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SECURE

Security of Energy Considering its Uncertainty, Risk and Economic implications

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SECURE – Security of Energy Considering its Uncertainty,
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Final report on Multi Criteria Decision Analysis (MCDA), revised

Petrissa Eckle, Peter Burgherr & Stefan Hirschberg (PSI)

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Abstract

The SECURE project, carried out by 15 major European research institutions, started in 2008 and aims at building a comprehensive framework for measuring the security of energy supplies in the EU. Assessing the risks related to geopolitics, price formation and the economic and technical design of energy markets inside and outside of the EU, the SECURE project focuses on both qualitative and quantitative analyses, adopting a global as well as a sectoral approach.

One of the key elements of the SECURE project are various energy scenarios developed with the POLES model.

To compare the performance of the policy scenarios developed in POLES, a Multi-Criteria Decision Analysis (MCDA) was developed.

Multi-Criteria Decision Analysis (MCDA) is a technique to systematically assess trade-offs between different alternatives to assist rational decision making in complex problems. By clearly separating objective analysis of the alternatives from the subjective weighting of the preferences, MCDA allows to decompose a problem and subsequently to simultaneously take into account all aspects of a decision problem, something that becomes impossible to do mentally for all but the simplest decisions.

The performance of the scenarios was assessed for a range of criteria measuring security of supply as well as the classical dimensions of sustainability, i.e. ecological impact, economical performance and social aspects.

For these criteria, thirteen indicators have been calculated for each scenario on the basis of the scenario results as well as additional assessments, e.g. for accident risk or the risk of terrorism.

To implement the MCDA, an online tool (www.secure-mcda.net) was developed that allows stakeholders to perform the MCDA interactively online.

The following conclusions can be drawn from the analysis

No single scenario meets all sustainability and security of supply criteria used in SECURE; thus, trade-offs are inevitable.

Given balance between environmental, economic, social and security of supply criteria, the global regime climate regime scenarios (without shocks) perform best while the baseline scenario is consequently worst.

This result is with two exceptions quite stable with respect to the variations of preferences. The exceptions are economy-centered profiles and/or high importance assigned to the aversion towards worst consequences of severe accidents. The earlier issue is mitigated by the fact that within the SECURE project it was not possible to account for costs of avoided health and environmental damages due to reduced use of fossil energy carriers (i.e. for avoided external costs). Based on earlier experiences the cost of such damages may match or even outweigh the

increased overall costs of systems employing to a large extent environmentally friendly technologies.

There are clear synergies between protection of climate and security of supply. Meeting ambitious GHG-emission reduction goals by means of successful decarbonisation of the energy supply system through expansion of renewables, nuclear and CCS, combined with very extensive efficiency improvements, is also highly beneficial for security of supply.

1 Introduction

In recent years, energy security has become a major issue on the international agenda (Scheepers, A. Seebregts, J. de Jong, & Maters, 2006; World Economic Forum, 2006; 2008). In the analysis of energy security the distinction between short and long term energy security was established, where short term refers to sudden supply interruptions, while for long term security a wider range of concerns such as resource availability, geopolitical issues, long term development of demand etc. play a decisive role. In this regard, rather than only considering supply of energy, the role of increasing demand has come into focus (Jansen & A. J. Seebregts, 2009) and curbing demand is now considered an important lever to increase energy security. In addition, the importance of a systemic approach rather than a sectoral analysis (IRGC, 2008) to account for interdependencies (Rinaldi, Peerenboom, & Kelly, 2001) was recognized.

To form the basis of decision making however, a framework is needed that allows a comprehensive assessment of energy security, analyzing and comparing the influences of the different energy sectors including their mutual dependencies as well as comparing all aspects of energy security. To allow comparisons between energy sectors and countries and to forecast and track the development of energy security in time, a comprehensive set of indicators needs to be developed and where possible quantified.

