multiplying the total by 100/48 results in the risk assessment sub-index (a value between 0 and 100).

Measures to mitigate short-term sudden supply interruptions are in place in many OECD member countries. This is partly due to international commitments such as the IEA Treaty and partly due to national contingency planning. Such measures can be summarised in five groups: (1) strategic or emergency stocks; (2) demand restraint including rationing; (3) fuel switching capabilities; (4) reserve capacity; and (5) locked-in production capacity. Table 2.4 shows the checklist that can be used to assess the mitigation measures. If a measure is implemented this measure will be rated with “1”; if it is not available the value will be “0”. The value will become “2” if the measure is implemented and tested, i.e. the measure should have been demonstrated in practice or procedures should have been tested. The scores are again multiplied by the relative share in PES or FED similar as in the Risk Assessment checklist. The value of this MA sub-index can be calculated when the total score of the checklist is multiplied by 10, resulting in an index value between 0 and 100.

Table 2.3: Checklist for the risk assessment (RA) of sudden supply interruptions

Category	Element in energy system	Risk factor	Weight 1)	Score 2)	Value	
Domestic primary energy production	Domestic oil production	Technical/Organisational factors	Norm. share oil in total PES production	w1	0-1-2-3	v1
		Human/political factors			0-1-2-3	
		Natural events			0-1-2-3	
	Domestic natural gas production	Technical/Organisational factors	Norm. share gas in total PES production	w2	0-1-2-3	v2
		Human/political factors			0-1-2-3	
		Natural events			0-1-2-3	
	Domestic coal (solids) production	Technical/Organisational factors	Norm. share coal in total PES production	w3	0-1-2-3	v3
		Human/political factors			0-1-2-3	
		Natural events			0-1-2-3	
	Domestic renewable energy production	Technical/Organisational factors	Norm. share renewable in total PES production	w4	0-1-2-3	v4
		Human/political factors			0-1-2-3	
		Natural events			0-1-2-3	
Energy conversion	Power plants	Technical/Organisational factors	Norm. share electricity in total FED	w5	0-1-2-3	v5
		Human/political factors			0-1-2-3	
		Natural events			0-1-2-3	
	Refineries	Technical/Organisational factors	Norm. share oil (proxy transport fuels) in total FED	w6	0-1-2-3	v6
		Human/political factors			0-1-2-3	
		Natural events			0-1-2-3	
Inland energy transport	Gas pipelines	Technical/Organisational factors	Norm. share gas in total FED	w7	0-1-2-3	v7
		Human/political factors			0-1-2-3	
		Natural events			0-1-2-3	
	Electricity lines	Technical/Organisational factors	Norm. share electricity in total FED	w8	0-1-2-3	v8
		Human/political factors			0-1-2-3	
		Natural events			0-1-2-3	
Energy import	Oil production abroad	Technical/Organisational factors	Norm. share oil import in total energy import	w9	0-1-2-3	v9
		Human/political factors			0-1-2-3	
		Natural events			0-1-2-3	
	Natural gas production abroad	Technical/Organisational factors	Norm. share gas import in total energy import	w10	0-1-2-3	v10
		Human/political factors			0-1-2-3	
		Natural events			0-1-2-3	
	Electricity production abroad	Technical/Organisational factors	Norm. share electricity import in total energy import	w11	0-1-2-3	v11
		Human/political factors			0-1-2-3	
		Natural events			0-1-2-3	

Table 2.3: Checklist for the risk assessment (RA) of sudden supply interruptions (cont'd)

Category	Element in energy system	Risk factor	Weight 1)	Score 2)	Value	
Energy import transport	Sea transport routes gas	Technical/Organisational factors	Norm. share LNG import in total energy import	w12	0-1-2-3	v12
		Human/political factors			0-1-2-3	
		Natural events			0-1-2-3	
	Sea transport routes oil	Technical/Organisational factors	Norm. share oil import by sea in total energy import	w13	0-1-2-3	v13
		Human/political factors			0-1-2-3	
		Natural events			0-1-2-3	
	Land transport routes gas	Technical/Organisational factors	Norm. share pipeline gas import in total energy import	w14	0-1-2-3	v14
		Human/political factors			0-1-2-3	
		Natural events			0-1-2-3	
	Land transport routes oil (pipelines)	Technical/Organisational factors	Norm. share pipeline oil import in total energy import	w15	0-1-2-3	v15
		Human/political factors			0-1-2-3	
		Natural events			0-1-2-3	
	Land transport routes electricity	Technical/Organisational factors	Norm. share electricity import in total energy import	w16	0-1-2-3	v16
		Human/political factors			0-1-2-3	
		Natural events			0-1-2-3	
					Sum	RA Value (RAV)
				Max	48 (16 x 3)	
				RA index	(RAV/48)*100	

- 1) PES: primary energy source; FED: final energy demand.
Share = normalised share within the category sub-group, add up to 1 for each category.
- 2) No risk: 0; low risk: 1; medium risk: 2; high risk: 3.

Source: Scheepers, *et al.*, 2007.

Table 2.4: Checklist for the mitigation assessment (MA) of measures to address sudden supply interruptions

Category	Element in energy system		Weight 1)		Score 2)	Value
Emergency stocks	Oil	Oil stocks	Norm. share oil in total PES	w1	0-1-2	v1
	Coal (incl. peat)	Coal (peat) stocks	Norm. share coal (incl. peat) in total PES	w2	0-1-2	
	Gas	Gas stocks (LNG and UGS)	Norm. share gas in total PES	w3	0-1-2	
Demand restraint and rationing	Electricity	Demand response contracts	Norm. share electricity in total FED	w4	0-1-2	v2
		Rationing procedures			0-1-2	
	Gas	Interruptible contracts	Norm. share gas in total FED	w5	0-1-2	
	Transport fuels (oil-based)	Priority users	Norm. share oil based transport fuels in total FED	w6	0-1-2	
		Rationing procedures			0-1-2	
		Other procedures			0-1-2	
Fuel switch capabilities	Electricity	Multi fuel capacity (i.e. oil/gas) power plants	Norm, share electricity in total FED	w7	0-1-2	v3
	Heat	Multi fuel capacity (i.e. oil/gas) industrial boilers	Norm, share "heat" in total FED	w8	0-1-2	
Reserve capacity	Electricity	Import capacity	Norm, share electricity in total FED	w9	0-1-2	v4
		Generation reserves			0-1-2	
	Gas	Reserve capacity transmission pipelines	Norm. share gas in total FED	w10	0-1-2	
	Refineries	Spare capacity for production transport fuels	Norm. share oil-based (transport) fuels in total FED	w11	0-1-2	
Locked-in production	Oil	Domestic oil production	Norm. share oil in total PES	w12	0-1-2	v5
	Coal (incl. peat)	Domestic coal (incl. peat) production	Norm. share coal (incl. peat) in total PES	w13	0-1-2	
	Gas	Domestic gas production	Norm. share gas in total PES	w14	0-1-2	
					Sum	MA Value (MAV)
					Max	10 (5 x 2)
					MA index	MAV/10*100

- 1) PES: primary energy source; FED: final energy demand.
Share = normalised share within the category sub-group, add up to 1 for each category.
- 2) Not available: 0; implemented: 1; implemented and tested: 2.

Source: Scheepers, *et al.*, 2007.

Whether a country has an adequate capability to handle sudden energy supply interruptions can be judged by comparison of the MA sub-index to the RA sub-index. Although this comparison does not say anything about the capability of a country to mitigate specific supply interruptions, it gives an overall indication of how well a country is prepared in comparison to its risk exposure. If the RA sub-index is much higher than the MA sub-index the country may be vulnerable for sudden supply interruptions, i.e. the CCI has a value of less than 100. The CCI can in this case be calculated with the formula:

$$CCI = MA/RA \times 100.$$

If the RA sub-index is similar to or lower than the MA sub-index, the crisis capability of a country may be sufficient in comparison to the probability and impact of sudden supply interruptions. In that case the CCI will be 100. It should be noted that if the MA sub-index is much higher than the RA sub-index the costs associated with crisis capability measures may be exceeding the probability and costs of sudden supply interruptions.

The two assessments provide policy-makers with clear insights where a country's energy system is most vulnerable in the short term and where mitigation measures might be inadequate. In that way, it provides policy-makers with a framework to assess short-term impacts and mitigation options in a structured way. The method has also a number of limitations. Detailed supply risk information is sometimes classified information for reasons of national security. Hence, objective data and standardised procedures may not be available for measuring supply security risks, their effects and the effectiveness of mitigation measures. This can impede the comparison of the CCI between countries. Finally, it is sometimes difficult to assess energy supply interruption risks in the presence mitigation measures. Redundant components and backup systems thus reduce the risks of supply interruptions. Such measures to mitigate risks should be fully taken into account in order to assess the remaining risk of supply interruptions.

2.4.4 Conclusions

Mean-variance portfolio models provide insight into the strong portfolio effect nuclear can bestow on a portfolio of generating assets, given the rather different cost-risk attributes of nuclear-generating technology compared to fossil-fuel-based technology. This stands in stark contrast with conventional power system expansion modelling approaches which only consider stand-alone technology costs without regard to technology cost risk attributes within the full generating portfolio context. As these models are based on projected unit cost per cost category, their respective projected cost risk and pair-wise projected covariances of cost categories among generating technologies these models can only be used for short- to medium-term, forward-looking analysis.

Power system reliability models such as the decision analysis model discussed in Section 2.4b above can provide profound insight into the extent that nuclear power generating assets contribute to security of supply, contingent on the evolution of total nuclear capacity within the portfolio of generating assets of a country as well as network capacities. Given their probabilistic nature, they can be used for short-term or (at most) medium-term, forward-looking analysis only.

Fuzzy logic "data mining" models such as the Hungarian fuzzy logic model can yield unexpected insights into the kind of factors correlated with supply security, including soft qualitative factors. They use historical information in a semi-heuristic way to generate probabilities and tolerance margins of power systems. These models can generate approximate probabilities for future system failures without diagnosis of the weakest components of the system warranting priority attention in the way power system reliability models can deliver.

Economically oriented system models, such as the ones used by CRIEPI allow deriving economic values to the performance of nuclear generating assets in the power system of a country. They can generate insight into issues such as how cost-effective contribution can nuclear make to the future power system output and how much value does nuclear yield in terms of future supply security of the national power system.

The Crisis Capability Index, finally, places itself at the intersection of economic and political considerations. Integrating both objective quantitative indicators as well as more subjective qualitative ones, it is, of course, an easy target for methodological criticism. However, it underlines once more that the security of energy supply remains also a political issue. It thus has a double function. On the one hand, it highlights the hybrid nature of all security of supply models, whose parameters and assumptions are a function of the specific points the respective researchers want to address. On the other hand, it remains a transparent, pragmatic and ultimately useful tool to organise all the different information pertaining to energy supply security in a given country. After preceding discussion it is obvious that this can again be only a partial input to the ongoing discussion about what energy supply security means for different countries and different stakeholders.

2.5 The Supply/Demand Index

The S/D Index is a composite supply security indicator for a defined region in the medium and long run that includes major underlying supply-side and demand-side factors. This index is normalised to range from 0 (extremely low security) to 100 (extremely high security). It covers final energy demand, energy conversion and transport and primary energy supply and, hence, in principle the entire energy system.¹ The S/D Index is also at the basis of the SSDI employed in Chapter 3 of this publication to track the evolution of the energy supply situation in selected OECD countries over the past 40 years in a systematic manner. The difference in the SSDI and the S/D Index is essentially that the SSDI was adapted to be able to work with the only available consistent data available for the past 40 years, i.e. the *IEA Energy Statistics*. The applicability of the scoring rules (see below) has also been simplified and adapted from the European Union and Norway to the whole of the OECD.

The S/D Index uses four types of inputs, two objective types and another two of a more subjective nature. The more or less objective inputs concern the shares of different supply and demand categories (i.e. for supply: oil, gas, coal, nuclear, RES and other; for demand: industrial use, residential use, tertiary use and transport use) and the values characterising efficiency, adequacy, and reliability in conversion and transport based on the secondary energy carriers (electricity, gas, heat, and transport fuels). Figure 2.12 displays the conceptual framework of, and the elements considered in, the overall S/D Index model. The subjective inputs concern the weights that determine the relative contribution of the different components in the S/D Index (such as the relation between supply and demand outputs in the Index, or the relation between EU imports and non-EU imports) and the scoring rules for determining various S/D Index values reflecting different degrees of perceived vulnerabilities.

2.5.1 Scoring rules

Examples of scoring rules are:

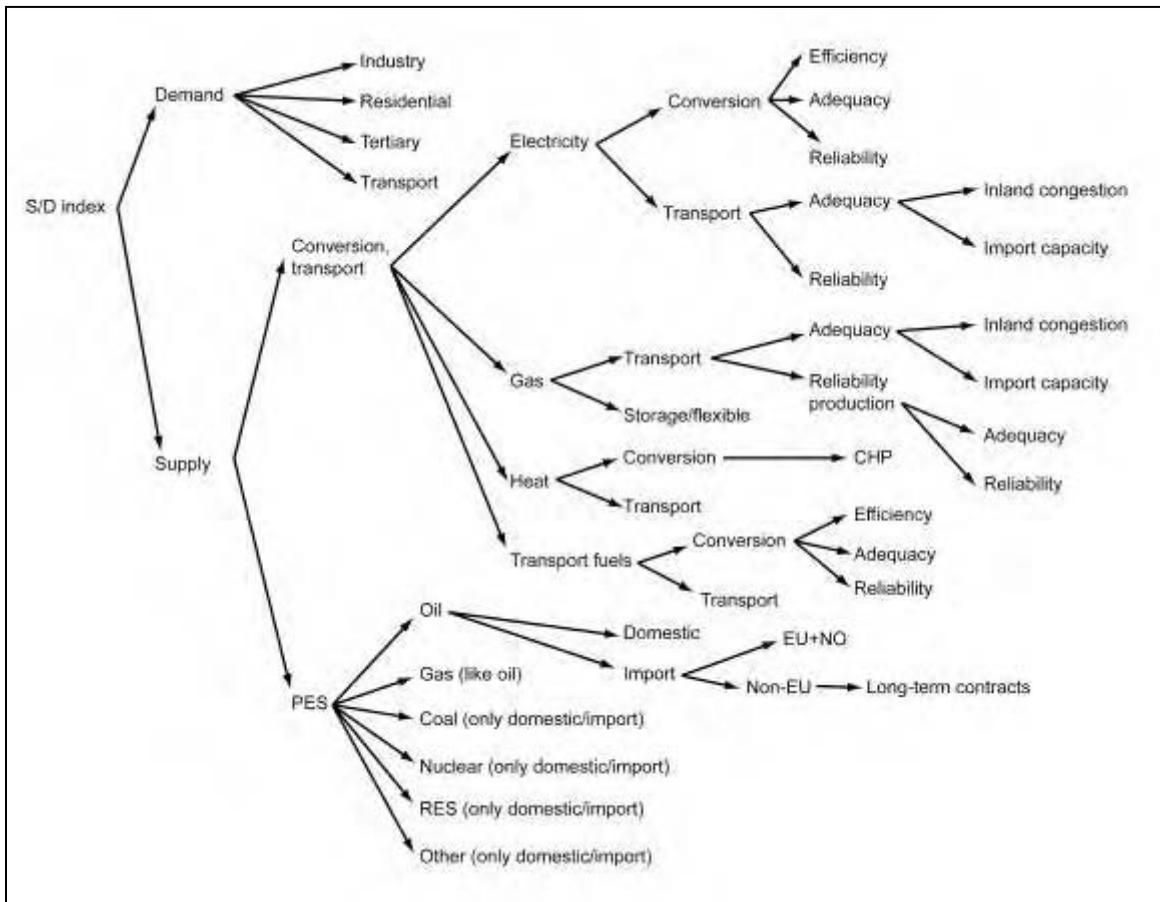
- *Import of oil and gas* will only get a positive score if the import share from EU and Norway and a weighted share from non-EU governed by long term contracts is above a minimum threshold value.

1. This section is largely based on Scheepers, *et al.*, 2007.

- In the PES, *nuclear energy* has a default index value of 100 because supply risks for uranium are deemed to be negligibly low.
- Because *coal, renewables (mainly biomass) and other energy supplies* are expected to be sufficiently diversified, the index for these PES types has a minimum value of 70 if the total supply is imported. The score will increase proportionally with decreasing shares of imports (and increasing domestic shares).
- *Electricity generation efficiency* (part of energy conversion branch) is assessed by attaching minimum and maximum scores to minimum and maximum efficiency values, 35% and 50% respectively. In between, a proportional score applies.
- *Electricity network adequacy* is associated with both inland congestion and import capacity. The import capacity score is proportional to a ratio in between 0% and 5%. The maximum value is derived from the Barcelona “target”. At the Barcelona European Council in 2002, it was agreed to increase minimum interconnection levels between Member States to 10% of the production capacity at national level. Above 5%, import capacity is fully taken into account into a reserve factor including both domestic capacity and import.

Although, the scoring rules are subjective by nature, the extent to which the value of the parameters can be plausibly varied, expressed through weights attached to different components in the S/D Index, is rather limited.

Figure 2.12: The structure of the Supply/Demand Index



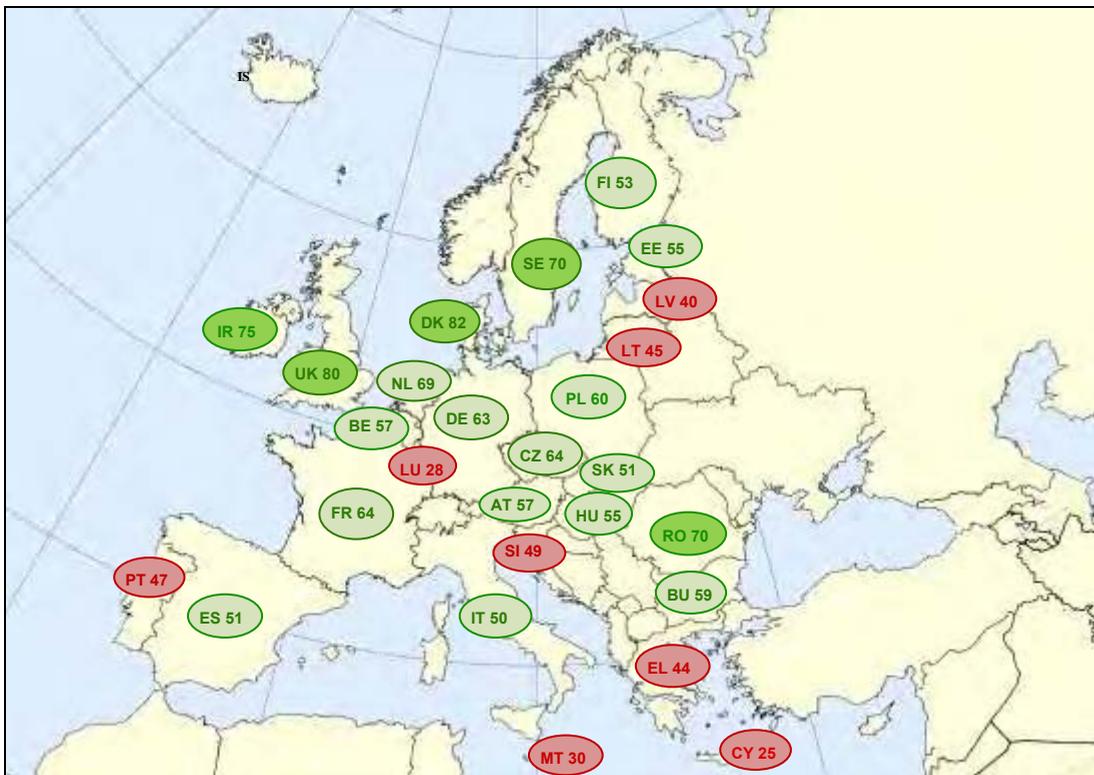
Source: Scheepers, *et al.*, 2007.

Examples of applications

The use of the S/D Index can be illustrated with examples for the EU-27 and its Member States for the years 2005 and 2020 (see respectively Figures 2.13 and 2.14). The examples are based largely on information contained in energy balances, derived from mainly Eurostat (Eurostat, 2006) and IEA statistics (IEA, 2006) and the *European Energy and Transport Trends to 2030 – update 2005* baseline scenario (EC, 2006). The S/D Index model combines that information with certain default weighing factors and scoring rules.

The non-weighted average of the S/D Index values for the EU-27 Member States in 2005 is about 56. The range is from 25 (Cyprus) to 82 (Denmark). In the default situation, the primary underlying factor accounting for the differences in scores between EU Member States consists of differences in the primary energy sources sub-index. Member States with high import dependencies for oil and gas, combined with high shares of these imports originating from outside the EU/Norway, have a relatively low score. Such member states include: Cyprus, Greece, Latvia, Lithuania, Luxembourg, Malta and Portugal. On the other hand, member states mainly importing oil and natural gas from within EU/Norway, deploying renewables or combined heat and power (CHP) also achieve relatively high S/D Index values. Examples are Denmark (82), Ireland (75), and to a lesser extent Sweden (70). Furthermore, France (64) has a high score due to the large share of nuclear in the PES mix, while also Slovakia and Lithuania experience large contributions of nuclear to their S/D Index scores (increasing their low S/D indices substantially). As most of the larger Member States (France, Germany and the United Kingdom) exhibit relatively high scores, the score for the whole EU-27 region is also relatively high (65). Projections of S/D Index values in year 2020 for EU Member States suggest some noteworthy future developments.