Several complementary approaches to quantify different aspects of energy security have been developed and applied (Scheepers, J. de Jong, Maters, & A. Seebregts, 2007). For medium and long term energy security a supply/demand index was devised, measuring shares of demand and supply types, their capacity and reliability. (Scheepers et al., 2007; World Energy Council, 2008).

To quantify in particular short term energy security, probabilities of threats as well as the possible impacts need to be known. Threats can for example be accidents or intentional attacks that disrupt physical supply as well as geopolitical tensions or market distortions that compromise the availability of energy in a particular sector. In energy security, the usual definition of risk ($R = C \times p$) being the product of probability (p) and consequences (C) is modified to incorporate vulnerability, i.e. the ability of the energy system to cope with a threat so that consequences are not fully realized (Burgherr & Hirschberg, 2009). Risk (R) becomes then the product of threat (T), vulnerability (V) and consequences (C): $R = T \times V \times C$. The distinction between threat and vulnerability is particularly important in cases where threats cannot be influenced directly, as for example in natural hazards or in threats that originate outside the reach of national influence. Mitigation measures can then be used to reduce vulnerability and thus effectively reduce the risk from a particular threat. Reserve capacity in a particular energy chain can be used as an indicator for vulnerability, but in general it is a property of the energy system as a whole. Indicators characterize then substitutability or diversity, for example in import sources or the diversity of primary energy sources in electricity generation. Some vulnerability indicators at a macroeconomic level are given in (World Energy Council, 2008) : price volatility, exchange rate, rate of energy dependency, rate of energy diversity, import concentration index, rate of energy bill and level of technology performance. Those defined at microeconomic level vary depending on the type of energy consumer and supplier.

The goal of the present work for the SECURE project was to develop measures of energy security and quantify these indicators for a range of scenarios developed in the project. Multi Criteria Decision Analysis (MCDA) was then used to compare the performance of those scenarios under all the aspects quantified by the indicators simultaneously while allowing setting the relative importance of the aspect freely according to personal preferences.

1.1 Scope of the MCDA

Energy security is a complex concept covering many disciplines including (1) engineering responsible for technical safety and sufficient capacity, (2) economy concerned about functioning energy markets, and (3) political sciences analyzing geopolitical security threats. Thus, it is not surprising that there is no unique definition that grasps all aspects. A minimal definition of energy security that concentrates on physical and economical threats to energy supply is “physical availability at an affordable price” (IEA, 2007; World Energy Council, 2008). While there seems to be a consensus that all possible threats should be considered, the scope of possible impacts of these threats that should be part of a definition of energy security remains under discussion. The European commission defines energy security as ”the uninterrupted physical availability of energy products on the market, at a price which is affordable for all consumers (private and industrial), while respecting environmental concerns” (EU, 2000) . This definition sets environmental concern as a constraint to achieve supply security. It could however be argued, that climate change for example will most likely have an influence on the risk to energy security posed by natural hazards. In this regard, CO_2 production in energy supply can well be viewed as a long term threat to energy security, even in a narrow supply security definition of energy security.

In a broader definition of energy security, impacts of the energy production chain on health and social welfare can be considered, covering normal operation as well as accidental events. Recognizing that long term energy security should also incorporate social and ecological impacts suggests integrating sustainability criteria in the definition. Sustainability itself is still an evolving concept comprising environmental, economic and social aspects. A major step towards a comprehensive definition and quantification of sustainability in the energy domain was achieved in the recently completed NEEDS project (Hirschberg, Bauer, Burgherr, Dones, Simons, et al., 2008; Schenler, Hirschberg, Burgherr, & Marek Makowski, 2009).

It is clear that for the SECURE project only a limited number of indicators can be considered in particular in the sustainability dimensions. The range of indicators is limited by the information available from the model output, with the exception of the social indicators that are partially based on additional analyses independently from POLES.

2 MCDA

Multi-Criteria Decision Analysis (MCDA) is a technique to systematically assess trade-offs between different alternatives to assist rational decision making in complex problems. By clearly separating objective analysis of the alternatives from the subjective weighting of the preferences, MCDA allows to decompose a problem and subsequently to simultaneously take into account all aspects of a decision problem, something that becomes impossible to do mentally for all but the simplest decisions.

Often stakeholders have a preconceived mental ranking of the alternatives. By iteratively adjusting the preference profile and comparing the resulting ranking of alternatives to this preconceived ranking, MCDA supports learning and helps to identify the drivers of the performance of alternatives.

MCDA is a two step process, first the performance of the different alternatives is measured as objectively as possible. In the second step the decision makers can set their subjective preferences by weighting the importance of the different indicators.

2.1 Indicator matrix

Quantifying the indicators for N alternatives $A_{1..N}$ and M indicators $I_{1..M}$ results in a MxN table of values v_{ij}:

	Alternatives					
Indicators	A_1 (e.g. scenario 1)	A_2 (e.g. scenario 2)	A_j	A_{j+1}	…	A_N
I_1 (e.g. GHG emissions in tons)	v_{11}					v_{1N}
I_2 (e.g. expenditure in $)						
I_i	v_{1j}	..	..	..		
…						
I_M	v_{M1}		v_{Mj}			v_{MN}

Table 1 Schematic MCDA Matrix

The weighted sum algorithm (see 2.3) requires rescaling of all indicators to the same scale. As all the indicators assessed within SECURE are on a ratio scale[1] (i.e. ratios have a meaning and a natural zero exists), the indicators are scaled in such a way that the maximum value equals 1. This is achieved by dividing all indicator values in line j in the table ($v_{1..N,j}$) by the maximum value in line j (max of $v_{1..N,j}$).

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[1] More information on scales can be found here: http://people.math.sfu.ca/~cschwarz/Stat-301/Handouts/node5.html).

On the final scale 0 means worst performance, and 1 best. In the case that the performance of the original scale was inverse (i.e. higher values indicating a worse performance), e.g. for CO_2 emissions, the final values s_{ij} are calculated as $1 – v_{ij}$.)

2.2 Weights

In the second step the users or stakeholders can set their preferences by weighting the importance of the indicators independently of the alternative, i.e. an indicator can only be set to be important or unimportant for all alternatives.

The indicators can optionally be prearranged in a tree, where the weights can be set for individual indicators as well as for groups of indicators. Figure 1 shows the tree used in the SECURE MCDA:

The indicator weights are then just multiplied with the relative weight of the branch on each level.

Figure 1 Indicator tree for the secure MCDA

2.3 Weighted Sum Algorithm

Many different methods or algorithms have been developed to calculate the final ranking from the indicator table and the weights. For a review see for example (Triantaphyllou, 2000) .

The choice of algorithm depends on the size and characteristics of the specific problem (M. Makowski, Granat, & Ren, 2009). In this case the "weighted sum" algorithm was chosen as it provides a transparent and simple way to derive a ranking.

To calculate the weighted sum, the weights $w_1..w_M$ are multiplied with the respective scaled indicator values s_{ij} and summed for each alternative:

$$S_{ij} = \sum_{i=1}^{N} w_i \cdot s_{ij}$$

The alternatives can then be ranked according to S_j, the higher the value, the better the alternative performs under the given preferences.

2.4 Example

A user assigns the following indicator values from a scale between one and ten on the top level:

Environment	2
Security of Supply	3
Economy	4
Social	1

The relative weight for environment is thus 0.2 (i.e. 2 divided by the sum of all values on this level, 10 = 2 + 3 + 4 + 1).

On the next lower level below ecology, the user gives GHG world a value of 6 and CO_2 EU27 a value of 2. The relative weight of GHG world is then 6 / (6+2) = 0.75 and for CO^2 EU27 0.25.

The TOTAL weight for these indicators is then the product of the values of the different levels, i.e.

0.2 * 0.75 = 0.15 for GHG world, and

0.2 * 0.25 = 0.05 for GHG EU 27.

The indicator value of each scenario is then multiplied with this weight to yield the final result.