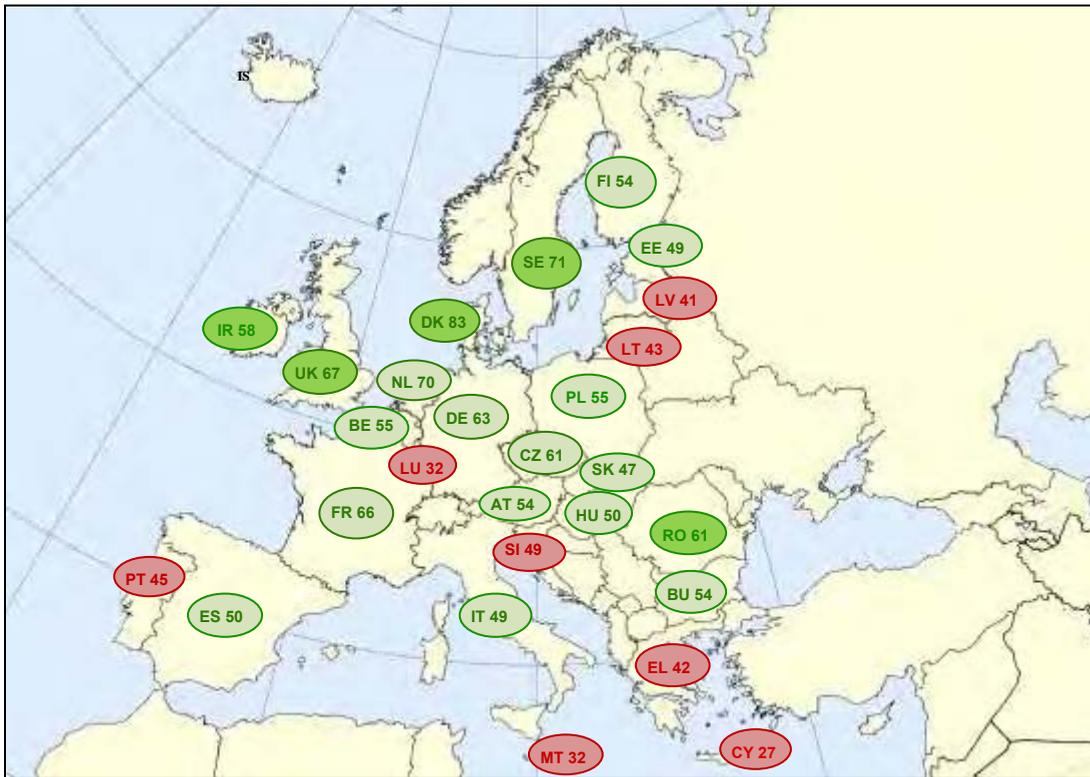
Figure 2.13: The S/D Index of EU Member States in 2005



Source: based on Scheepers, *et al.*, 2007.

The overall supply security level in the EU is likely to decrease. For example, for Ireland and the United Kingdom a quite large decrease in energy supply security as captured by the S/D Index is projected, as a surge in sourcing of primary energy sources outside the EU/Norway is envisaged for these countries. Among the countries with a large share of nuclear in the primary energy supply, France shows a further improvement due to the anticipated rising share of nuclear, whereas Slovakia and Lithuania (shut-down of the Ignalina nuclear plant) show a lower S/D Index value due to a decreasing share of nuclear energy. In the case of Lithuania the projected decline in the S/D Index is exacerbated by projected less favourable developments on the demand side.

Figure 2.14: The S/D Index of EU Member States in 2020



Source: based on Scheepers, *et al.*, 2007.

Assessment

The index was tested and applied to gauge the energy security situation of several countries. It can readily be used for comparison purposes. The strength of the essentials of its methodology its transparency, i.e. one can easily understand the scope and structure of analyses by the index diagram shown in Figure 2.12. Another advantage is its modularity. The user can easily build a variant index of his own liking based on this diagram and thereby develop an informed view on supply security from his own perspective. Furthermore, a major advantage of the S/D Index compared to most alternative composite indices would seem to be its relative comprehensiveness with the inclusion of some important demand-side aspects.

The method has also a number of limitations. Firstly, the model details are fairly complex. However, this does not dilute details of single components: the role of single components can be determined with relative ease. Second, to its credit the index accounts for the importance of energy demand within the economy. Yet in the modelling structure of demand is separated from supply.

Consequently, subjective weight factors have to be attached to demand as well as supply branches. Ideally, the index model would identify the impact of potential supply disturbances in an integrated supply-demand chain setting (ECOFYS, *et al.*, 2009, p. 297). Third, electricity generation is only a small part of the model. Fourth, the model does not take into account externalities other than the security of energy supply. Issues such as carbon intensity and local pollution (coal and gas), proliferation and waste disposal (nuclear) or intermittency (renewables) have thus not been considered. Fifth, the S/D Index model is in essence a static one-period model as no dynamic features over time are generated by an individual model run. Last but not least, in the supply chain up to primary energy supply, the geopolitical-political dimension is captured less well, compared to for instance diversity-based indices.

2.6 Concluding observations

This chapter has reviewed a variety of approaches that can be pursued to measure supply security risks and risk mitigation responses with policy-relevant indicators. Special reference was made to the role of nuclear in security of supply risk mitigation. As supply security is a complex, multi-faceted issue with divergent stakeholder and country perspectives, there is no single approach that provides complete insight. Several dedicated indicators can thus provide quantitative information on specific security of supply aspects.

Moreover, a variety of modelling approaches, each with its strengths and weaknesses provide policy-makers with information to make better-informed decisions to ensure adequate levels of supply security, provided due explanation is given regarding the quantified security of supply information. Finally, a good understanding is necessary of the general framework conditions and more qualitative external and internal factors that impact the future security of energy service systems.

In the end, each researcher has to work with the indicators that are most apt to provide policy-relevant answers to the questions being asked. In the context of this NEA project on the *The Security of Energy Supply and the Contribution to Nuclear Energy*, a simplified version of the S/D Index as presented in Chapter 3 was considered the most meaningful representation of the security of energy supply situation in OECD member countries in order to identify the contribution that nuclear energy can make.

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Chapter 3

EVOLUTION OF THE SECURITY OF ENERGY SUPPLY IN OECD COUNTRIES

In the first chapter of this report, security of energy supply was defined and discussed from the economic and geopolitical viewpoints, and the contribution of nuclear energy was analysed. The second chapter reviewed indices and models aimed at quantifying various aspects of the security of energy supply.

In the present chapter, a model is developed to evaluate the level of security of energy supply over time, and to analyse the role played by nuclear energy in improving the security of electricity generation. It is built on the S/D Index presented in Section 2.5. The different indicators for this chapter have been developed by the NEA on the basis of the most recent data available from a selection of International Energy Agency (IEA) publications (see references for details).

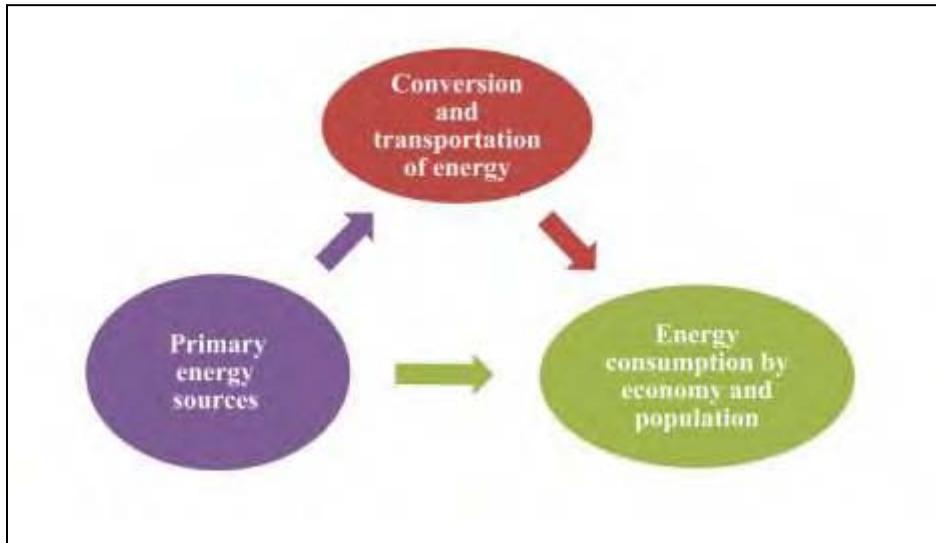
3.1 Time-dependent quantification of the security of energy supply

In order to compare the evolution of the level of the security of energy supply in given countries, a time-dependent quantitative criterion is needed. The most relevant approach should include all major technical, economic and political aspects.

For the technical operational strength of power supply systems, a reliability analysis is usually performed. Based on the historical failure frequencies for elementary parts, the time-dependent probability that the whole system will perform its intended function can be calculated. Although this kind of reliability assessment is well-established for technical systems, it is difficult to use it for estimating the level of the security of energy supply. The reason for this is that no probability distribution could be built to describe risks related to strong changes in the energy producers' prices, politics or technological knowledge. This refers to the issue discussed above in Section 1.2 that energy supply security must remain an issue for public policy making.

The alternative approach consists in analysing the degree of diversification of the primary energy sources of supply, redundancy of conversion and transportation infrastructure and the efficiency of the final energy use (see Figure 3.1). These are the main components determining the security of energy supply.

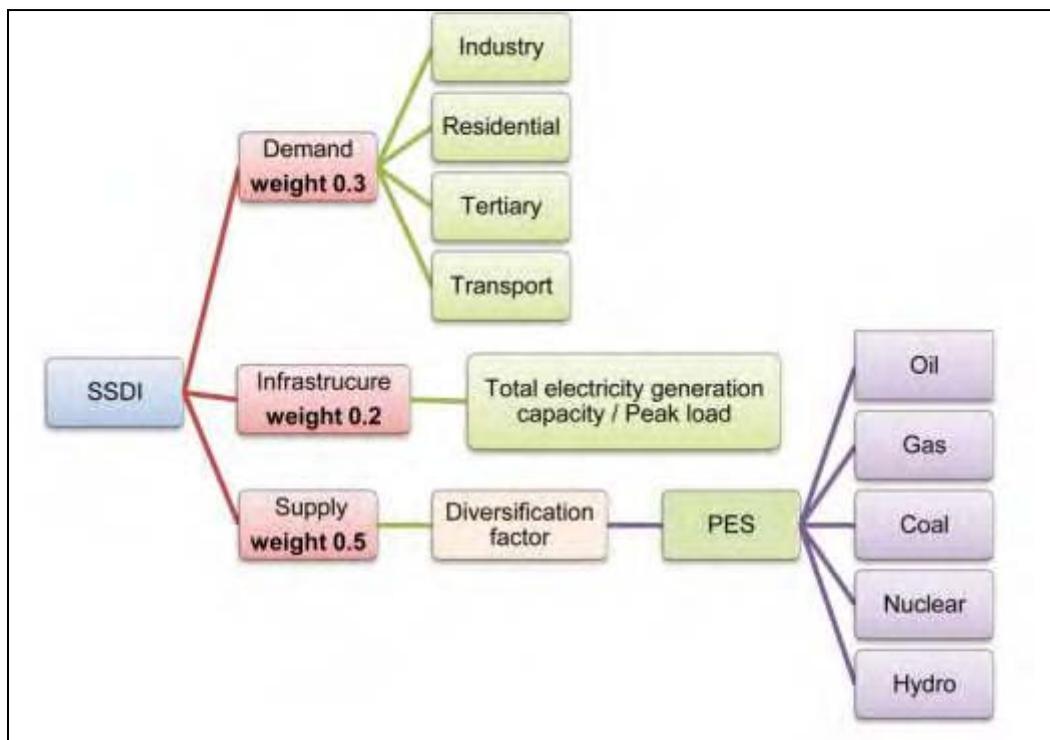
Figure 3.1: General scheme of energy flows in an economy



Simplified Supply and Demand Index

The Simplified Supply and Demand Index (SSDI) is based on the Supply/Demand Index (S/D) developed by the Energy Research Centre for the Netherlands (ECN), and described in Scheepers (2007). However, the SSDI is slightly simpler than the S/D Index and the underlying construction changes in a number of points.

Figure 3.2: Shares and weights used in the Simplified Supply and Demand Index



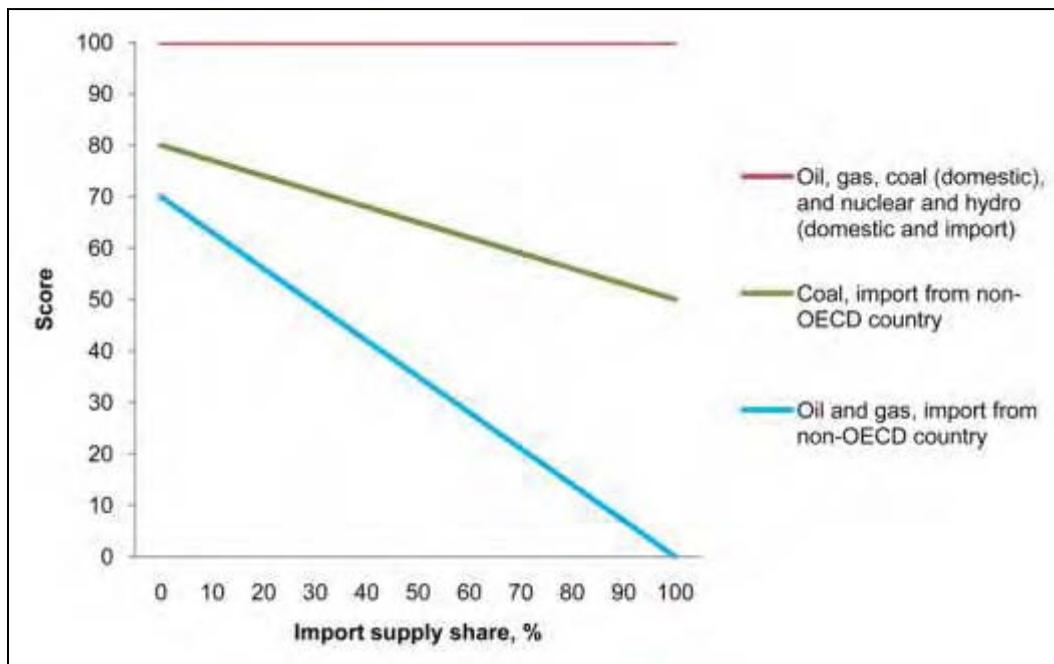
The SSDI is composed of three weighted contributions: demand, infrastructure and supply (see Figure 3.2). These contributions take in account the degree of diversity and supply origin of different energy carriers, the efficiency of energy consumption by main the economic sectors, and the state of the electricity generation infrastructure. The values of weights determining the relative contribution of the demand, infrastructure and supply branches are close to those used in the original S/D model, where they were adjusted to reflect the perceived vulnerability of the branches. A higher weight indicates increased vulnerability.

The SSDI takes its values from 0 to 100 describing, respectively, poor and perfect state of the security of energy supply. As described below, a maximal score 100 refers to a country with low energy intensity, developed electricity generation infrastructure, perfectly diversified primary energy sources, with the latter all domestically produced or imported from trustworthy sources. On the contrary, a score 0 corresponds to a country with low energy efficiency, an electricity capacity unable to satisfy the peak load, and importing the totality of the energy carriers from unreliable sources.

The demand part of the SSDI indicates the efficiency of the energy consumption in the industrial, residential, tertiary and transport sectors (see Table 3.1). The reference values are the average of the three lowest energy intensities among all OECD countries considered and over the whole time period considered (from 1970 to 2007). The score for the demand contribution to the SSDI is proportional to the ratio of the energy intensity of an economy sector in a country to a corresponding reference value. The weight of the demand part in the final SSDI is 0.3 (see Figure 3.2).

The supply part of the SSDI reflects the degree of diversity of types and the origin of primary energy sources supply (see Figure 3.3). The domestic and OECD-origin import shares of oil, gas, coal, nuclear and hydro sources are scored at the maximal rate of 100.

Figure 3.3: Index score values for primary energy sources as a function of the share and origin of supply



The shares of the corresponding resources imported from non-OECD countries get lower scores that decrease when the share of imports increases (see Figure 3.3). For example, if a country imports all its oil from non-OECD countries, the corresponding score would be zero.¹ The scores corresponding to each type of PES are weighted with respect to their shares in the country's energy mix. The weight of the supply part in the final SSDI is 0.5 (see Figure 3.2).

The PES score is multiplied by an overall normalised Shannon diversification factor (Sterling, 1998) that takes into account the distribution between different PES. If a country entirely relies on only one type of PES the value of the Shannon diversification factor is 0, and in the case of equal shares of all PES the value of the diversification factor is 1.

One may argue that long-term oil and gas supply contracts are as reliable as the domestic ones, and thus their SSDI score should not decrease with the import share. Indeed, oil and especially gas import from far away regions requires considerable investment, and governments are often involved in securing the contracts. However, an important number of oil and gas exporting economies are subject to political instability, for instance in the Middle East and Central Asia. This is partly due to endogenous reasons as resource-based economies can be subject to high volatility of economic growth and conflicts over rent distribution. In the case of an interruption, the remaining producers cannot satisfy the world demand in oil and gas. For this reasons, the SSDI scores of oil and gas decrease from 70 to 0 when the corresponding import share increases from 0 to 100%. Coal is being traded more and more across national borders. The import of coal from non-OECD countries is scored from 80 (low import share) to 50 (total import dependency). Tables 3.1 and 3.2 below provide the algorithms for calculating the SSDI in detail.

The infrastructure part of the SSDI corresponds to the conversion and transport branch of the S/D Index (Scheepers, 2007). In the S/D Index, a detailed analysis of the infrastructure for electricity and heat generation, gas logistics and transport fuels storage and conversion is included. Because of poor data availability for the countries and time period considered, and for simplicity's sake, the Infrastructure part of the SSDI only evaluates the degree of development of the electricity generation capacity, electricity playing a crucial role in the economy.

The key parameter is the ratio of the total electricity generation capacity and the peak load for the given year (see Figure 3.14). The score is obtained by comparing this ratio with benchmark values obtained from the average of three highest and lowest cases among the considered countries (see Table 3.3). The weight of the Infrastructure part in the final SSDI is 0.2 (see Figure 3.2).

1. An additional diversification factor for every kind of PES taking in account the precise origin of importation (country, company, etc.) would strengthen the model. This approach has not been followed because of the poor data availability.