3 POLES Scenarios

This chapter is a summary of key aspects of the POLES scenarios (Criqui & Mima, 2010) based on the extensive description given in (Checchi, Behrens, Georgiev, & Egenhofer, 2010). More information on the scenarios can be found in (CEPS, 2009)

A key elements of the SECURE project are various energy scenarios developed with the POLES (Prospective Outlook on Long-term Energy Systems) model. The POLES model provides a tool for the simulation and economic analysis of world energy scenarios under environmental constraints. It is not a General Equilibrium, but a Partial Equilibrium Model for the energy sector, with a dynamic recursive simulation process. Figure 2 gives an overview over the POLES model. From the identification of the drivers and constraints in the energy system, the model allows to describe the pathways for energy development, fuel supply, greenhouse gas emissions, international and end-user prices, from today to 2050. The approach combines a high degree of detail in the key components of the energy systems and a strong economic consistency, as all changes in these key components are largely determined by relative price changes at sectoral level. The model identifies 47 regions for the world, with 22 energy demand sectors and about 40 energy technologies (including generic “very low energy” end-use technologies). Therefore, each scenario can be described as the set of economically consistent transformations of the initial Reference case (i.e. the Baseline described below) that is induced by the introduction of policy constraints.

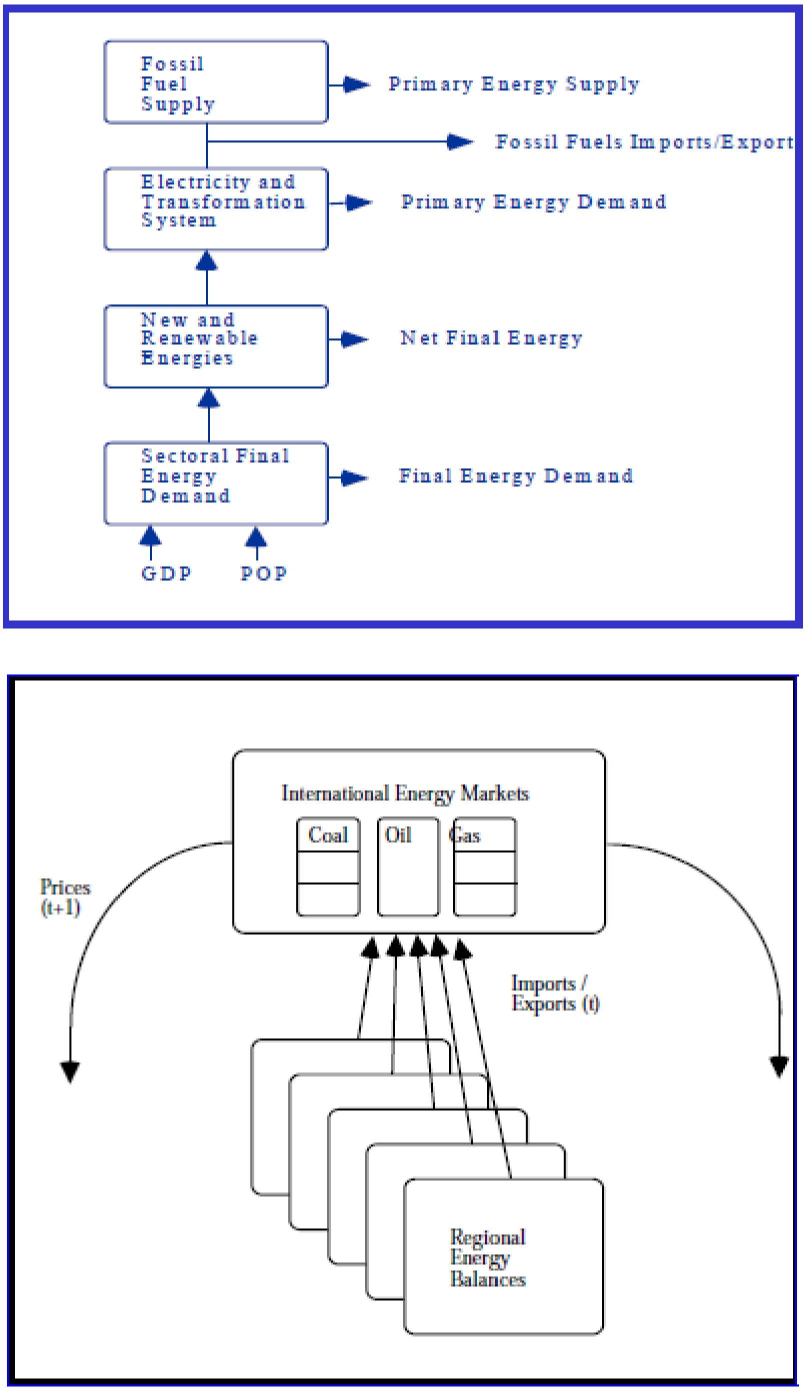

Figure 2 Overview over the POLES model (Criqui, 2001)

World population and GDP are scenario independent inputs to POLES. GDP is assumed to grow on average 1.5 % yearly from 2000-2030 and by 1.3% between 2030 and 2050 in the EU 27. The population is assumed to grow until 2020 by 0.3 % per year, stagnating until 2030 and then to slightly fall by 0.1% per year.

World wide, GDP is assumed to grow by 3.9% on average until 2020, by 2.9% until 2030 and by 2.4% until 2050. At the same time world population is assumed to increase on average by 1.2 % until 2020, by 0.8% until 2030 and by 0.6% until 2050.

4 basic scenarios were modeled

BL : Baseline scenario: a world without climate policy

MT : Muddling Through: Copenhagen forever

EA : Europe Alone: Climate policy with target of reducing grenhouse gas emissions by 60% in 2050 compared to 1990 levels only in Europe

FT : Full trade, a global climate regime following a potential agreement in Johannesburg with two sub scenarios

In addition 3 shocks were simulated:

Nuca : Nuclear accident

Sh : Fossil Price shock

No CCS : No Carbon Capture and Storage (CCS)

3.1.1 GDP POLES

The GDP is given as an input to the POLES model and is the same for all scenarios, as shown in Figure 3 for the world and Figure 4 for EU27.

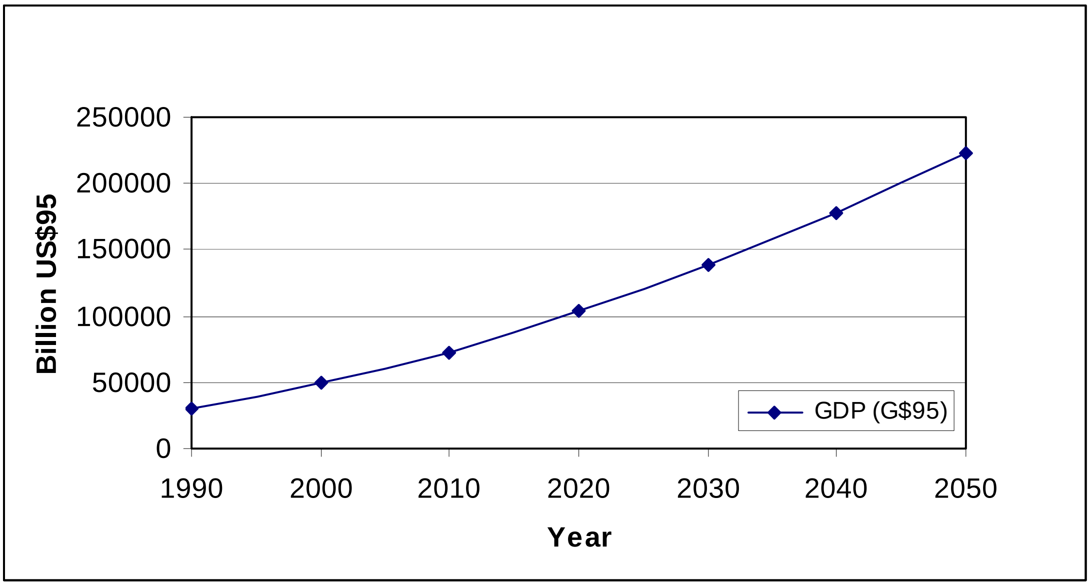

Figure 3 GDP world in all scenarios

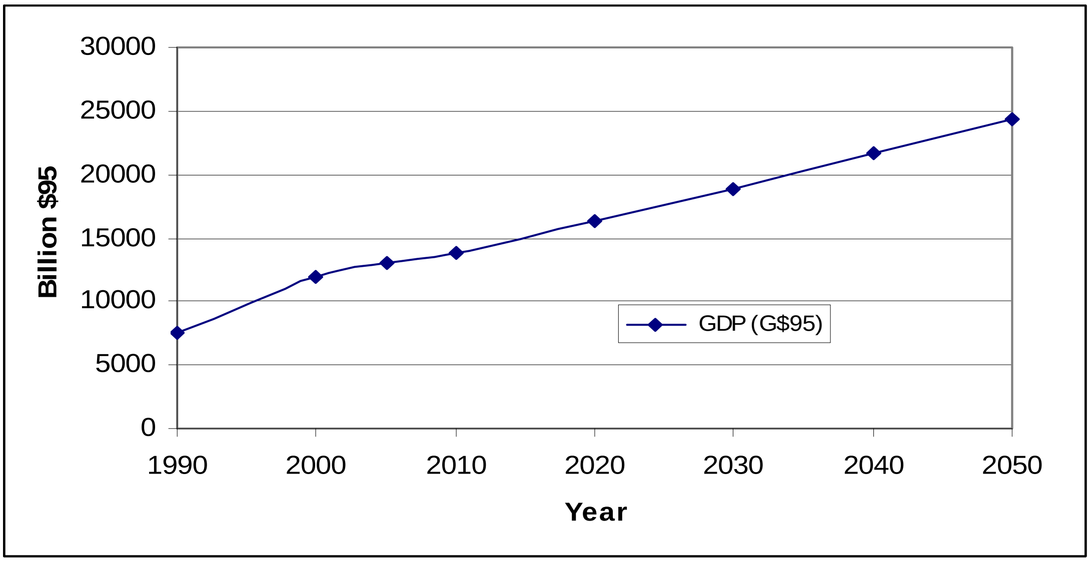

Figure 4 GDP EU27 in all scenarios

3.1.2 Energy mix in 2050

Figure 5 and Figure 6 show the energy production mix worldwide and in the EU27, respectively. The scenario values are for the final year of the mode, i.e. 2050, for comparison also the mix in the year 2000 is shown (the same for all scenarios).