Table 3.1: Scoring rules for the demand branch of the SSDI

$[\text{SSDI demand}] = [\text{SSDI demand industry}] + [\text{SSDI demand residential}] + [\text{SSDI demand tertiary}] + [\text{SSDI demand transport}]$
$[\text{SSDI demand industry}]$
<p>$[\text{SSDI demand industry}] = [\text{Demand industry sector share}] \times [\text{SSDI demand industry score}]$</p> <p>$[\text{SSDI demand industry score}] = \min \left\{ \frac{[\text{Reference energy intensity on added value for the industrial sector}]}{[\text{Energy intensity on added value for the industrial sector}]}, 1 \right\} \times 100$</p> <p>$[\text{Energy intensity on added value for the industrial sector}] = \frac{[\text{Energy demand in industrial sector}]}{[\text{Value added in industry, 2000 prices}]} \times \frac{\text{toe}}{\text{M\\$ 2000}}$</p> <p>$[\text{Reference energy intensity on added value for the industrial sector}] =$ Average of 3 smallest $[\text{Energy intensity on added value for the industrial sector}]$ <small>All countries, All years</small></p>
$[\text{SSDI demand residential}]$
<p>$[\text{SSDI demand residential}] = [\text{Demand residential sector share}] \times [\text{SSDI demand residential score}]$</p> <p>$[\text{SSDI demand residential score}] = \min \left\{ \frac{[\text{Reference energy intensity of the residential sector}]}{[\text{Energy intensity of the residential sector}]}, 1 \right\} \times 100$</p> <p>$[\text{Energy intensity of the residential sector}] = \frac{[\text{Energy demand in residential sector}]}{[\text{Population}]} \times \frac{\text{toe}}{\text{capita}}$</p> <p>$[\text{Reference energy intensity of the residential sector}] =$ Average of 3 smallest $[\text{Energy intensity of the residential sector}]$ <small>All countries, All years</small></p>
$[\text{SSDI demand tertiary}]$
<p>$[\text{SSDI demand tertiary}] = [\text{Demand tertiary sector share}] \times [\text{SSDI demand tertiary score}]$</p> <p>$[\text{SSDI demand tertiary score}] = \min \left\{ \frac{[\text{Reference energy intensity on added value for the tertiary sector}]}{[\text{Energy intensity on added value for the tertiary sector}]}, 1 \right\} \times 100$</p> <p>$[\text{Energy intensity on added value for the tertiary sector}] = \frac{[\text{Energy demand in tertiary sector}]}{[\text{Value added in trade, 2000 prices}]} \times \frac{\text{toe}}{\text{M\\$ 2000}}$</p> <p>$[\text{Reference energy intensity on added value for the tertiary sector}] =$ Average of 3 smallest $[\text{Energy intensity on added value for the tertiary sector}]$ <small>All countries, All years</small></p>
$[\text{SSDI demand transport}]$
<p>$[\text{SSDI demand transport}] = [\text{Demand transport sector share}] \times [\text{SSDI demand transport score}]$</p> <p>$[\text{SSDI demand transport score}] = \min \left\{ \frac{[\text{Reference energy intensity for transport sector}]}{[\text{Energy intensity for transport sector}]}, 1 \right\} \times 100$</p> <p>$[\text{Energy intensity for transport sector}] = \frac{[\text{Energy demand in transport sector}]}{[\text{Value added in trade, 2000 prices}]} \times \frac{\text{toe}}{\text{M\\$ 2000}}$</p> <p>$[\text{Reference energy intensity for transport sector}] =$ Average of 3 smallest $[\text{Energy intensity for transport sector}]$ <small>All countries, All years</small></p>

Table 3.2: Scoring rules for the supply branch of the SSDI

$[\text{SSDI supply}] = [\text{Diversification factor}] \times ([\text{SSDI supply Oil}] + [\text{SSDI supply gas}] + [\text{SSDI supply coal}] + [\text{SSDI supply nuclear}] + [\text{SSDI supply hydro}])$
[Diversification factor]
$[\text{Diversification factor}] = -\frac{1}{\ln 5} \left\{ \sum_{i=1}^5 [\text{PES}_i \text{ supply share}] \cdot \ln [\text{PES}_i \text{ supply share}] \right\}$
[SSDI supply oil]
$[\text{SSDI supply oil}] = [\text{Supply oil share}] \times [\text{SSDI supply oil score}]$ $[\text{SSDI supply oil score}] = [\text{Domestic oil supply share}] \times [\text{SSDI domestic oil supply score}] + [\text{Import oil supply share}] \times [\text{SSDI import oil supply score}]$ $[\text{SSDI domestic oil supply score}] = 100$ $[\text{SSDI import oil supply score}] = 70 \times (1 - [\text{Import oil supply share}])$
[SSDI supply gas]
$[\text{SSDI supply gas}] = [\text{Supply gas share}] \times [\text{SSDI supply gas score}]$ $[\text{SSDI supply gas score}] = [\text{Domestic gas supply share}] \times [\text{SSDI domestic gas supply score}] + [\text{Import gas supply share}] \times [\text{SSDI import gas supply score}]$ $[\text{SSDI domestic gas supply score}] = 100$ $[\text{SSDI import gas supply score}] = 70 \times (1 - [\text{Import oil supply share}])$
[SSDI supply coal]
$[\text{SSDI supply coal}] = [\text{Supply coal share}] \times [\text{SSDI Supply coal score}]$ $[\text{SSDI supply coal score}] = [\text{Domestic coal supply share}] \times [\text{SSDI domestic coal supply score}] + [\text{Import coal supply share}] \times [\text{SSDI import coal supply score}]$ $[\text{SSDI domestic coal supply score}] = 100$ $[\text{SSDI import coal supply score}] = 80 - 30 \times [\text{Import coal supply share}]$
[SSDI supply nuclear]
$[\text{SSDI supply nuclear}] = [\text{Supply nuclear share}] \times [\text{SSDI supply nuclear score}]$ $[\text{SSDI supply nuclear score}] = [\text{Domestic nuclear supply share}] \times [\text{SSDI domestic nuclear supply score}] + [\text{Import nuclear supply share}] \times [\text{SSDI import nuclear supply score}]$ $[\text{SSDI domestic nuclear supply score}] = 100$ $[\text{SSDI import nuclear supply score}] = 100$
[SSDI supply hydro]
$[\text{SSDI supply hydro}] = [\text{Supply hydro share}] \times [\text{SSDI supply hydro score}]$ $[\text{SSDI supply hydro score}] = [\text{Domestic hydro supply share}] \times [\text{SSDI domestic hydro supply score}] + [\text{Import hydro supply share}] \times [\text{SSDI import hydro supply score}]$ $[\text{SSDI domestic hydro supply score}] = 100$ $[\text{SSDI import hydro supply score}] = 100$

Table 3.3: Scoring rules for the infrastructure branch of the SSDI

[SSDI infrastructure]
Note: Fitted values were used for years for which the data is missing (see Figure 3.19 and 3.20).
$[\text{SSDI infrastructure}] = 50 \times \left\{ 1 + \frac{\alpha - \alpha_{\min}}{\alpha_{\max} - \alpha_{\min}} \right\}$ $\alpha = \frac{[\text{Total electricity generation capacity}]}{[\text{Peak load}]}, \quad \alpha_{\min} = \text{Average of 3 smallest } \alpha, \quad \alpha_{\max} = \text{Average of 3 highest } \alpha$ <div style="display: flex; justify-content: space-around; font-size: small;"> <div style="text-align: center;"> All countries, All years </div> <div style="text-align: center;"> All countries, All years </div> </div>

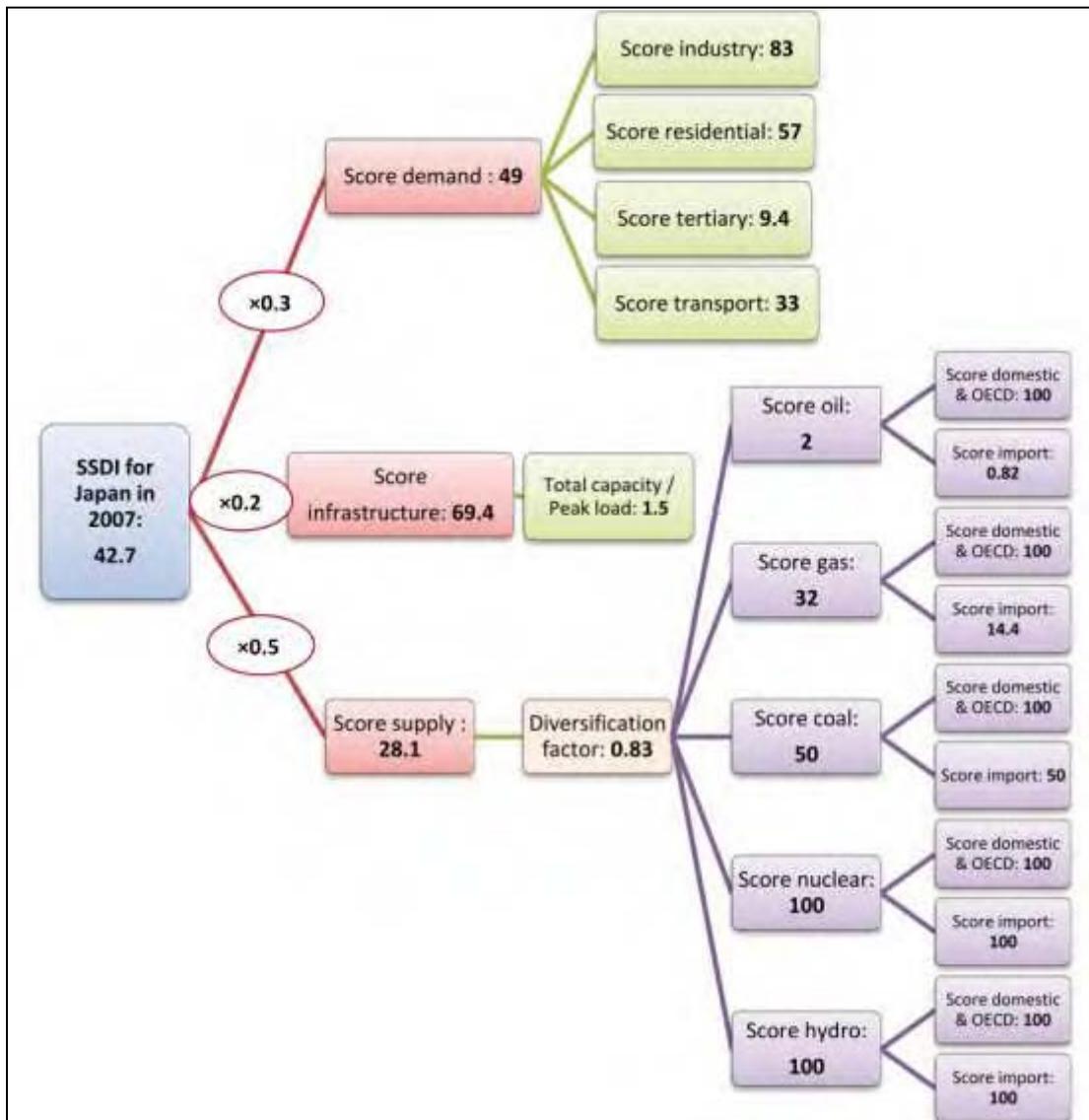
It would be more relevant to use the ratio of the capacity at peak over the peak load (see Figure 3.13 and Section 3.3 for detailed discussion) to describe the state of the infrastructure, because it shows the real state of the electricity generation capacity, and sometimes indicates the lack in

maintaining or investment. However, no data is available for the period 1970-2007 and for some countries there is no data at all. More information is available on the total electricity generation capacity, and still, for many years the data are missing. Fitted values were used for the years for which the data are not available (for details, see Table 3.3 and Figures 3.19 and 3.20 in the appendix to this chapter. The scoring rules for the demand, infrastructure and supply contributions to the SSDI are described in details in Tables 3.1 and 3.3 and Figure 3.3).

Examples of SSDI calculation

An illustrative example of the SSDI calculation for Japan (year 2007) is presented in Figure 3.4, and Figure 3.5 shows the results for the same calculation for the United Kingdom (year 2007).

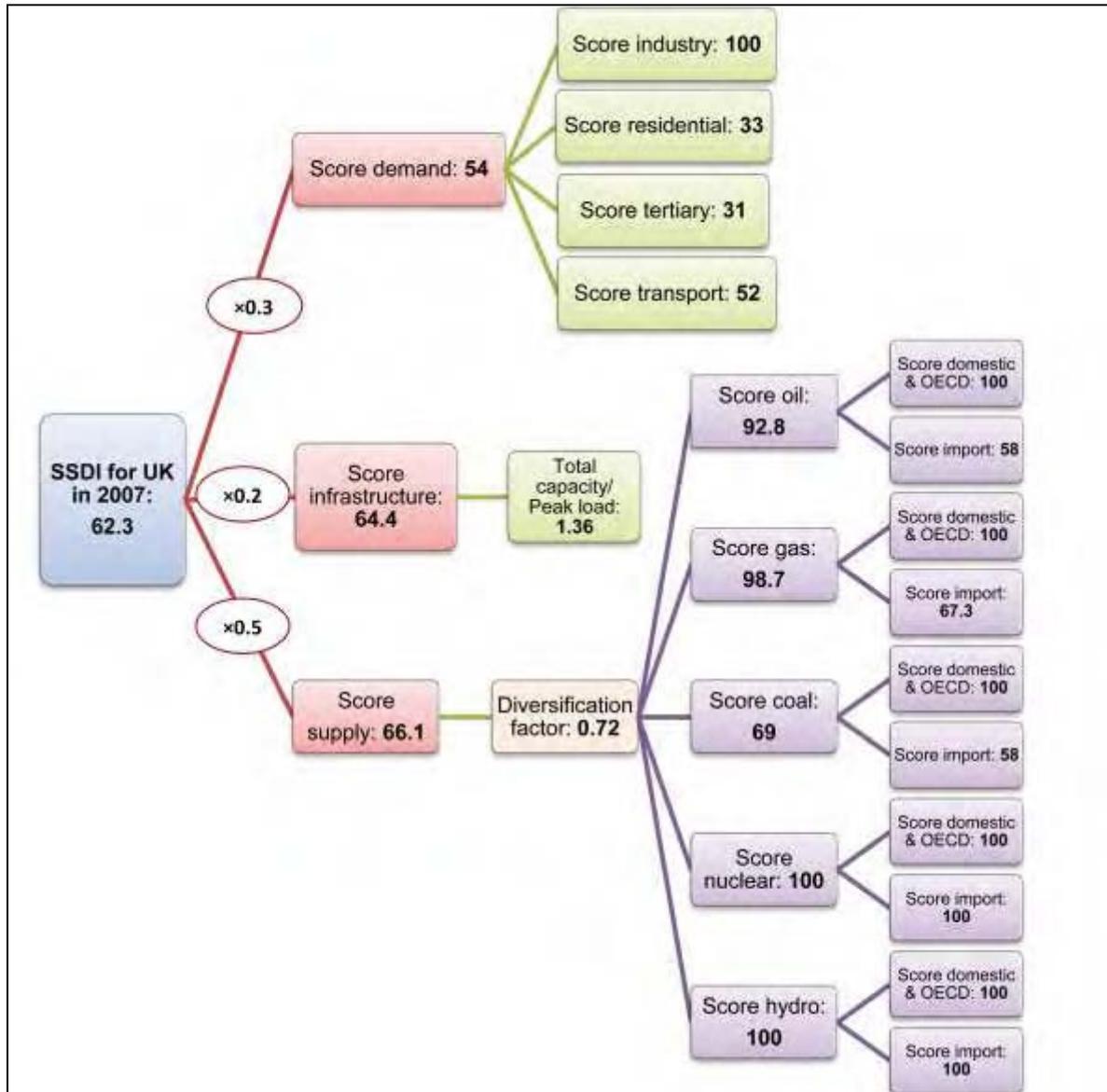
Figure 3.4: SSDI data flow in the case of Japan (2007)



Source: NEA calculations based on IEA 2009a-2009d.

Japan imports almost all fossil resources needed from non-OECD countries, while the United Kingdom has considerable domestic resources of oil, gas and coal, which are also imported from the nearby European countries. Thus, the score for the supply branch of the SSDI in the case of Japan (28.1) is considerably lower than in the case of the United Kingdom (66.1).

Figure 3.5: SSDI data flow in the case of the United Kingdom (2007)



Source: NEA calculations based on IEA 2009a-2009d.

On the energy demand side, the United Kingdom has a higher score because it has lower energy intensity of the industrial, transport and especially tertiary sectors (see Table 3.4). However, the difference between the scores for the demand branch of the SSDI for Japan and the United Kingdom is considerably smaller than the ones for the supply branch. Because of very strong PES import dependence of Japan, the final score of the United Kingdom (62.3) is higher than in the case of Japan (42.7).

Table 3.4: Demand branch calculation for Japan and the United Kingdom (2007)

Energy intensities	Japan (2007)	SSDI score	United Kingdom (2007)	SSDI score
Industry sector [toe/M\$ 2000]	118.93	83	99.15	100
Transport sector (transport sector/value added in trade and services) [toe/M\$ 2000]	135.38	33	87.39	51
Residential [toe/capita]	0.38	57	0.66	33
Commerce and public services [toe/M\$ 2000]	105.60	9.4	30.97	31

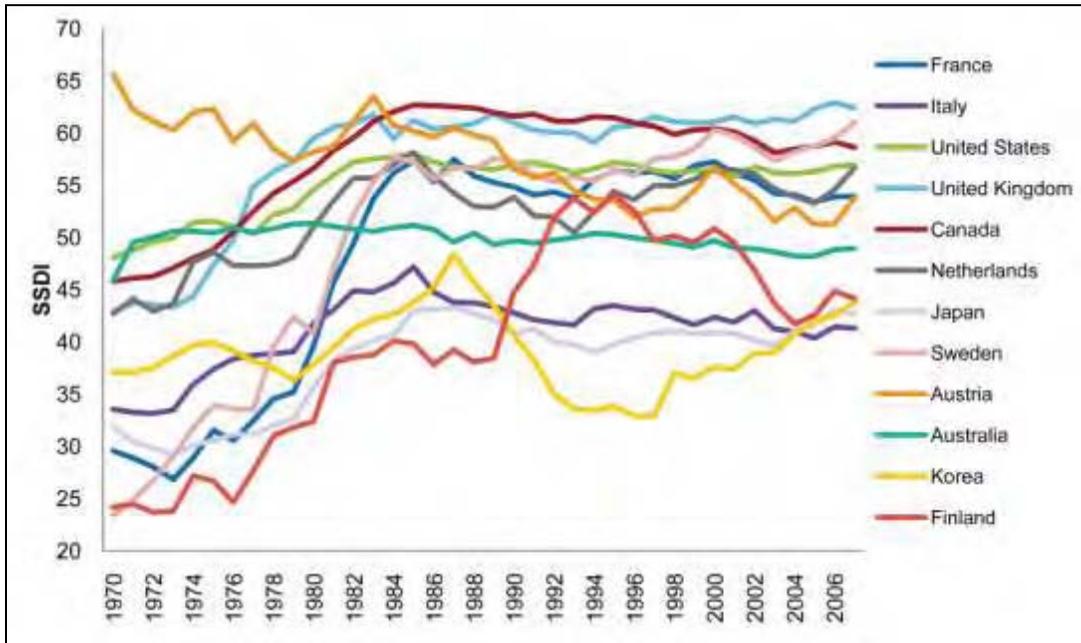
3.2 Changes in security of supply in selected OECD countries

In this section the evolution of the SSDI over time is analysed for some of the OECD countries. They include: Australia, Austria, Canada, Finland, France, Italy, Japan, Korea, the Netherlands, Sweden, the United Kingdom and the United States. By intuition, Canada and the United Kingdom are countries with very strong security of energy supply, because almost all kinds of energy carriers and related conversion facilities are available domestically. On the contrary, France, Japan and some other countries strongly depend on the import of the energy carriers. The analysis was performed for the period from 1970 till 2007, using the SSDI with data inputs from the following sources:

- OECD *Fact Book 2009* (GDP, population, value added in industry, share of trade in goods and services);
- IEA *Electricity Information 2009* (total electricity generation capacity, capacity at peak and the peak load);
- IEA *Energy Balances of OECD Countries 2009* (energy demand by sector and primary energy sources supply);
- IEA *Oil Information 2009* (oil supply, share of domestic production and the origin of imports); and
- IEA *Natural Gas Information 2009* (natural gas supply, share of domestic production and the origin of imports).

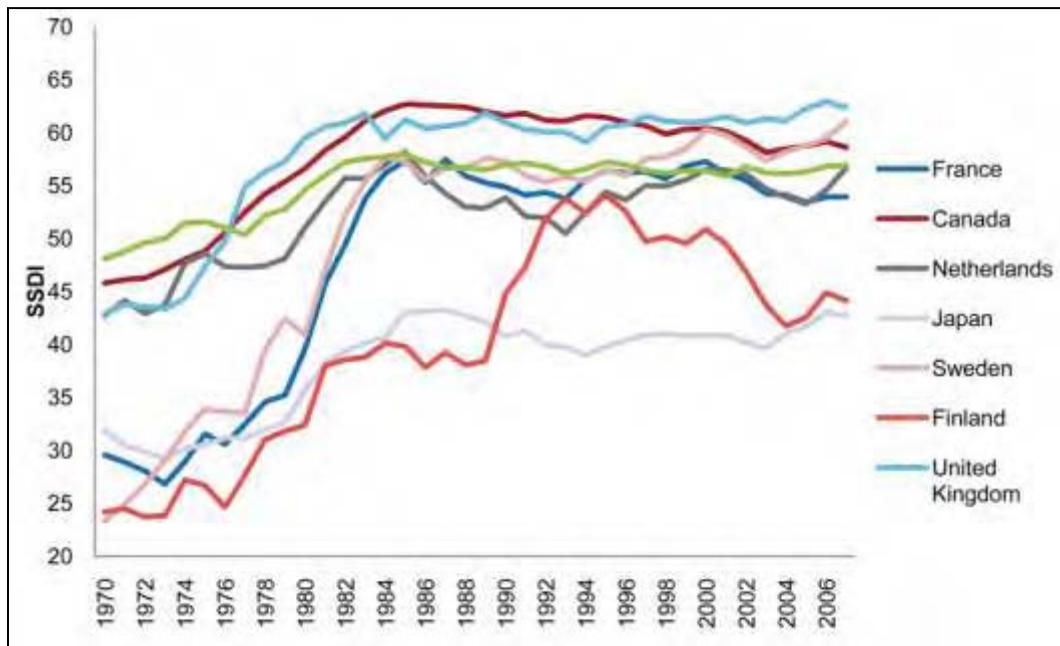
This allows to track changes in the SSDI and provides an interpretation of the security of energy supply of the selected countries for the last forty years, when important policy changes have been implemented. For example, the United Kingdom switched from coal to gas for its electricity generation, France and the United States introduced an ambitious nuclear programme, and Italy started a nuclear programme and then stopped it. Germany was not included in the study because some data prior to the reunification is difficult to reconstruct. The change in the SSDI for the countries listed above is given in Figure 3.6.

Figure 3.6: Evolution of the SSDI for selected OECD countries



One can see that the value of the SSDI has considerably increased between 1970 and 2007 in the case of most economies under study: Australia, Canada, Finland, France, Japan, the Netherlands, Sweden, the United Kingdom and the United States (see Figure 3.7). On the contrary, the value of the SSDI is low or not increasing between 1970 and 2007 for Austria, Italy and Korea (see Figure 3.8). Also, the gap among different countries has decreased.