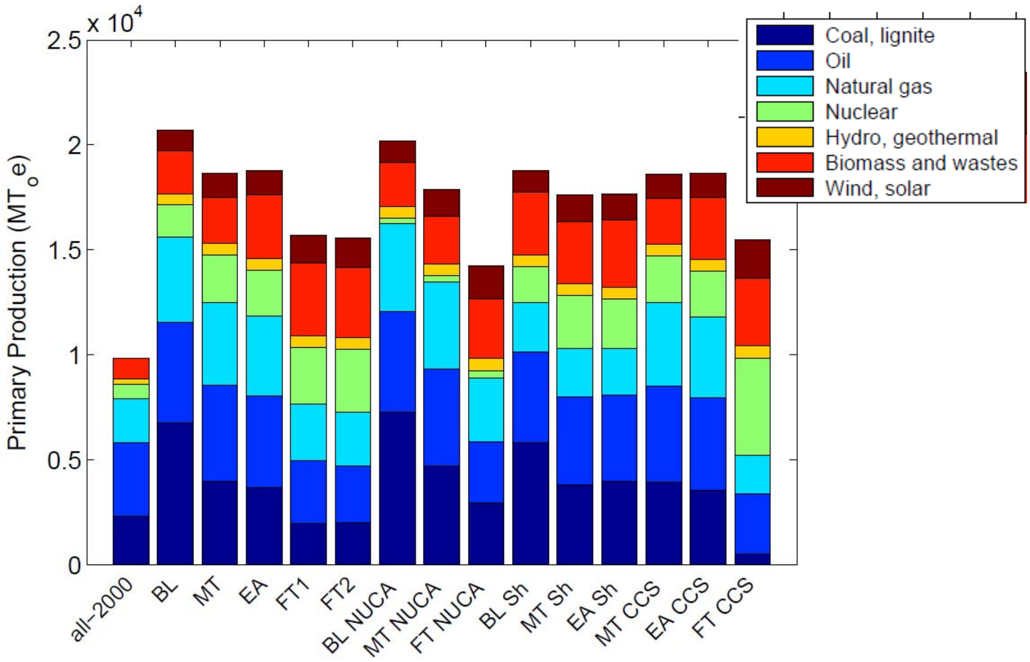

Figure 5 Energy production mix in 2050 worldwide (data in 2000 for comparison)

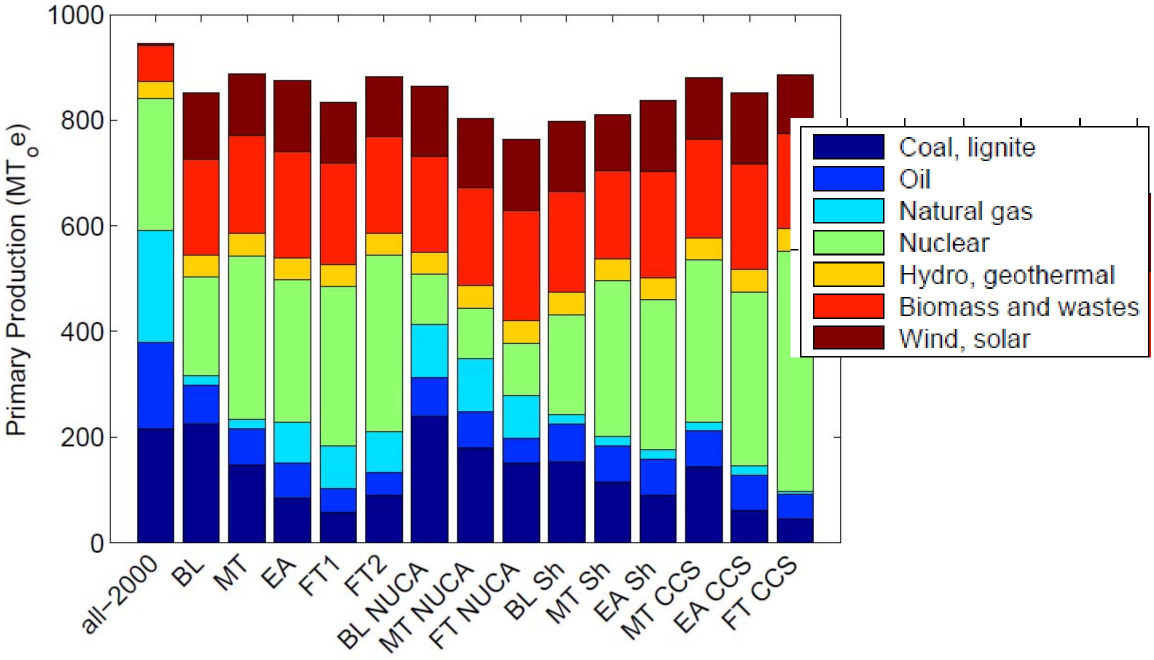

Figure 6 Energy production mix in 2050 EU27 (data in 2000 for comparison)

3.2 Basic Scenarios

The scenario descriptions are taken from (Checchi et al., 2010).