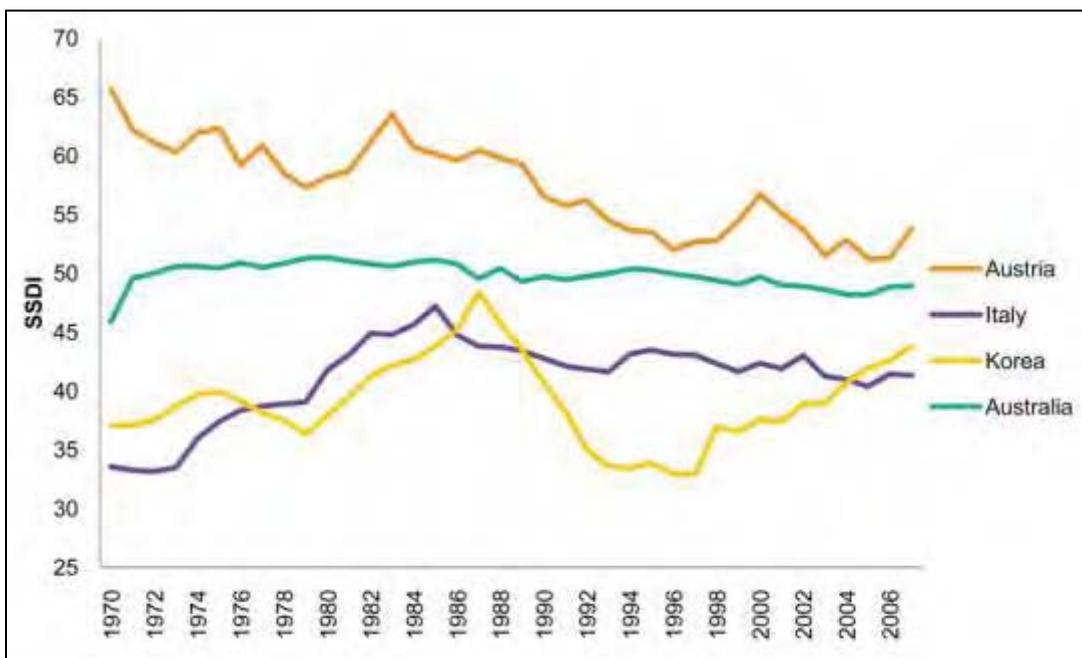
Figure 3.7: OECD countries with high values or increases in the SSDI between 1970 and 2007



Australia, Canada, the Netherlands and the United Kingdom have large domestic resources of fossil energy carriers, and thus their SSDI scores are high. However, during the last ten years the SSDI for the Netherlands showed a tendency to decrease because of gas and oil resources depletion in the North Sea. Electricity generation in Sweden is mainly ensured by hydro and nuclear power, explaining the high value of the SSDI. The situation in Finland, France, Japan and Korea also started to improve in the 1970s-1980s, when nuclear power was massively introduced.

In the United States, the value of the SSDI is generally high, because of large domestic resources of fossil energy carriers and an important share of reliable importations from Canada. One can note an important increase in the SSDI in the second part of the 1970s, because the energy intensity of the United States' economy decreased and nuclear power plants started to be widely deployed.

Figure 3.8: OECD countries with low values or low growth in the SSDI between 1970 and 2007



In the United Kingdom, the value of the SSDI has considerably increased from the mid-1970s until the mid-1980s, due to the development of domestic or nearby oil and gas resources. However, during the 1990s, gas replaced coal as the primary energy source for the United Kingdom's electricity generation. Because of this, the SSDI for the United Kingdom is expected to decrease since gas and oil reserves in the North Sea have started to deplete.

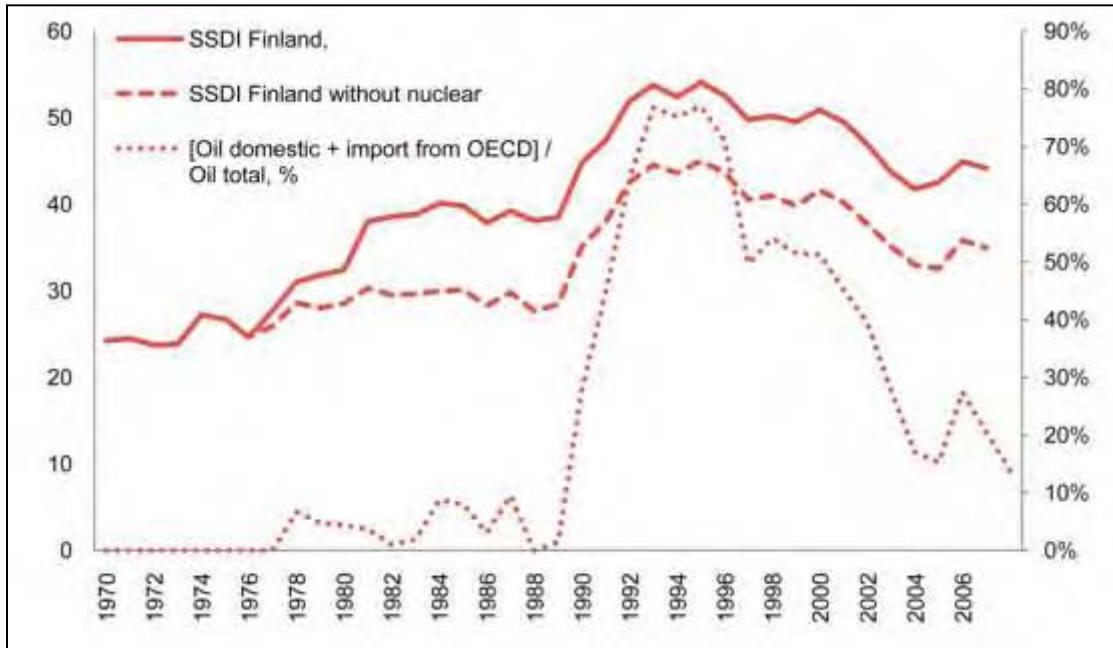
The SSDI for Italy started to decrease in the middle of 1980s. At that time, more than a half of Italian gas was imported from non-OECD countries, and the decision to phase out nuclear power was taken on the basis of a referendum (following the Chernobyl accident). Today, Italy imports almost all its gas and oil from non-OECD suppliers, and the value of the SSDI for Italy is the lowest among the considered countries.

Two special cases: Finland and Korea

Two countries deserve a particular analysis: Finland and Korea. Both economies have shown a considerable increase of the SSDI followed by a sharp decrease of it. At the end of the 1980s, Finland

started to import almost all its oil from Denmark, Norway and the United Kingdom (see Figure 3.9). This explains an important increase of the SSDI during the 1990s. In the second part of the 1990s, Russia (a non-OECD country) became the primary oil supplier to Finland. Because of this, the SSDI values decreased during the last 15 years.

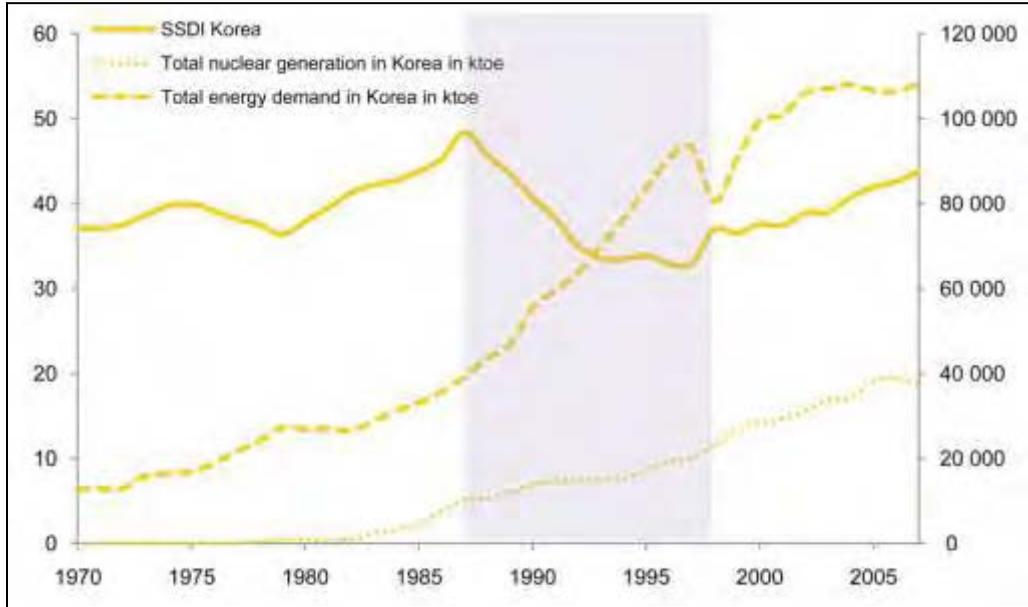
Figure 3.9: The SSDI of Finland



Korea showed an important increase in the SSDI in the beginning of the 1980s (see Figure 3.10). After 1987, the SSDI values for Korea started to fall, and only since 1996-97 has the country's score begun to rise. One may note that total energy demand in Korea was growing very fast since the mid-1970s, in line with economic development. The first sharp increase in energy demand (from 1982 to 1987) was satisfied by the introduction of nuclear power plants. Because of this, the SSDI rose during this period.

Between 1987 and 1997, the Korean economy was growing at a very high rate, and the corresponding energy demand was essentially satisfied by oil imported from the Middle East. Since the year of 2000, the increase in energy demand in Korea has stabilised. A continuous increase of the SSDI since 1996 may be explained by an important increase in nuclear power generation that was multiplied by a factor of more than 2.5 between 1994 and 2006 (see Figure 3.10).

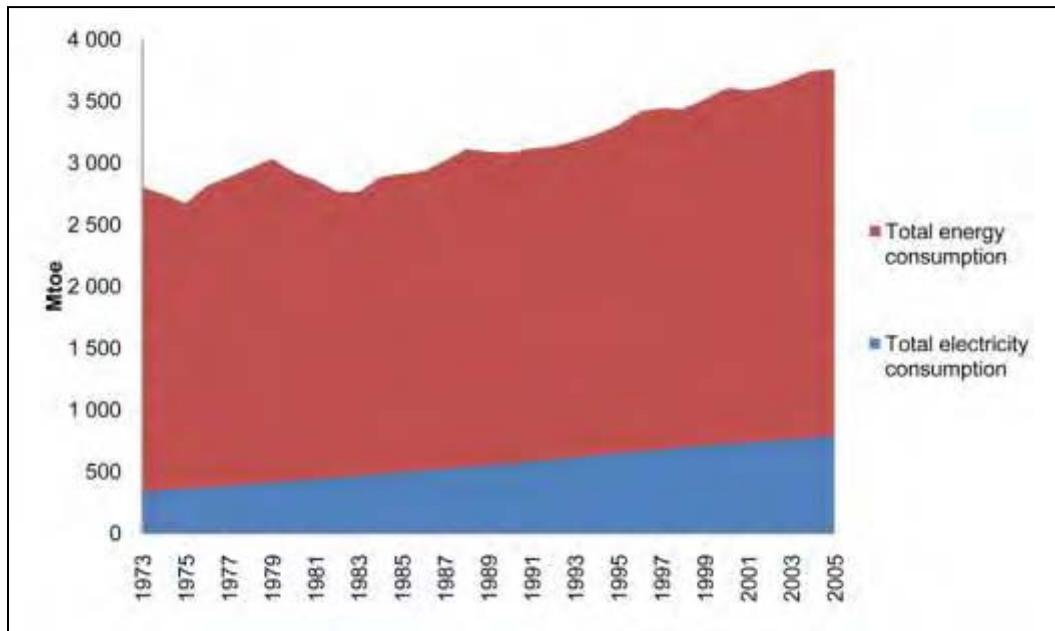
Figure 3.10: The SSDI of Korea



3.3 Electricity generation and the security of energy supply

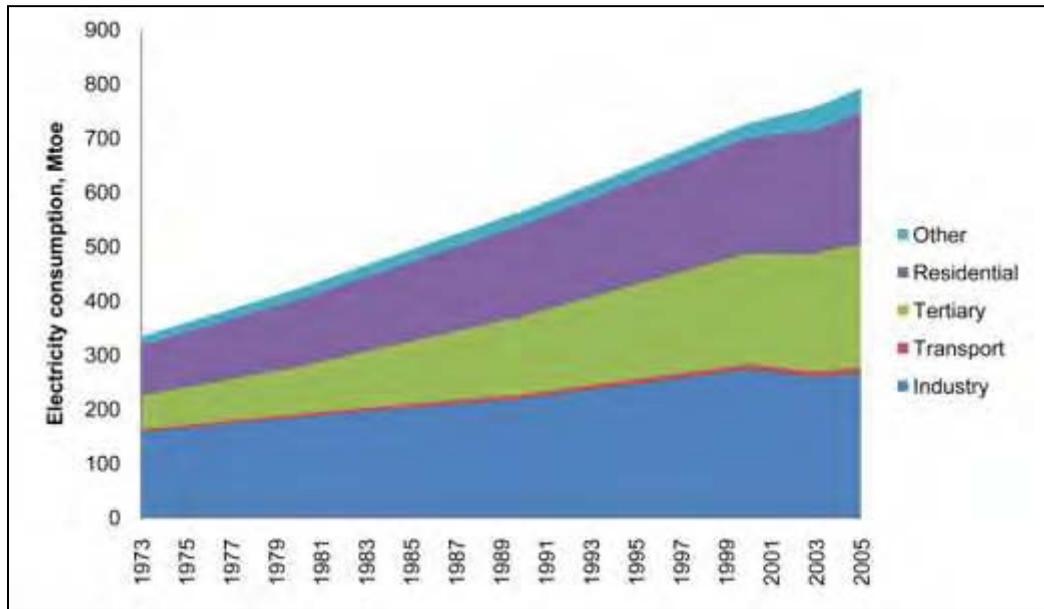
In OECD countries, electricity consumption represented 11% of total energy consumption in 1973, and about 20% in 2005 (see Figure 3.11). This increase is mainly due to the growth of electricity consumption in the residential and tertiary sectors (see Figure 3.12).

Figure 3.11: Share of total electricity consumption in the total energy consumption of OECD countries



Electricity plays a crucial role in a country's economy. Hence, the state of the electricity generation and transport infrastructure is an important component of the security of energy supply.

Figure 3.12: Electricity consumption by sector, OECD countries



Two quantities allow one to assess the ability of the electricity generation capacity to respond to a country's needs:

$$TC/PL = \frac{[\text{Total capacity}]}{[\text{Peak load}]} \quad \text{and} \quad CP/PL = \frac{[\text{Capacity at peak}]}{[\text{Peak load}]}$$

The notions of capacity and peak load are defined in Table 3.5 (IEA, 2009a).

Table 3.5: Definitions of electricity capacity and peak load demand

Total capacity	Net maximum electrical capacity: the sum of the net maximum capacities of all stations taken individually at a given period of operation.
Peak load	The highest value of the power absorbed or supplied by a network or combination of networks within a country.
Capacity at peak	The available capacity of an installation at peak periods is the maximum power at which it can be operated under the prevailing conditions at the time. It depends in the technical state of the equipment and its ability to operate.

The **CP/PL** gives a running assessment of the state of the electricity generation capacity. It depends on the technical state of equipment, but also the weather conditions the day when the peak-load occurs. The evolution of the CP/PL for some OECD countries is presented in Figure 3.13. Although almost all the considered economies have CP/PL higher than one,² the evolution tendency of some countries is decreasing. This is the case of Finland, Italy, Korea, the Netherlands and Sweden.

The **TC/PL** allows evaluation of the country's theoretical ability to satisfy domestic needs in electricity. It measures the amount of the electricity that could be generated if all stations were fully operational. Thus, it estimates the margin a country has in case of a rapid mid-term electricity consumption increase, for example due to economic growth.

2. Exceptions are Finland and Sweden, whose economies are part of a common electricity market (Nordpool) and which thus import large amounts of energy from Norway. Their CP/PL ratio may thus be below unity.

The evolution of the TC/PL for some OECD countries is presented in Figure 3.14. One may note that TC/PL is considerably higher than CP/PL. In the case of Austria, the total capacity was almost two times higher than the capacity at peak in the middle of the 1990s. Globally, the TC/PL values remain stable for most of the OECD countries. However, in some countries the trend is decreasing. In Korea, the total capacity increased considerably at the end of the 1990s (because of its considerable nuclear programme), but the high economic growth rate led to considerable electricity consumption, resulting in an important decrease of TC/PL in 2000-2007.

Figure 3.13: Capacity at peak/peak load

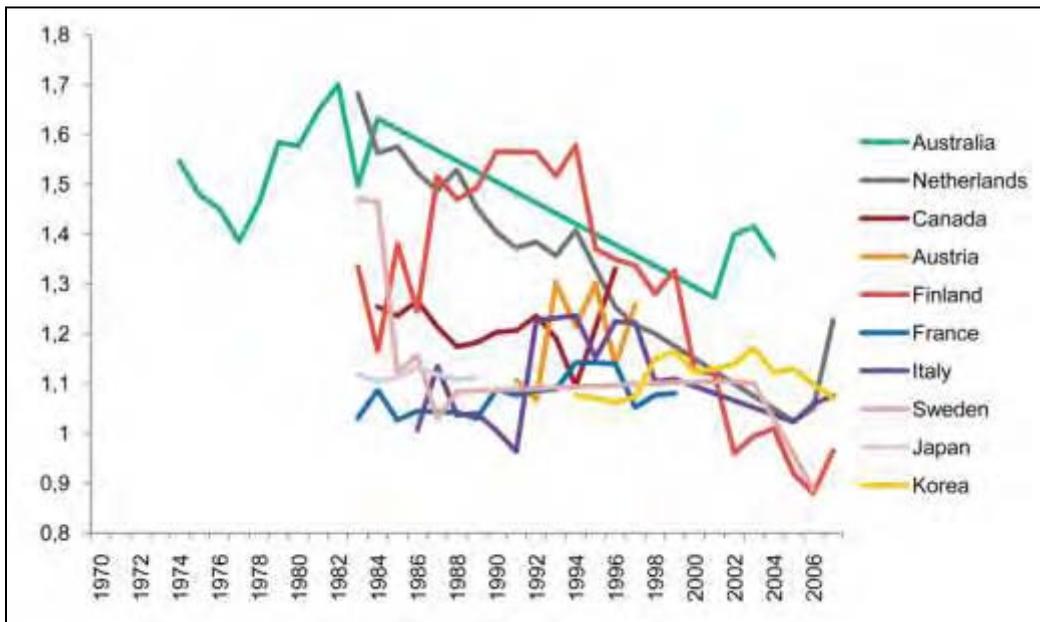
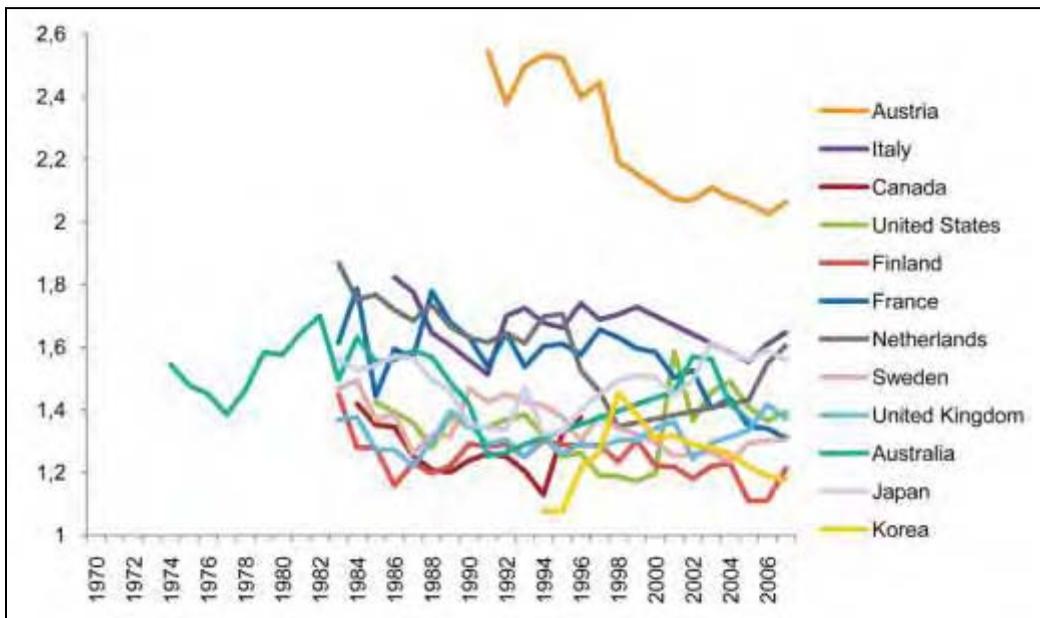


Figure 3.14: Total electricity generation capacity/peak load



3.4 The contribution of nuclear energy and energy intensity to the security of energy supply

Nuclear power offers a concentrated (high energetic density) and economically competitive electricity generation source (IEA/NEA, 2010). The electricity generated by nuclear is only slightly sensitive to the variations of the price of uranium, contrary to energy sources burning fossil fuel. Uranium resources are well-distributed around the world, with an important share in OECD countries (especially Australia, Canada and the United States). Because of these properties, nuclear energy plays an important role in ensuring the security of energy supply in many countries. This is illustrated by the evolution of the SSDI discussed above.

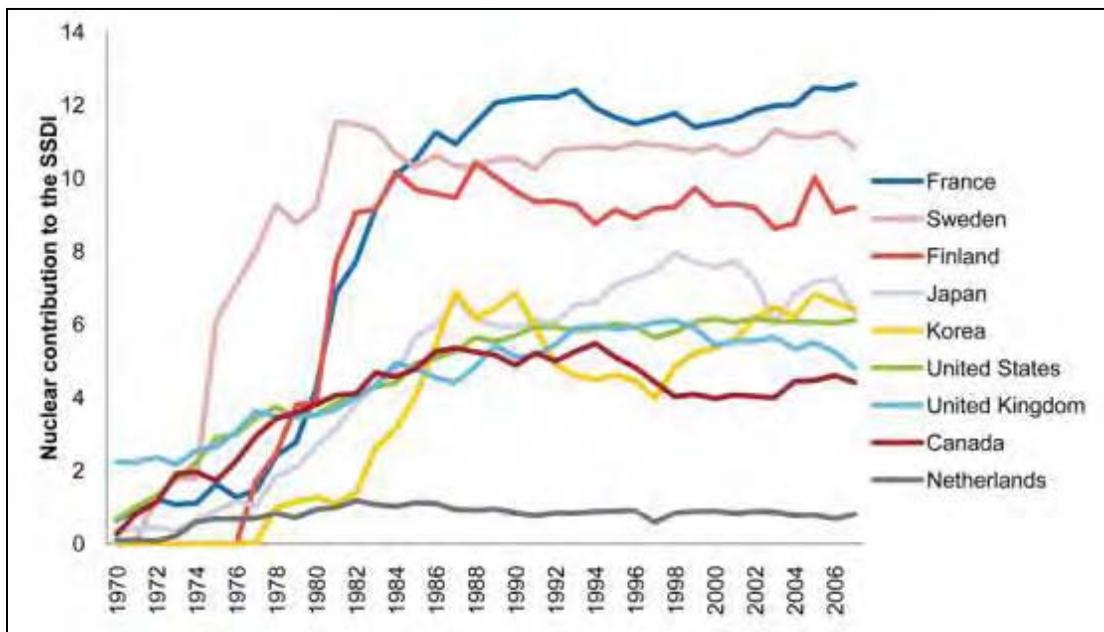
Some countries are currently showing interest in developing nuclear power to strengthen their level of security of supply. Particular examples are the countries that have decided to phase out the nuclear power in the past: Belgium, Italy and Sweden. Ukraine – the country that suffered the most from the Chernobyl accident – approved in 2006 a strategy to build 11 new reactors to strengthen its energy independence (NEO, 2008).

For countries like Finland, France, Japan and Korea the increase of the SSDI is partly due to the introduction of nuclear power plants. The absolute value of the contribution of nuclear energy to the SSDI, defined as:

$$\text{SSDI}(t) - \text{SSDI}_{\text{w/o nuclear}}(t)$$

and is presented in Figure 3.15.

Figure 3.15: The contribution of nuclear power to progress in the SSDI



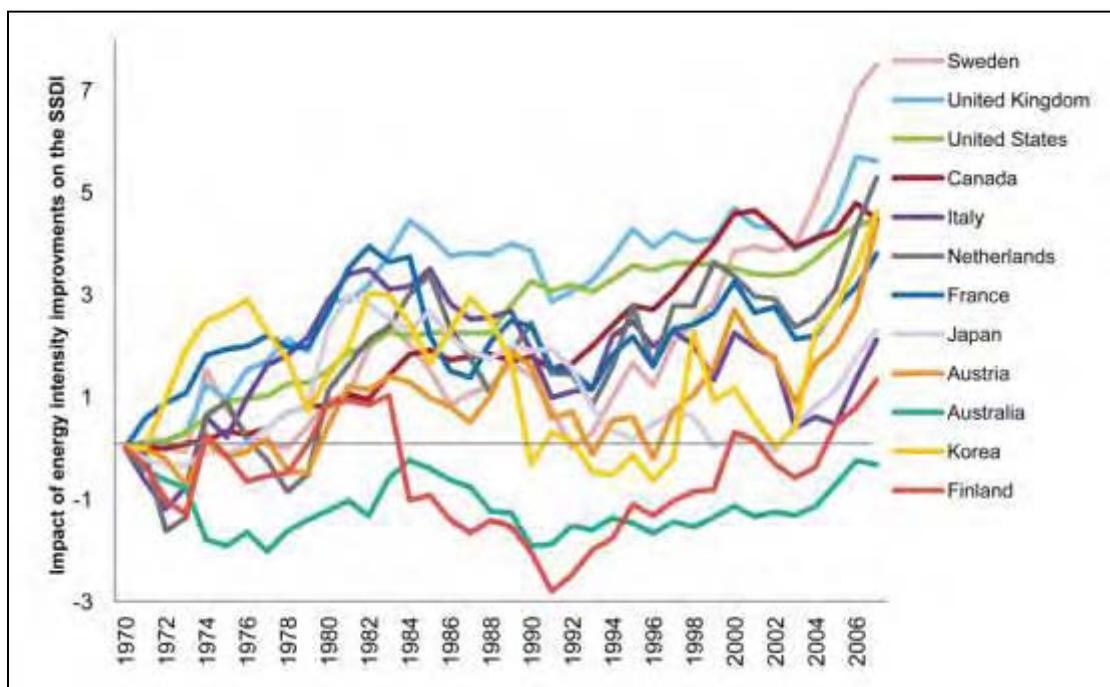
The value of the $\text{SSDI}_{\text{w/o nuclear}}$ for the year t was evaluated by recalculating the index for a hypothetical energy mix obtained from the real country's mix by redistributing the nuclear share among other sources of energy. It is therefore only illustrative. In the case of France, the contribution of nuclear power to the SSDI is more than 12 points in 2007 (about 30% of the SSDI score), followed by Sweden with 11 points (21%), Finland with 9 points (26%), and Japan and Korea with approximately 6 points (about 17% of the total SSDI score).

Another important factor influencing the increase of the SSDI is the improvement in the energy intensity of the economies (see Figure 3.15). For a given country, it is defined as:

$$SSDI(t) - SSDI_{EI\ 1970}(t),$$

that is the difference of the SSDI value for the year t and a hypothetical value of the SSDI recalculated with energy intensities of the same country in 1970. Most of the OECD countries considered have significantly improved their energy intensity during the last decades. For example in Sweden the improvement in energy intensity added more than 7 points to the SSDI in 2007 (about 12% of the value). It is followed by the Netherlands and the United Kingdom. Among the countries considered, the average energy intensity of the economy increased (negative contribution to the SSDI) only in Australia because of intense mineral extraction development.

Figure 3.16: Impact of energy intensity improvements on the SSDI



3.5 The geographical distribution of SSDI values

The geographical distribution of SSDI values is given in Figure 3.16 for the year 1970 and in Figure 3.17 for the year 2007. They provide an overview of SSDI developments in the different OECD regions.

According to these graphs and the data from Figure 3.15, the countries for which the development of nuclear power was the most beneficial from the viewpoint of improving of the security of energy supply are Finland, France, Japan, Korea and Sweden.

Figure 3.17: The geographical distribution of SSDI values in 1970

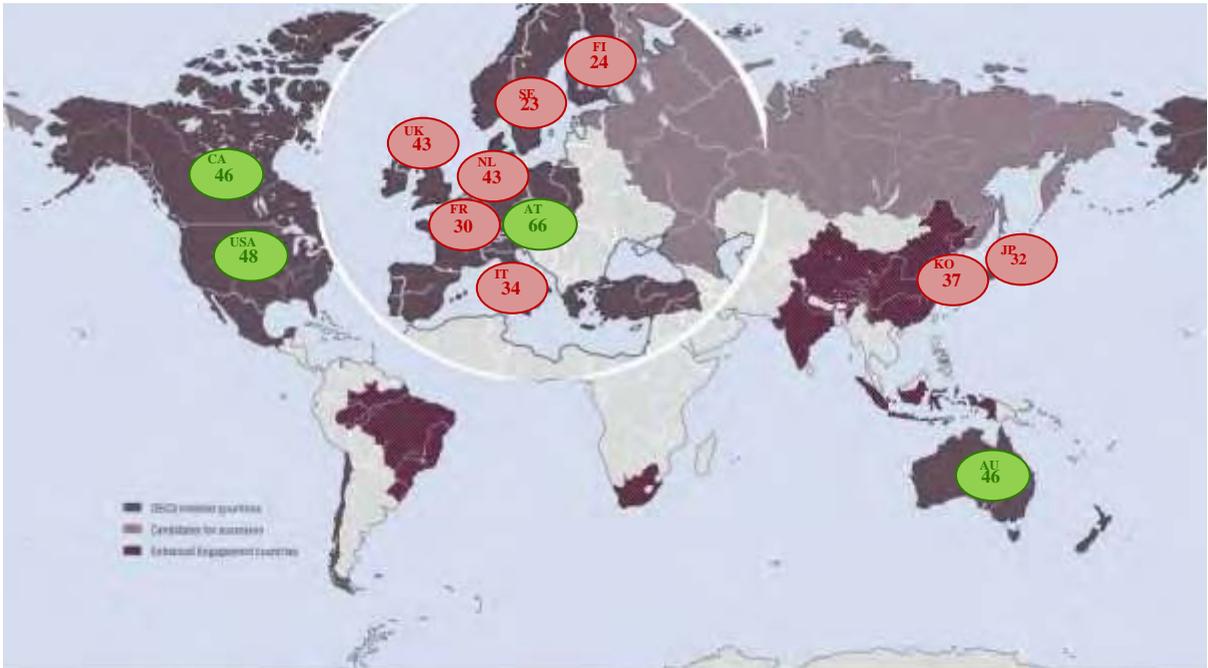
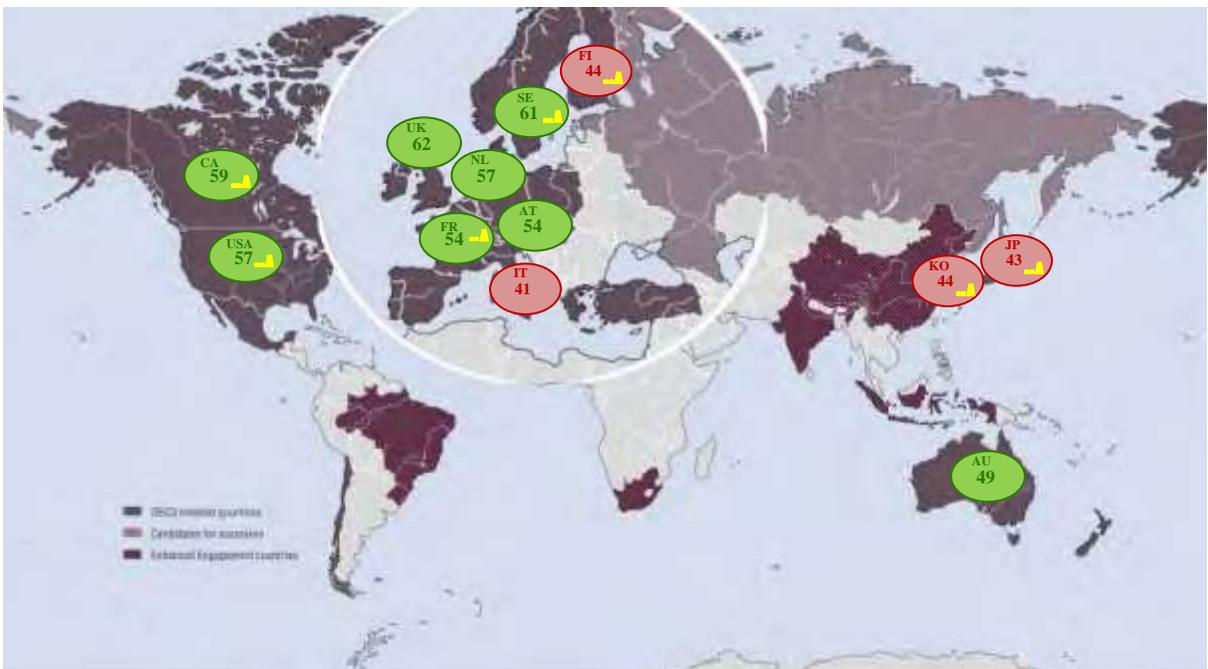


Figure 3.18: The geographical distribution of SSDI values in 2007
 (Yellow symbols indicate countries where nuclear power contributed significantly to SSDI progress)



3.6 Conclusions

In order to compare the evolution of the level of security of energy supply in given countries, a time-dependent quantitative criterion is needed. In this chapter a composite index (SSDI) based on the Supply/Demand Index was used to analyse the change in the security of energy supply in selected OECD countries over the past 40 years, and to quantify the role of nuclear power in strengthening that security.

The Simplified Supply/Demand Index (SSDI) takes into account the degree of diversification of primary energy source supply, the reliability of the electricity generation infrastructure and the efficiency of the final energy use. The evolution of the SSDI for the period 1970-2007 was analysed in the case of Australia, Austria, Canada, Finland, France, Italy, Japan, Korea, the Netherlands, Sweden, the United Kingdom and the United States.

It has been found that for a very large majority of countries, the level of security of energy supply has significantly increased since 1970. Three factors were crucial role for this increase:

- the introduction of nuclear power for electricity generation;
- a decrease in national energy intensity; and
- greater diversification of primary energy sources.

Nuclear power offers a high energetic density and an economically competitive electricity generation source. The electricity generated by nuclear is only slightly sensitive to the variations of the price of uranium, contrary to energy sources using fossil fuel. Uranium resources are well-distributed around the world, with an important share in OECD countries (especially Australia, Canada and the United States). Because of these properties, nuclear energy played an important role in ensuring the security of energy supply in many OECD countries.

Chapter 4 will discuss to what extent the evidence of nuclear power's contribution to the security of energy supply in OECD countries has improved the conditions for nuclear power to be actually being adopted as an option for power generation.

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Chapter 4

PUBLIC ATTITUDES TOWARDS NUCLEAR ENERGY AND SECURITY OF ENERGY SUPPLY

As suggested by the Simplified Supply and Demand Index (SSDI) analysis of a sample of OECD countries provided in the preceding chapter, nuclear energy has played an important role in enhancing security of energy supply, an objective that is increasingly important on the national policy agenda in a number of OECD countries. In this context, a source of energy such as nuclear, which is not strongly dependent on the access to imported fuels and can produce electricity with domestic infrastructures at a stable cost, provides the basis for reliable energy supply.

However, it is clear that, while statistical indicators like the SSDI provide technical analyses to assess the degree of security or insecurity of a country's supply, the way public opinion perceives the level of security of energy supply is quite different. This reaction is often focused on single events and circumstances rather than complex indicators. For that reason, this chapter analyses the evolution of public attitudes towards nuclear energy, and especially how security of supply issues affect how people view the role nuclear energy. In recent years, several opinion polls, in particular in Europe, have gauged the level of concern about these issues. The results are of interest because they shed light on one way of strengthening the political feasibility of increasing the share of nuclear energy in OECD countries, using the driver of improving the security of energy supply.

4.1 Public interest in energy supply security and related issues in the European Union

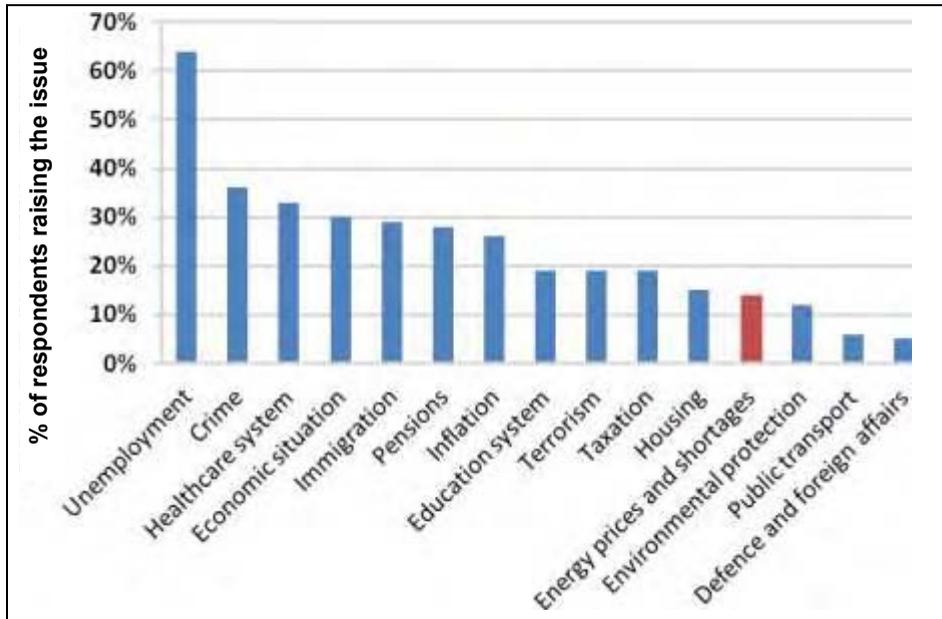
As previously mentioned, energy is fundamental to the economic and social well-being of all countries, exporting and importing alike. The extent to which energy issues constitute a matter of concern to Europeans was studied by several Eurobarometer surveys, including *Energy Technologies: Knowledge, Perception, Measures* issued in 2007, and the last one, *Europeans and Nuclear Safety*, published in 2010.¹ It is important to note that the last survey in 2010 did not provide an update on the issues discussed in the 2007 survey, but it still provides some new material on public attitudes towards nuclear energy, and in particular its acceptability in different countries.

Spontaneously, energy prices and shortages are not the issue of highest concern

To gauge the weight the EU citizens attribute to energy issues, the 2007 survey asked the respondents to state spontaneously which of the issues facing their country today they consider the most important. Figure 4.1 illustrates the results.

1. Eurobarometer is a series of surveys regularly performed on behalf of the European Commission since 1973. It produces reports of public opinion of certain issues relating to the European Union across the member states.

Figure 4.1: What are the most important issues facing your country today?



Source: European Commission, 2007.

Unemployment was cited as the issue of highest concern by a clear majority of those polled, followed by crime, healthcare, the economic situation, immigration, pensions, rising prices, education, terrorism, taxation and housing. Energy issues, namely energy prices and shortages, were mentioned next, by 14% of respondents. This seems not to be spontaneously the main issue of European citizens. This does not necessarily imply a perception of the irrelevance of energy as an issue but reflects its ranking among other concerns that have a more tangible and immediate impact upon people's daily lives. Interestingly, while energy-related issues ranked relatively low on the list of pressing concerns, the security of energy supply aspects – its affordability and reliability – were spontaneously and expressly emphasised in the responses when people were asked to name the most important energy-related issue.²

No doubt reflecting a sense of growing anxiety over rising oil prices, one-third of the respondents to this 2007 survey named “energy prices”, and one-quarter invoked a number of different other concerns relating directly to security of supply. Thus, although the term “security of energy supply” was not expressly singled out among the energy-related issues deemed important by the respondents, significant numbers (or a significant percentage) of answers mentioning “electricity supply”, “limited energy resources” and “energy dependence” are indicative of the concerns about the security or insecurity of energy supply in EU countries.

Among energy issues, security of supply is a top public concern

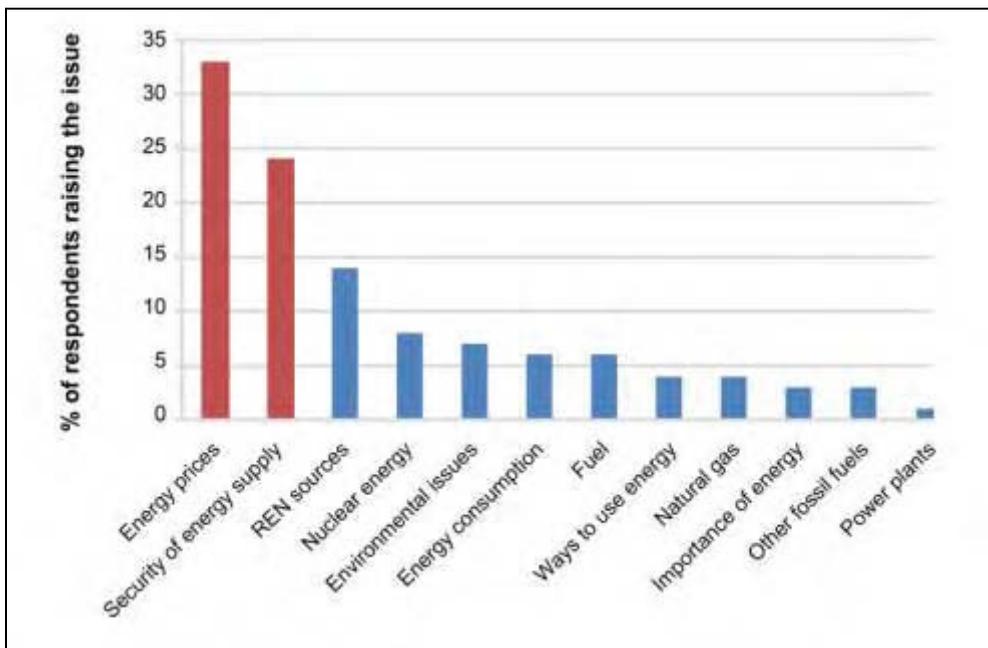
In the listing of energy-related issues, nuclear energy as such was spontaneously mentioned by 8% of respondents. Refining this share country-by-country, one can see that nuclear was mentioned by

2. Security of energy supply has a cost equal to one's “willingness to pay”; people actually buy a certain degree of security of energy supply. Implicitly people accept a certain risk for lack of energy supply since a physical insurance to guarantee delivery at all times is simply too costly. Any willingness to pay is also dependent on the collective risk preferences, which may vary from country to country.

a significantly higher number of respondents in Sweden and France (30% and 22%), which are also the countries where the lowest percentage of those polled expressed concern over energy prices (18%). This is partially not surprising since 45% of Sweden’s and 77.9% of France’s electricity supply come from nuclear (IEA, 2009a). It merits pointing out that the 8% of respondents that answered “nuclear” did so in a very generic manner referring to “nuclear energy” without qualifying their view or calling attention to any specific issues associated with nuclear energy. Similarly, 14% answered renewable energy (REN) and 4% mentioned natural gas.

Figure 4.2 summarises the results concerning this question, with energy price and security of energy issues coloured in red. Under “Security of Energy Supply”, the graph regroups the shares of “Electricity Supply” (12%), “Limited Energy resources” (9%) and “Energy dependence” (3%) responses. Clearly, concerns related to security of energy supply are among the most pressing energy-related issues on the minds of EU citizens.

Figure 4.2: When you think about energy-related issues, what comes into your mind first?



Source: European Commission, 2007.

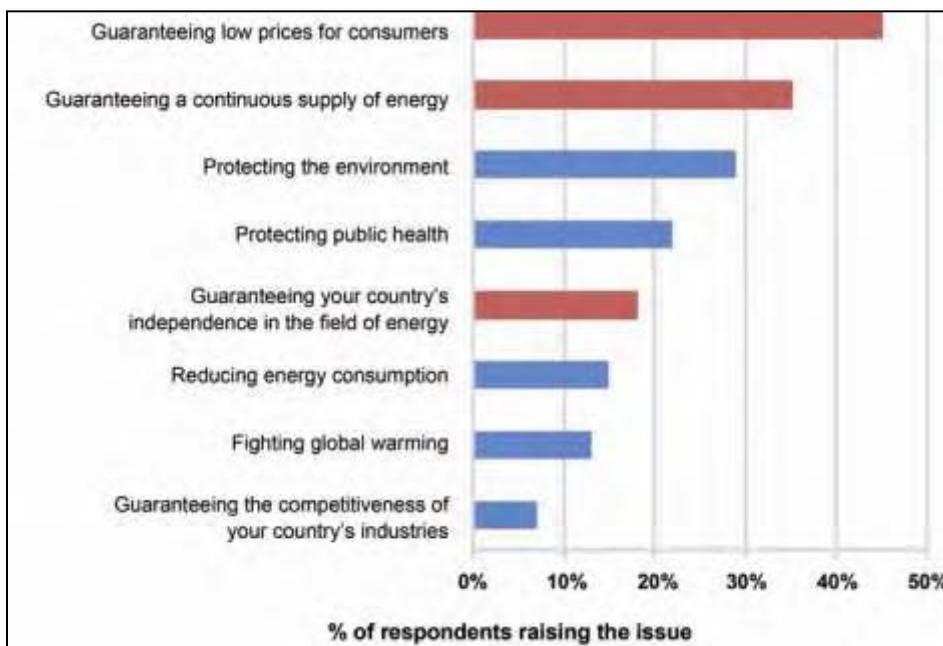
These results provide insight into the way Europeans think about security of energy supply: their main concerns actually focus on volatility of energy prices, which is linked to dependency on a particular source of energy, and is considered a source of insecurity of supply. They also associate shortages and limited energy resources as a threat for their security of supply.

In the medium term, public opinion is focused on security of supply threats

Europeans also mainly fear a rise in energy prices: the Eurobarometer Special Report on Energy Technologies (2007) examined peoples’ threat perceptions asking the respondents to categorise energy-related threats to their respective countries over the next three years: 76% thought “very likely” or “somewhat likely” a doubling or more of energy prices, 48% a significant disruption in gas supply, 40% a terrorist attack on energy infrastructure and 36% a national electricity blackout.

Considering the dominance of security of supply concerns and threat perceptions, it is hardly surprising that when asked to identify preferences for the future direction of national energy policies in their countries, many spoke in favour of measures aiming at enhancing security of supply, directly or indirectly. The results are shown in Figure 4.3.

Figure 4.3: Which two issues should be given priority in your government’s energy policy?



Source: European Commission, 2007.

As shown, when prompted to name two priority measures for government energy policy from a list, 45% chose guaranteeing low prices, 35% guaranteeing a continuous supply of energy and 18% guaranteeing national energy independence. Protecting the environment and fighting global warming were mentioned by 29% and 13% respectively. Again, the price and security of energy supply concerns are uppermost in the minds of Europeans when they consider the desired priorities for their countries’ energy policy.

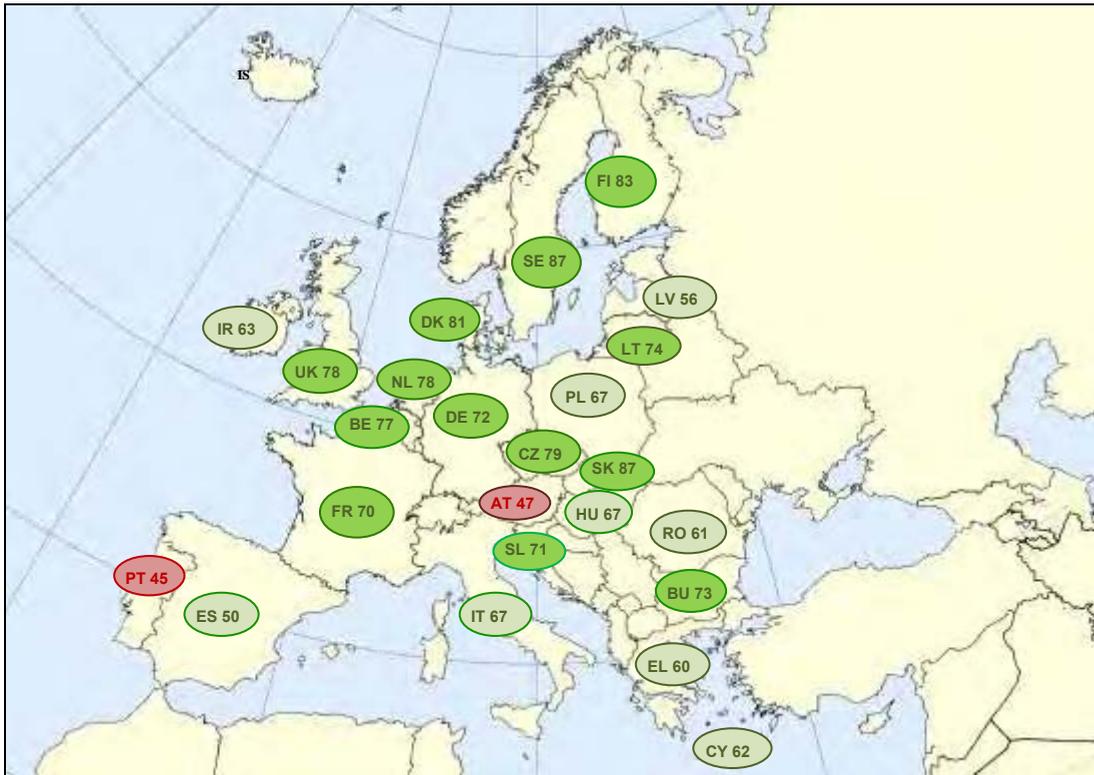
Strong public awareness of the role of nuclear energy in strengthening security of supply

If Europeans are directly asked about whether nuclear energy helps make them less dependent on fuel imports, such as gas and oil, 68% of the respondents in 2010 agree. More importantly, the evolution of public opinion between 2007 and 2010 shows that more and more Europeans consider nuclear energy as an option to help the energy supply situation faced by developed societies.

A country-by-country analysis reveals that in most EU Member States, the role of nuclear energy in limiting energy dependence on fossil fuels is visibly less controversial than before. Figure 4.4 shows the percentage of respondents that agree with the following proposition: “nuclear energy makes us less dependent on fossil fuel imports”. In Sweden, almost 9 out of 10 citizens agree with this proposition, followed by 83% of Finnish respondents, 82% of Slovak interviewees and 81% of Danish respondents. Although Portugal turns out to be the least confident country about the benefits of nuclear energy in terms of security of energy supply, Austria appears as an exception to the actual

pattern (which is that more Europeans agree that nuclear energy reduces fuel import dependency than disagree), with citizens clearly divided on this issue (47% of the Austrian population agree while 48% disagree, whereas Portugal has only 22% of respondents who disagree, and 33% do not know).

Figure 4.4: Do you agree with the statement “Nuclear energy helps to make us less dependent on fuel imports, such as gas and oil”?



Source: NEA Secretariat on the basis of European Commission, 2007.

Countries in pale green gave agreement in the range between 50% and 70%. It appears that these countries are also those where public opinion of the role nuclear energy plays in limiting dependency has notably evolved. Poland (+10 points), Estonia (+11) and Cyprus have had the most favourable evolution of its public opinion on the advantages for security of supply that nuclear energy may bring. It should also be noted that this evolution of the future share of nuclear power in the energy mix is in most EU countries accompanied by losses on the opposing side; indeed, the proportion of interviewees answering that the share of nuclear energy in the energy mix should be reduced decreased consequently from 39% in 2006 to 34% in 2009.³ Only Austria, Spain and Sweden differ from this pattern.

4.2 What kind of indicators do consumers use to evaluate their security of energy supply?

It would not be surprising if perceptions of consumers regarding security of supply differ from statistical indicators of security of energy supply such as the SSDI. Intuitively it would be expected that public opinion would not make use of developed models to evaluate the level of their security of

3. QA15 (Eurobarometer 2010): “In your opinion, should the current level of nuclear energy as a proportion of all energy sources be reduced, maintained the same or be increased?”.

energy supply over time. We would thus expect that the way they analyse the role played by nuclear energy in improving the security of electricity generation is directly or indirectly based on simple, but also perhaps incomplete or biased, indicators that need to be elucidated in order to understand the public attitude towards nuclear energy in ensuring security of supply. Given the previous discussion, it is proposed that the concerns of the polled Europeans about the security of supply situation in their countries may correlate with two main indicators:

- import dependency; and
- volatility of energy prices.

Import dependency

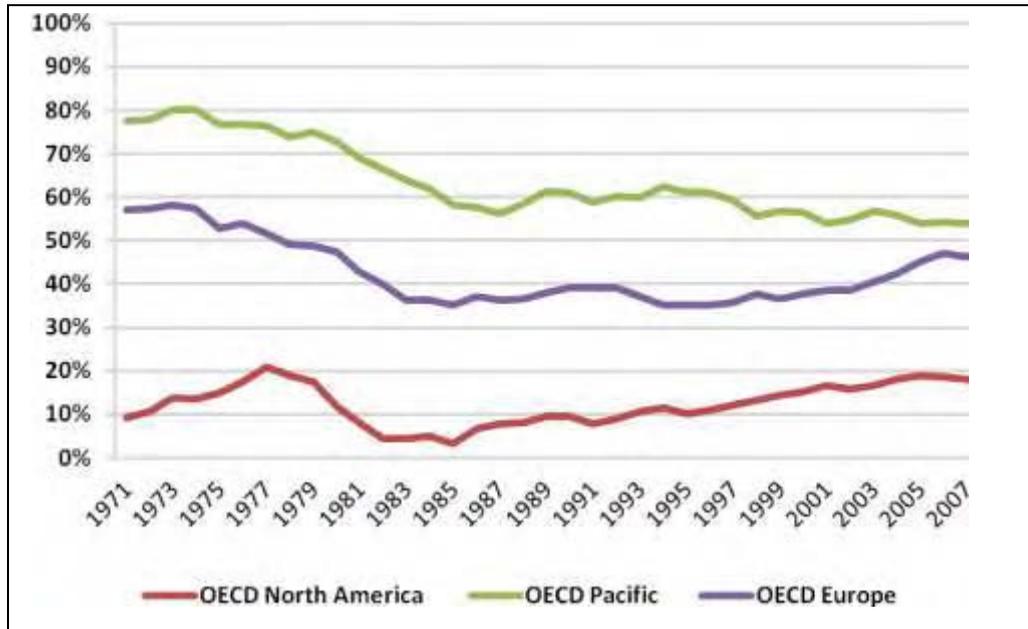
As shown in the preceding sections, EU citizens are somewhat aware of the fact that energy dependency is one of today's most challenging energy questions. They also seem to be fairly knowledgeable of the energy dependence rate of their country. The 2007 Eurobarometer highlights the fact that there are some false beliefs concerning the energy dependency of the European Union. When comparing the respondents' opinion and indicators, one discovers that the results of the survey are paradoxically not that close to the simplest and most transparent indicator of import dependence, which is the import ratio, but actually is correlated more closely with the values of the Simplified Supply and Demand Index (SSDI) elaborated in Chapter 3.⁴

Firstly, this study develops to what extent the import ratio may contribute as a simple indicator for consumers on the aspect of dependence in the definition of security of supply, and then explains the example of European OECD countries and their differences of perceptions on energy dependency.

Figure 4.5 provides an overview of the evolution of import ratios for the OECD countries grouped by region – North America, Pacific, and Europe – for the period from 1971 to 2008. The import ratio for the countries of the OECD Pacific and Europe remains higher than the other regions in terms of import dependency (around 50% by 2007). OECD North America and Europe exhibit an upward trend in the relationship between its imported energy and total energy consumed, even if the import ratio for OECD North America is low at 16% in 2008. Europe (845.09 Mtoe), North America (564.19 Mtoe), Asia (390.84 Mtoe) and Pacific (473.01 Mtoe) are the four energy importing regions, while Latin America (-135.70 Mtoe), Africa (-448.46 Mtoe), Russia (-607.94 Mtoe), and Middle East (-945.26 Mtoe) are net suppliers. This indicator does not of course take into account intra-regional trade, so that the import dependency of individual countries within the OECD regions can vary, sometimes widely, from the regional results. This import ratio is particularly interesting if put together with the issue of energy suppliers. For example, for the EU Member States the most important suppliers of crude oil and natural gas are Russia (33% of oil imports and 40% of gas imports) and Norway (16% and 23% respectively).

4. Total energy imports (net of exports) divided by total primary energy supply (TPES), expressed as a ratio.

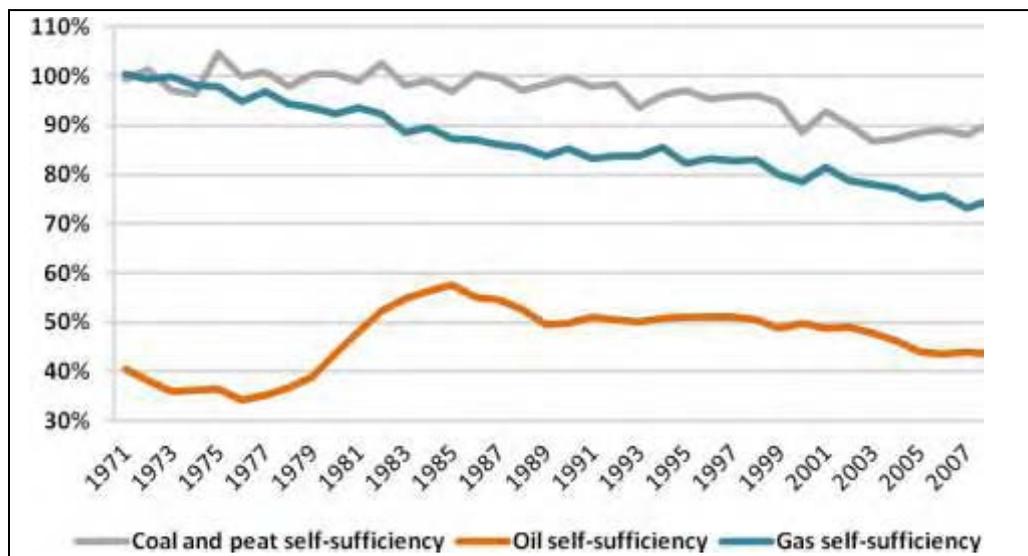
Figure 4.5: Energy import ratios in different OECD regions



Source: IEA, 2009b.

There is also, in addition to regional variation, a degree of differentiation in the import dependencies for each fuel type individually considered. Figure 4.6 illustrates a breakdown of energy self-sufficiency across the OECD area into (1) coal and peat self-sufficiency; (2) oil self-sufficiency; and (3) gas self-sufficiency.⁵

Figure 4.6: Energy self-sufficiency for different energy carriers in the OECD



Source: IEA, 2009b.

5. Peat is an accumulation of partially decayed vegetation matter. It is harvested as an important source of fuel in certain parts of the world. Self-sufficiency is calculated as total energy production divided by total primary energy supply (TPES), expressed as a ratio.

The lowest self-sufficiency ratio is observed in oil production, standing at 44% in 2008. Gas and coal self-sufficiency ratios for the whole of the OECD area are relatively high, but they are in a marked decline too. In itself, import dependency does not automatically signal a situation of alarmingly dwindling energy security of a country or a region. Theoretically, in a perfectly functioning international market for energy carriers, any insufficiency in energy supplies would be immediately filled by energy producers, domestic or foreign, alerted by the efficient price signals. In the world of imperfect international and inter-regional energy markets, however, high or consistently growing import dependency can be, and often is, a matter of concern for policy-makers and general public alike.

The import ratio underlines the dependency of OECD countries on imported energy, and the majority of citizens are aware of this general dependence. However, for a number of reasons subjective perceptions can diverge from statistical indicators such as the import ratio, which shows the limits of using import ratio as an indicator of public opinion concerning security of supply. 61% of respondents believe that their country is entirely or very much dependent on energy coming from abroad. European Union countries face different situations of energy dependency: Denmark is the only country where energy exports exceed energy imports, while the energy dependence rate is highest in small countries such as Cyprus, Luxembourg, Malta and Portugal. Then, for example EU citizens appear to be fairly knowledgeable of the energy dependence rate of their country. Cyprus (89%) and Malta (84%) have the highest number of respondents indicating that their country is entirely or very much dependent on energy coming from abroad. More specifically, in these two countries, 73% and 63% of respondents respectively are aware of the fact that their country is entirely dependent on energy imports. But for example, for Ireland, the energy dependency rate is approximately at 90%, but only 64% of its citizens are aware of that.

In terms of the EU as a whole, respondents who consider that their country is highly dependent on energy imports also believe that this is the case EU-wide. In 16 out of 25 countries polled in the Eurobarometer (2007) over 50% of citizens think that the EU is entirely or very much dependent on energy. 39% of Cypriots, 29% of Luxembourgers and 28% of Hungarians think that the EU is completely dependent on energy imports. On the contrary, Spanish respondents, despite their country's high dependency on energy imports, believe that the EU is somewhat self-sufficient in terms of energy.

Table 4.1: Comparison between indicators on energy dependency
(Public perception, SSDI and import ratio)

	"Is your country dependent on energy coming from abroad?" Percentage of respondents answering "yes, entirely", "yes, very much" and "yes, somewhat"	SSDI value (2007)	Import ratio (%)
Austria	86	53.8	69.1
Finland	94	44.1	53.8
France	80	53.9	50.4
Italy	83	41.3	85.3
Netherlands	86	56.7	38.6
Sweden	87	61.0	36.1
United Kingdom	79	62.4	20.1

Note: Eurobarometer (2007); possible responses were "yes, entirely", "yes, very much", "yes, somewhat", "yes, but only very little", "no, not at all", and "don't know".

Source: NEA Secretariat and European Commission, 2007.

Nevertheless, it appears that the Simplified Supply and Demand Index results from Chapter 3 for OECD Europe actually correlate better with the public perception of energy dependence than the import ratio (Table 4.1). For example, Chapter 3 shows that the values of the SSDI of the United

Kingdom are approximately on the same level as the perceived energy dependency in public opinion polls. They differ, however, from the import ratios as Sweden has a share of imported energy that is almost double the share of imports in the United Kingdom. Perceptions of import dependence and the SSDI in these cases correlate closer with each other rather than with the simple import ratio, since both (public perception and the SSDI) include the origins of imports, which the simple import ratio does not. This bears two lessons. First, never underestimate the “wisdom” of crowds even in matters as complex as energy supply security. Second, while simple indicators have the welcome properties of simplicity and transparency, they are inevitably prone to disregard important parameters of the issue.

Energy price volatility

Energy price increases are also high on the agenda of the Eurobarometer respondents. The 2007 survey underlines that the most important energy-related issue to respondents is energy prices. As the report was being written, the crude oil price per barrel had just hit a new record which was almost four times higher than the price at the beginning of 2000. Energy price increases and thus volatility are the first thing to come to mind for one-third of Europeans (33%). An overview of the price data over the last few years corroborates public concerns about energy price volatility, as a multitude of factors do indeed affect energy markets on a continual basis (Figures 4.7-4.10).

Figure 4.7: Crude oil spot prices (Brent)

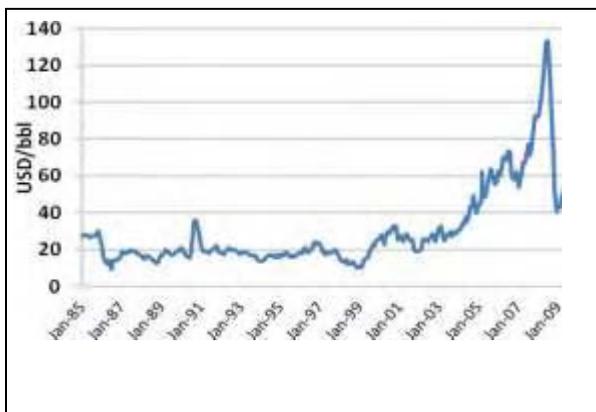


Figure 4.8: Natural gas prices

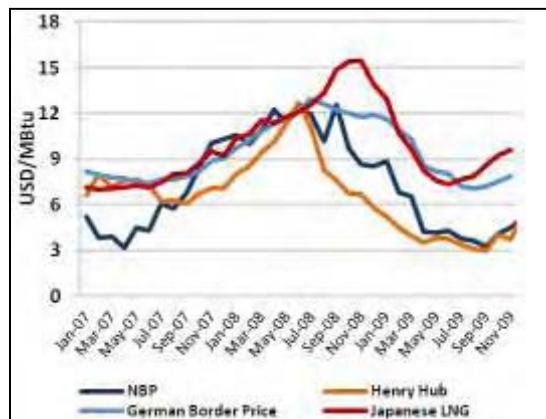


Figure 4.9: Coal prices

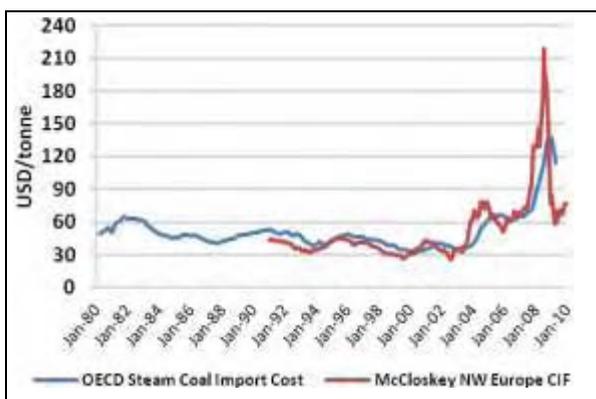
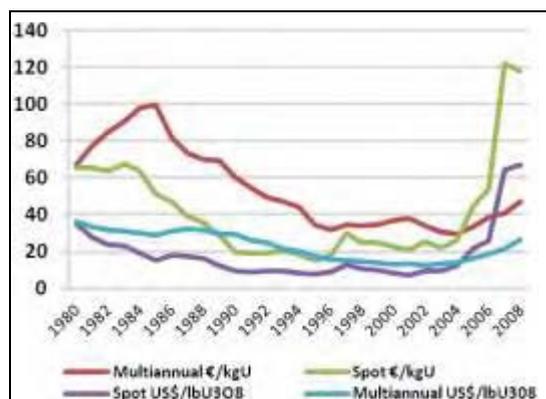


Figure 4.10: Uranium prices



Sources: IEA/NEA, 2010; and IEA, 2009c.

As a matter of fact, it is not the high price levels as such – they could be relatively easily accommodated by efficient well-functioning markets – but rather the volatility of energy prices that poses the most problems from the security of supply point of view.⁶ The mechanisms that reflect how volatile prices of energy sources can impact security of supply are necessary to understand public attitude towards nuclear energy. Almost every source of energy has become a traded commodity, with for some fuels an historical world wholesale market (oil for example), and for others, intervention of the energy market liberalisation process that changed for example gas or electricity industry from a government controlled monopoly to a competitive market, meaning that customers have the freedom to choose their energy supplier. During that process, a commodity market for wholesale transactions is established, and then the commodity can be traded in large volumes, but just like other historical commodities, the wholesale price is driven by traders' perceptions of the relationship between supply and demand. These are based on their analysis of factors which include: current economic climate, changes to prices of related commodities such as oil and carbon, short and long-term weather forecasts, impact of international events such as natural disasters and politics, etc. The constantly changing relationship between these factors leads to volatility in wholesale prices.

Prices of commodities such as oil, gas or coal may more directly impact the consumer than nuclear energy does on electricity prices. Crude oil prices have a major influence on the fuel price for the consumer, indeed in the United States, crude oil constitutes 69% of the price of a gallon of regular gasoline (where refining only costs 9%, distribution and marketing 8%, and taxes 14%).⁷ Gas prices are more complex, since there exist three regional gas markets (North America, Europe and Asia) with strong historical relations due to the pipeline infrastructure on these continents. At the same time, a new type of gas transportation is rapidly accelerating: liquefied natural gas (LNG), which can be shipped over long distances albeit only with specially equipped tankers since it requires constant cooling at minus 162°C.

The LNG and gas from pipelines can also be contracted for the long term (direct 15- to 25-year contracts between the producer and the supplier) or bought by the supplier at the wholesale market (which gives a spot price). Usually, the long-term price of gas is indexed to oil product prices, and consequently follows its volatility.⁸ Lately, the spot price has been decorrelated from the long-term price, which is demonstrated in Figure 4.8 by the path difference between Japanese LNG and German Border Price on the one hand, and the National Balancing Point (NBP) and Henry Hub (wholesale markets) on the other hand. These evolutions in prices strongly impact the price but also security of supply. Indeed, by developing wholesale markets, the diversification of sources may deepen the decorrelation to oil product prices and thus prevent importing volatility from the oil market.

Against the background of the high volatility of fossil energy products, nuclear power generation appears to have two important advantages: the low sensitivity to fuel price swings and the structure of

6. Volatility is one of the several key inputs into option pricing models along with market price, strike price, term until expiration and short-term interest rates. While market price movements exert the most obvious impact upon the option premium, volatility plays a very important role as well. One of the most widely used methodologies to quantify the volatility of prices, commodity and otherwise, is by analysing price movement in the market underlying the option of interest. "Historical volatility" can then be measured as the annualised standard deviation of daily price movements in the corresponding market. An annualised historical volatility (HV) is generally calculated over a particular prior time period such as 30 days or 90 days.

7. U.S. Energy Information Administration, *Gasoline and Diesel Fuel Update*, March 2010.

8. From 1998 to 2009, oil and natural gas long term prices have moved more or less in tandem. Heating oil and natural gas are indeed substitutes in electricity generation and certain industrial uses, which induces fuel switching and price correlation in the short or medium terms.

the fuel supply market that shields it from much of the volatility observed in the evolution of oil, gas and coal prices.

Indeed, as explained in Chapter 1, uranium, which is widely available and easily storable, clearly does not constitute a crucial energy supply risk. In electricity generation for instance, gas-fired plants exhibit a very high sensitivity to fuel prices as a two-fold increase in the fuel cost can augment the cost of generating electricity by over a third (IEA/NEA, 2010). On the contrary, for nuclear power plants the fuel price risk is generally much lower than for fossil-fuelled plants, since fuel costs are a small share of total cost, indeed even a doubling of the cost of uranium would only increase the share of fuel costs from 10% to about 20%, implying an increase of about 10% in the total cost of electricity produced by a nuclear plant. This translates into stable costs over the lifetime of a plant and, depending on market structure, potentially into stable electricity prices.

The structure of the nuclear fuel market is dominated by long-term contracts. In 2008 the ratio of spot to total deliveries in the EU-27 was 2.8% (Euratom Annual report, 2008). But contrary to other commodity markets, in the case of a disturbance in supplies, nuclear reactors operate without refuelling for 12 to 18 months (thus securing months of electricity supply before halting), and if delivery of fresh fuel is delayed, a reactor can still be operated for two to six months beyond its scheduled shut down, at gradually lower power, whereas strategic oil stocks correspond in most EU countries to 90 days' forward requirements. Thus shortages due to geopolitical or economic factors are far less harmful in the nuclear fuel market rather than in other commodity markets.

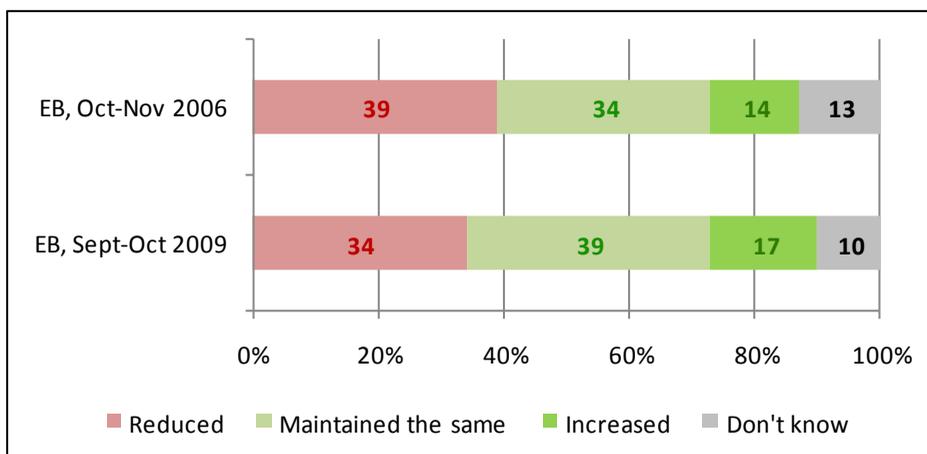
Public opinion surveys show that even if consumers do not have much knowledge of the market mechanisms of energy sources developed in the last paragraphs, they are aware of the energy mix at the EU level. In 2008, the EU-27's gross inland consumption consisted of 36.4% of oil, 25.1% of natural gas, 13% of nuclear energy and 12% of coal, for the most-used energy sources. Some 81% of respondents mention oil as one of the most-used energy sources, 77% gas and 36% nuclear energy, followed by coal at 35%. Their high degree of awareness of the energy mix can thus explain why respondents are focused on fuel price volatility: in the case of oil for example, which is the most-used energy source for a majority of Europeans, the signal transmitted by the price of the barrel can be considered as an indicator of consumers' confidence in the security of energy supply of its country.

4.3 Awareness of the importance of security of supply and public support for nuclear energy

What is interesting to consider is whether public opinion makes a clear connection between the seemingly acute need to enhance energy security, a concern that is on the minds of many Europeans as demonstrated by the results of the Eurobarometer Special Report, and the role that nuclear energy can play in it. To explore the possibility of correlation between the security of energy supply concerns and public attitudes towards nuclear energy that have been developed in the first part of this chapter, it is not sufficient to provide a snapshot into the state of public opinion on these issues. Rather, it is important to perform an analysis of the evolution of public attitudes to security of energy supply and to nuclear energy over time.

The picture of European opinion about the nuclear issue has changed compared to three years ago. Willingness to see a share of nuclear energy as a proportion of all energy sources increased, by three points, whereas on the contrary, the wish to see the share of nuclear energy reduced, as discussed in the first part of the chapter, dropped from 39% to 34%.

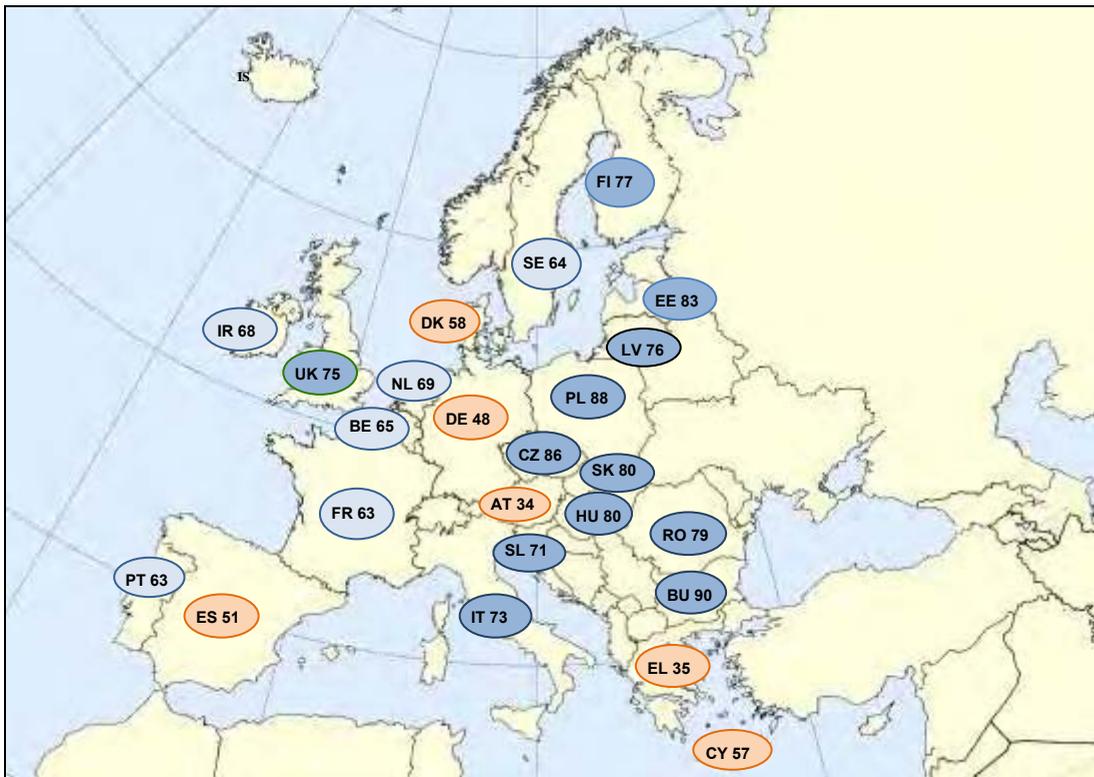
Figure 4.11: In your opinion, should the current level of nuclear energy as a proportion of all energy sources be reduced, maintained the same or be increased? – % EU-27



Source: European Commission, 2007; 2010.

The country-by-country analysis illustrates this subtle and yet significant change, even though care is needed in the interpretation of the detailed results. Most significantly, in the vast majority of EU Member States, citizens who believe that the share of nuclear energy should be maintained or increased greatly outnumber those who believe its share should be reduced, often by a factor of three or more. It is also worth noting that a number of EU Member States who have never operated nuclear power plants in the past have recently seriously examined this possibility. Poland is a good example. Poland relies mostly on coal to meet its energy needs, which are expected to rise by 80-90% by 2025. However, the need to reduce greenhouse gas emissions as part of Kyoto protocol and EU national allocation plan commitments has resulted in a shift in Polish energy policy towards nuclear energy, with a Government resolution adopted early in 2009 requiring that by 2020 part of the electricity consumed should be generated by nuclear power (FORATOM, Country Profile of Poland).

Figure 4.12: “Should the current level of nuclear energy as a proportion of all energy sources be maintained the same or increased?” – % EU-27



Source: NEA Secretariat on the basis of European Commission, 2007.

Moreover, some countries that in the past years shut down or put on hold their nuclear power reactor programmes, but have recently changed their policy towards nuclear energy, like Italy or the United Kingdom, appear also in the highest proportions of public support for nuclear energy. Indeed in Italy, following the Chernobyl accident, the last operating nuclear power reactors in the country had been closed. But in 2008, government policy towards nuclear substantially changed, with a new nuclear build programmes intending to have 25% of electricity supplied by nuclear power by 2030 (today, 10% of Italy’s electricity comes from nuclear power but all imported, 54% from gas-fired generation, 15% from coal, 9% from oil and 14% from hydro, which makes Italy heavily rely on imports – in 2008, Italy is the world’s largest net importer of electricity).

From 2003 to 2006, the United Kingdom government was very negative about the need for nuclear power, but this has changed: the opening paragraphs in Britain’s Road to 2010 underline this shift in position. “Nuclear power is a proven technology which generates low-carbon electricity. It is affordable, dependable, safe, and capable of increasing diversity of energy supply. It is therefore an essential part of any global solution to the related and serious challenges of climate change and energy security”. The UK government commitment to the future of nuclear energy is due to energy security concerns as current reactors approach the end of operating lives, but also due to the need to limit CO₂ emissions. This last aspect has an important role in the government energy policy to 2025 mainly focused on a “trinity” of low-carbon technologies: renewable, nuclear and carbon capture and storage (CCS), but also for public opinion (nearly 70% of the UK population agree with the fact that nuclear power is an advantage in producing less GHG emissions than other energy sources).

When polling nuclear countries, Japan is the country where nuclear is considered least dangerous. A large majority (61%) think that the current level of nuclear energy should be maintained. Nuclear energy accounts for almost 30% of Japan's total electricity production (29% in 2009), and there are plans to increase this to 41% by 2017. Japan is after all a country that needs to import some 80% of its energy requirements, which results in a high priority for security of supply concerns and for efforts to minimise fossil fuel imports. Nevertheless, the Japanese are far more likely than others (79%) to say that the risk of nuclear terrorist acts is high. This ambivalence is one element that explains the current status quo in Japan concerning nuclear energy.

Americans mainly associate (81%) nuclear energy with energy independence. Indeed, a survey in early March 2010 by Gallup underlines this fact: 62% said they favoured nuclear energy as one way to meet national electricity needs. Thus, public support for nuclear energy in the United States is strong: more than six out of ten adults favour the building of new nuclear power plants.

Finally, a socio-demographic analysis reveals common patterns in OECD countries. When asked to choose their preferred site for a new nuclear power plant, males are more likely to opt for a national location with national supervision than women. Women historically have softer and more changeable opinions about nuclear energy than men, probably because they are more inclined to feel concerned about the next generation's future than men. In the United States, 17% of women are strongly in favour of nuclear energy, versus 42% of men, and 48% of women agree with definitely building more nuclear plants, versus 71% of men. Also, better-educated segments of the population are more likely to support nuclear energy. Education also accentuates the gender gap. In the United States, 60% of women college graduates favour nuclear energy, compared with 48% of women who are not college graduates (for men it is 85% of college graduates versus 67% of non-college graduates).

These public opinion results emphasise the increasing support for nuclear energy today in a majority of OECD countries. An important fact of this outlook is that public support is increasing over these past few years, as the security of supply in the power sector seems to be more and more affected, facing numerous issues such as energy market liberalisation, volatile prices, increasing frequency of blackouts, environmental awareness, etc.

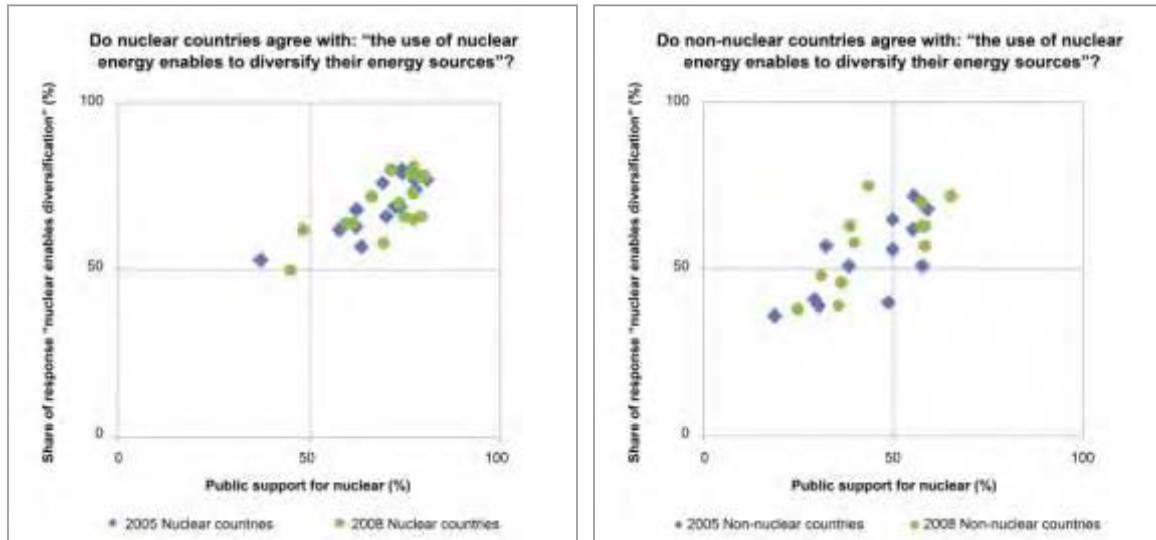
The correlation between security of supply concerns and support for nuclear energy

A study of the correlation between the change in public support for nuclear energy between 2005 and 2008 with the respondents' answers to other questions in the Eurobarometer questionnaire in the same years suggests some insights into the factors that influenced the evolution of public acceptance. In particular, it becomes clear that the benefits of nuclear power in terms of diversification of energy mix and alleviation of oil dependence were duly appreciated, and progressively more so, by the Europeans from 2005 to 2008. This in turn seems to have contributed to greater overall support for nuclear power generation.

Public acceptance of the fact that nuclear energy can play an important role in diversification of EU's energy sources is in a relatively strong correlation with increased public acceptance for nuclear energy, as evidenced from the comparison of the Eurobarometer findings for 2005 and 2008. Figure 4.13 illustrates the shares of positive and negative responses to the proposition "the use of nuclear energy enables European countries to diversify their energy sources" (on the vertical axis), and the share of support for nuclear energy (on the horizontal axis); the correlation is examined for nuclear and non-nuclear countries. The correlation coefficients are 0.87 for 2005 and of 0.78 for 2008. Relatively high correlation coefficients suggest that the role of nuclear power in the diversification of energy sources is one of the key drivers behind increasing public support for nuclear generation.

This correlation can be also explained by the surge in oil prices from 2005 until the second quarter in 2008 and the accompanying concerns on the part of many European consumers about the affordability of future oil imports, as well as their growing preference for energy sources with a significantly reduced carbon footprint.

Figure 4.13: Support for nuclear versus energy diversification



Source: Euratom (2008).

In Figure 4.13, there is a notable evolution from 2005 and 2008 in the relation between public support for nuclear and energy diversification, which is even more observable from a nuclear country point of view. This confirms the trends developed in the first part of the chapter: public opinion is more confident about the fact that nuclear energy can help in ensuring security of supply, especially because it adds another source of energy in the country's energy mix.

The contribution of nuclear energy to reducing importing countries' dependence on oil could be considered as another strong factor contributing to increasing public support, as can be seen in Figure 4.14. The share of positive reactions to the proposition "We could reduce our dependence on oil if we use more nuclear energy" is correlated with the change in public support for nuclear. The correlation coefficients are high for both years: 0.83 in 2005 and 0.84 in 2008.

Figure 4.14: Support for nuclear versus oil dependence alleviation

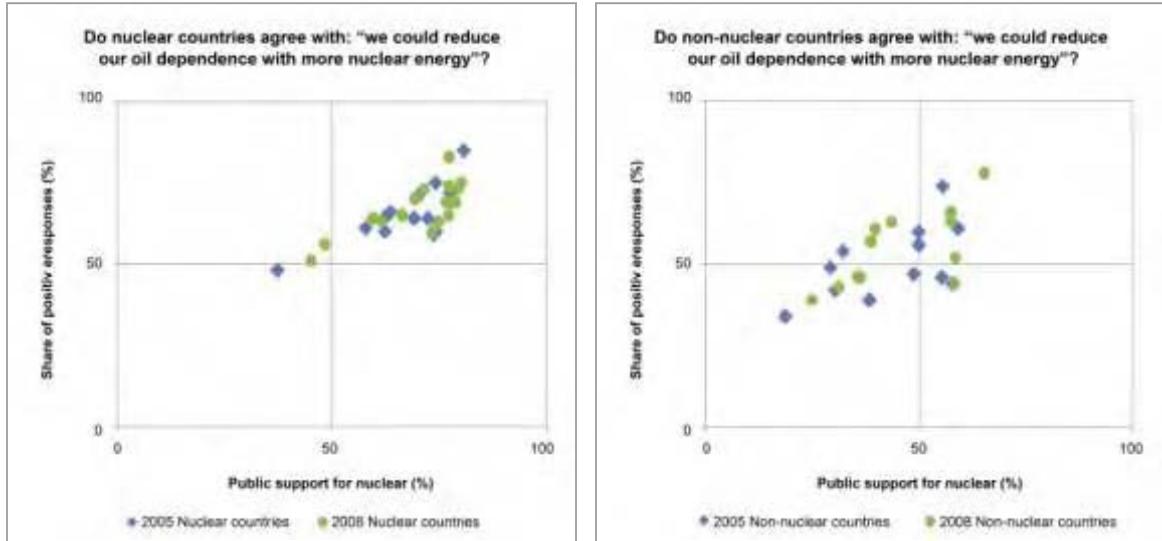
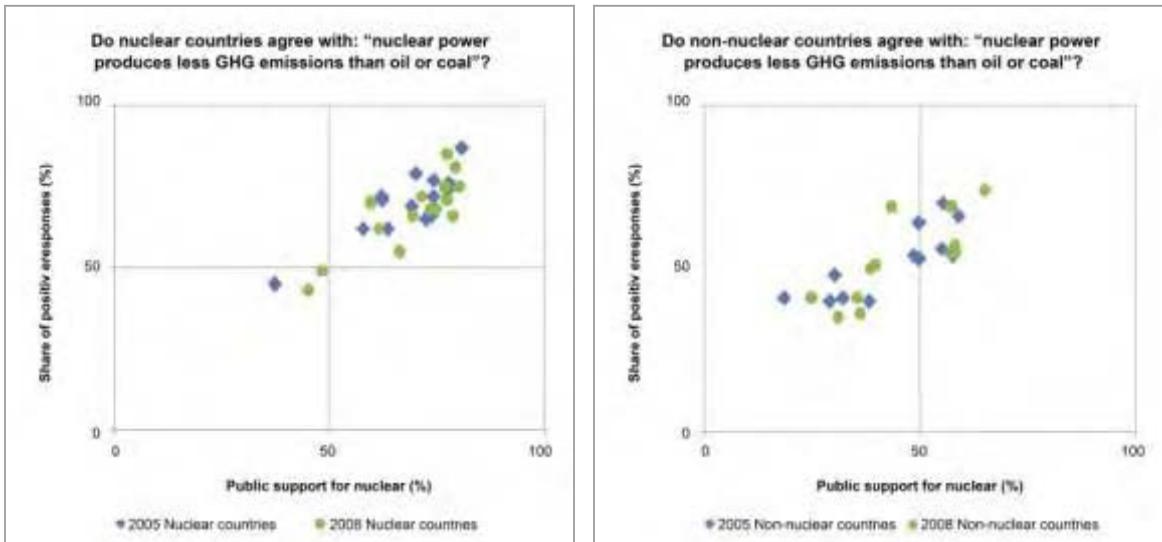


Figure 4.15: Support for nuclear versus reduction of GHG emissions



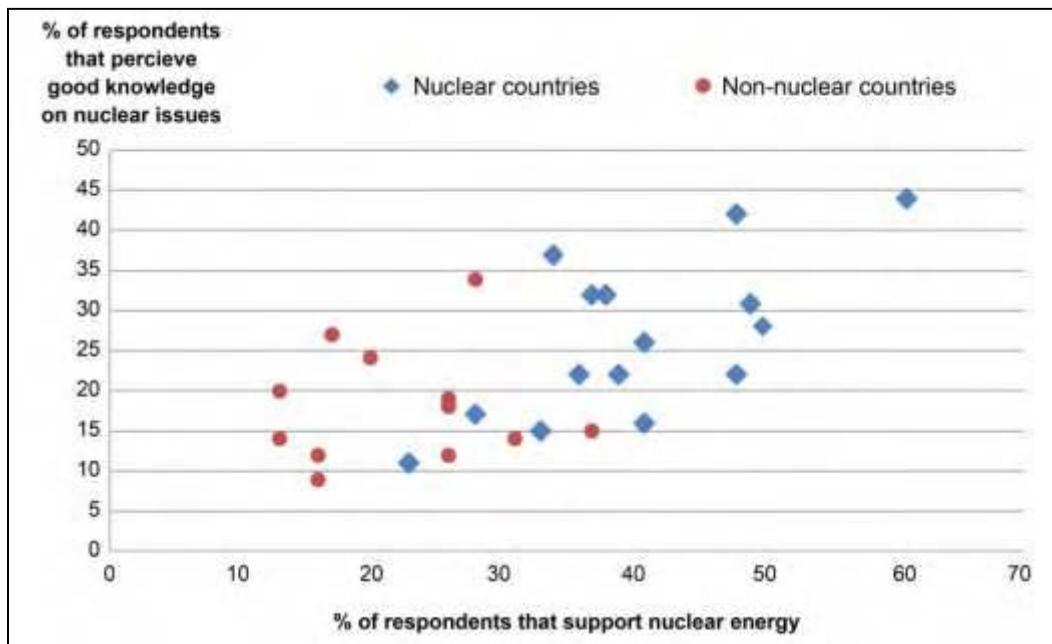
Source: Euratom (2008).

The importance of nuclear energy in terms of its role in reducing GHG emissions, especially when compared to other fossil energy carriers, is an additional driver of increasing public acceptance, as evidenced from the reactions to the proposition “An advantage of nuclear power, that it produces less GHG emissions than other energy sources such as oil or coal” (Figure 4.15). The correlation coefficient between the share of positive responses to this proposition and support for nuclear energy is even higher than in the case of energy source diversification; it is of 0.91 in 2005 and 0.86 in 2008. Most nuclear countries (with the exception of Estonia) can be found in the upper right-hand square indicating both high degree of awareness of the GHG avoidance advantage of nuclear power and high degree of support for nuclear generation. Importantly, one half of non-nuclear countries in Europe are found in the upper right-hand square that can be characterised as a section of improved public acceptance with improved knowledge about the strengths of nuclear energy.

This correlation also appears in poll results in the United States: most Americans think, as the Europeans, that nuclear energy is a source of reliable and affordable energy. Some 82% of US adults associate nuclear energy to some degree with energy independence, 79% with clean air, 77% with economic growth, and 68% with being a climate change solution. In Canada, results on the relationship between nuclear energy and climate change are similar: for 53% of Canadians, in order to have a cleaner air, the use of nuclear energy should be increased in Canada.

The surveys show that the benefits of nuclear power in terms of security of energy supply advantages such as diversification of energy mix and alleviation of oil dependence, as well as reduction of GHG emissions seem to be increasingly well understood by the European citizens. The correlation between the awareness of the benefits of nuclear energy and the degree of general acceptance manifests itself rather potently. This in turn contributes to greater overall acceptance of nuclear power. These results are far more observable in nuclear countries than in non-nuclear countries, which emphasises that a well-informed population on nuclear power better understands the ins and outs of this energy type, and thus the potential benefits on supply security and greenhouse gas emission reductions. In Figure 4.16, one can observe the aspect by comparing nuclear countries and non-nuclear countries on their level of public acceptance compared to their perceived knowledge of nuclear issues. With better knowledge on nuclear energy, the respondents are more inclined to support nuclear energy.

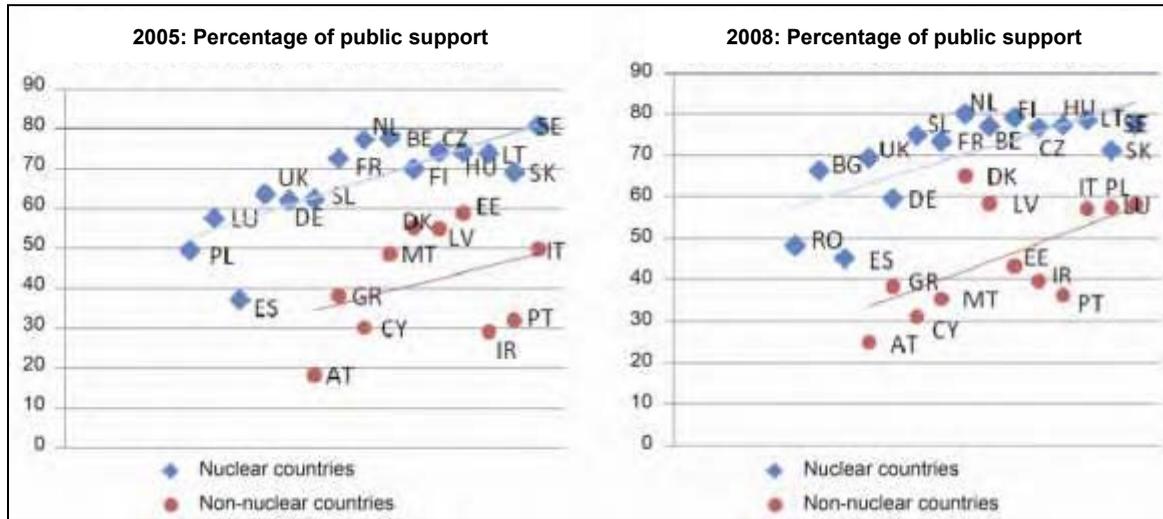
Figure 4.16: Level of public acceptance versus knowledge of nuclear issues



Source: Euratom, 2008.

Finally, one can draw a conclusion on the evolution of public support for nuclear energy. Whereas in 2005, the percentages of public support of non-nuclear countries were mainly below 50%, in 2008 most of these non-nuclear countries have evolved towards a majority public support. On the nuclear countries' side, in 2008, 11 countries on 27 have more than 70% of public support (Figure 4.17).

Figure 4.17: Public support for nuclear energy in 2005 and 2008



Source: Euratom, 2008.

4.4 Conclusions

Public attitudes towards nuclear have a long record of dichotomy, “a bipolar structure of hopeful and fearful images” as S.R. Weart wrote in 1988 (Weart, 1988, p. 422). But once it is analysed through the prism of security of energy supply, public attitudes are more encouraging. Having shown that nuclear can make a positive contribution to the security of energy supply, the object of this chapter was to identify the issues and indicators of how consumers assess their own views of security of supply.

The chapter developed two key notions that are important for individual citizens to assess their security of energy supply: import dependence and volatility of energy prices. However, in the case of import dependency, for example, opinions are sometimes more difficult to perceive if only one indicator is used, even if it is simple, such as the import ratio. But in the end, it seems that people are fairly aware of the energy consumption of their country, which thus leads to the conclusion that decreasing import ratios and stabilising prices may be the main factors that could garner public support on the subject of security of energy supply. Nuclear advantages in this context have been developed throughout the text. It is a source of energy that produces electricity domestically, is essentially carbon-free, does not suffer from price volatility of its fuel, uranium, and helps lower fuel imports and thus dependence.

In addition to concerns about greenhouse gases, the contribution of nuclear energy to progress in these indicators has indeed had an effect on public opinion. Since 2005, public support has increased for nuclear countries as well as for non-nuclear countries. Indeed, a strong correlation between ensuring security of supply and public acceptance of nuclear energy is observable through time. Security of energy supply aspects have played a major role in the evolution of energy policy, with the current rise and volatility of energy prices, but also the rarefaction of fuel sources. The correlation is even stronger in nuclear countries and this trend seems to be confirmed by the fact that public information on nuclear energy increases awareness of the benefits of nuclear energy.

Nuclear energy's political and social acceptability is dependent on a good explanation of its benefits to diversification, energy supply security and greenhouse gas emission reductions. It is up to the nuclear sector itself to make these points convincingly.

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Chapter 5

CONCLUSIONS

This publication has focused on assessing the contribution that nuclear energy makes to improving the security of energy supply in OECD member countries. As a source of power that produces electricity domestically with stable costs and no greenhouse gas emissions during operation, nuclear energy is, in principle, well-placed to make a positive contribution. Under the guidance of the Expert Group on Nuclear Energy and Security of Supply, the authors have concentrated on the question of whether nuclear energy was able to improve the security of supply of OECD countries over the past 40 years.

With the help of a series of transparent and policy-relevant indicators, the study shows empirically that nuclear energy has indeed contributed to improving energy supply security in OECD countries in a significant manner. Nuclear energy contributed to this result by diversifying the energy mix, and *a fortiori* the electricity mix, as well as by decreasing the overall share of fossil fuels imported from outside the OECD.

The study demonstrates this result in a systematic and transparent manner. The first chapter developed the notion of energy supply security and presented the different definitions and approaches that experts have formulated in order to examine this issue. Due to its complexity and the dynamic evolution of its many parameters, as well as the public perception of a “secure” supply, energy security remains an uninternalised externality or a public good that markets are unable to provide for at the appropriate level. Even in the presence of a globalised marketplace for most energy commodities, energy supply security remains a policy issue for which governments need to bear ultimate responsibility.

As a first approximation, one can identify an external and an internal dimension of energy supply security, in both of which nuclear energy can play a constructive role. The external dimension is mainly defined by concerns about import dependence from potentially unstable countries. Nuclear energy, which produces electricity domestically, can obviously reduce such dependence. The internal dimension instead is about creating the appropriate incentive mechanisms and framework to allow public and private actors to invest in adequate levels of production and transport capacity that provide continuous access to energy services at stable prices. Again, as a continuously operating baseload technology with very predictable operating costs, nuclear energy is poised to play a positive role. However, one needs to point out that the stability of operating costs is an advantage that is not always fully transmitted to consumers due to the peculiar price-setting mechanism in electricity markets. This element notwithstanding, the advantages continue to accrue of course at the societal level even if they are captured by electric utilities rather than by the retail consumer.

Consistent with the mandate of the NEA Expert Group “to identify a relevant quantitative approach to measuring the contribution of nuclear energy to security of supply”, Chapter 2 presented a broad range of indicators and models that quantitatively assess a country’s level of security of energy supply. Chapter 3 subsequently developed a specific composite indicator that enables the measurement of the level of security energy supply as well as the contribution of nuclear energy over the past 40 years, for those OECD countries for which a consistent data set was available. Of course, each one of the wide variety of security of supply indicators is designed to answer specific questions. No single

indicator can on its own provide a complete picture of a country's security of supply situation. Among the major categories of indicators discussed in Chapter 2 were: (a) diversification indicators that basically assess the degree to which countries have avoided "putting all their eggs into the same basket"; (b) technical indicators that assess the adequacy of a country's technical infrastructure; and (c) more complex composite indicators or "models" that synthesise a number of primary indicators, thus providing a picture of a country's situation in one single metric. In the end, researchers choose the indicator that is most apt to provide policy-relevant answers to the questions they are trying to address.

In the context of the NEA project on "Security of energy supply and nuclear energy", the most immediately useful composite indicator was the so-called S/D indicator (for supply and demand) developed by the Dutch research institute ECN. It was chosen by the NEA as the basis for its SSDI (Simplified Supply and Demand Index) which was presented in Chapter 3. On the basis of a complete set of energy data provided by the International Energy Agency's Data Services from 1970 to 2008, the SSDI tracked energy supply security based on both supply and demand data. This was the first time that such a systematic effort of developing security of supply indicators based on empirical data over 40 years was undertaken.

Chapter 3 also discussed the relative contributions of nuclear energy and energy efficiency improvements to the overall SSDI. It showed that the security of supply situation in OECD countries has unequivocally improved since the early 1970s. This was due to three different factors:

- the introduction of nuclear power for electricity generation;
- a decrease in national energy intensity; and
- greater diversification of primary energy sources.

In this context, of course, the contribution of nuclear energy is of particular significance. For the first time, this study was able to assess this claim quantitatively. While much of the quantitative results are driven by underlying assumptions, as an essentially carbon-free, largely domestic source, nuclear energy does indeed possess a number of attractive characteristics for improving the security of energy supply. Nuclear energy is a competitive power generation source with high energetic density and low sensitivity to the variations of the price of the uranium, contrary to fossil fuel technologies. Uranium resources are also well-distributed, with OECD countries such as Australia, Canada or the United States holding important shares. Overall, nuclear energy is well-placed to make a positive contribution to improving the security of energy supply in OECD countries.

Chapter 4 aimed to identify the implications of these findings for broader processes of public opinion formation and attitudes towards nuclear energy in OECD countries. Quite naturally, the public at large remains unconcerned by the development of complex indicators. However, individual parameters such as import dependence and price volatility are consistently highlighted as issues of public concern, in particular in the regularly published Eurobarometer opinion polls in the European Union. Chapter 4 highlighted that nuclear is viewed more favourably if it is not pushed as an autonomous issue for its own sake but if it is integrated into the context of broader policy objectives such as ensuring the security of energy supply or the reduction of greenhouse gas emissions. As far as public perception is concerned, nuclear energy is not an isolated issue but is considered more acceptable because of its relation to the need to address both climate change and security of supply. Nuclear energy is no longer a quasi-ideological "yes" or "no" issue. Instead, as an energy source that is producing electricity domestically with stable costs and no greenhouse gas emissions during production, it is increasingly thought of as a possible answer to specific problems.

This insight holds both promises and challenges for nuclear energy. The promise is to become accepted as an essential element of broad energy policy strategies. The challenge is to bring about an evolution in its features and decision-making mechanisms to engage in public debate on issues of siting, strategic technology choices, environmental protection, costs, safety and security as well as storage and decommissioning.

Due to its large fixed costs (not only at the level of the individual plant but also at the level of education, regulatory infrastructures, fuel cycle strategies, etc.) nuclear energy will never be wholly an ordinary industry. Nevertheless, nuclear is now being viewed more dispassionately and is judged on its merits as a solution to questions of security of supply, cost stability and the reduction of greenhouse gas emissions. Engagement with the broader public on issues of common concern is the logical implication of these results. Ultimately, such an integrated approach will enhance the overall sustainability of energy supply in OECD countries.

Annex I

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Annex 2

ACRONYMS

CAIDI	Customer Average Interruption Duration Index
CCGTs	Combined cycle gas turbines
CCI	Crisis Capability Index (CCI)
CCS	Carbon capture and storage
CHP	Combined heat and power plants
CML	Customer minutes lost
CSIS	Centre for Strategic and International Studies
DPSS	Daily peak supply shortfall
ECN	Energy Research Centre of the Netherlands
ENS	Energy not supplied
Entso-E	European Network of Transmission System Operators for Electricity
EPC	Engineering, procurement and construction
EU	European Union
EU ETS	European Union Emission Trading Scheme
Euratom	European Atomic Energy Community
FED	Final energy demand
GHG	Greenhouse gas emissions
GIF	Generation IV International Forum
HHI	Hirschman-Herfindahl Index
IAEA	International Atomic Energy Agency
IDC	Interest during construction
IEA	International Energy Agency
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles
LCA	Life cycle analysis
LCOE	Levelised cost of electricity
LNG	Liquefied natural gas
LSSPR	Largest single supplier, plant or route
LVH	Lower heating value
MVP	Mean-variance portfolio
NDC	Committee on Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle
NEA	Nuclear Energy Agency
NIMBY	Not-in-my-backyard
OECD	Organisation for Economic Co-operation and Development
PES	Primary energy sources
R/P	Reserve-production ratios

S/D	Supply and Demand Index
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SR	Short-run
SSDI	Simplified Supply and Demand Index
SWI	Shannon-Wiener Index
TSOs	Transport system operators
UCTE	Union for the Co-ordination of Transmission of Electricity
USGS	US Geological Survey
US NRC	United States Nuclear Regulatory Commission
VOLL	Value-of-lost-load

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The Security of Energy Supply and the Contribution of Nuclear Energy

What contribution can nuclear energy make to improve the security of energy supply? This study, which examines a selection of OECD member countries, qualitatively and quantitatively validates the often intuitive assumption that, as a largely domestic source of electricity with stable costs and no greenhouse gas emissions during production, nuclear energy can make a positive contribution. Following an analysis of the meaning and context of security of supply, the study uses transparent and policy-relevant indicators to show that, together with improvements in energy efficiency, nuclear energy has indeed contributed significantly to enhanced energy supply security in OECD countries over the past 40 years.



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