3.2.1 Baseline (BL) – No Climate Policy

The Baseline scenario provides a theoretical image of the development of energy systems until 2050 in the absence of any climate policy. Since climate policies are a reality, it should be considered merely as a reference to allow comparison with the three policy scenarios (MT, EA, FT). The Baseline scenario describes a world where the human population grows from almost seven billions in 2010 to over nine billions in 2050, where global real GDP triples, and where global primary energy consumption rises by 70% (POLES model). Fossil fuels account for 83% of global primary energy consumption in 2010 but, despite continuing absolute growth, only for 76% in 2050 (see Figure 5). In particular, coal consumption doubles between 2010 and 2050, oil consumption continues to increase reaching a peak around 2030, and the consumption of natural gas experiences a progressive - albeit declining - growth over the whole period. On the other hand, the share of renewables in global primary energy consumption remains modest with increases from 12% in 2010 to some 17% in 2050. As for Europe, primary energy consumption rises by about 16% between 2010 and 2050. While the share of oil decreases from 37% to 25%, the penetration of coal goes up from 17% to 25%. At the same time, the share of renewables in EU27 primary energy consumption increases to only 17% until 2050 (or 21% in terms of final energy consumption). Without a focus on domestic energy resources, the EU becomes more dependent on imports from third countries. While in 2010 the EU imported 53% of its energy consumption from abroad, this share increases to 58% in 2050.

3.2.2 Muddling Through (MT) – Copenhagen Forever

Despite decades of rhetoric on the need to take collective action to address climate change, national governments choose to focus on securing their energy supplies in the near future rather than to cooperate for a more sustainable energy system. International discussions on climate change stagnate, creating a paralysis that allows CO_2 emissions to grow continuously until 2050. The first missed opportunity for international climate change negotiations was Copenhagen 2009 when national governments – lead by a still skeptic United States Congress and some developing countries afraid of carrying a disproportional share of the costs – did not accept a significant share in reducing global GHG (Greenhouse Gas) emissions by 50% of 1990 levels by 2050. A number of other international agreements on climate change follow, but none of them makes up for the failure experienced in Copenhagen. The latter marks the beginning of a new era of energy nationalism, opening the path towards an unsustainable global energy environment. By 2100, CO_2 concentration stabilizes at above 500 ppmv (parts per million by volume) translating into a global temperature increase of 3-4°C above pre-industrial levels (IPCC, 2007). The socio-economic impacts in Europe are similar to those described in the Baseline scenario above, both in terms of type and geographical distribution. However, they are noticeably smaller in magnitude even though it should be kept in mind that the range of possible climate change effects is very wide due to various uncertainties. For example, under the PESETA[2] project, a stabilisation of CO_2 concentration at 500 ppmv could result in a GDP loss of €20 billion in the studied sectors and a corresponding annual welfare loss of only 0.2% in the 2080s (Ciscar et al., 2009).

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[2] Projection of Economic impacts of climate change in Sectors of the European Union based on boTtom-up Analysis

Compared to today, one million Europeans would be affected by coastal floods and some 2,000 km^2 of land could be lost in Europe. Concerning river floods, the rise in the amount of people affected would be only one quarter of that in the Baseline scenario, with only half of the respective annual losses.

3.2.3 Europe alone (EA) – Climate Policy only in Europe

Although reaching an international agreement on climate change has not been possible, the European Union does not abandon its energy and climate change ambitions. European member states not only stick to the 20-20-20 targets by 2020 as agreed in the 2008 Energy and Climate Change Package, but they decide to go further, cutting their GHG emissions by 60% by 2050 compared to 1990 and extending the EU-ETS (Emission Trading System) scheme indefinitely beyond 2020. However, in the absence of an international agreement, the overall benefits of the EU going alone and combating climate change are clearly very limited. The reduction of CO_2 emissions achieved by the EU is indeed largely off-set by the inaction of major polluting countries such as the United States, China, India and Brazil. The resulting rise in global emissions by 2050 leads to a global temperature increase and respective climate change impacts in Europe essentially identical to those in the previous scenario. The good news is that, thanks to its long-term commitment to sustainable energy policies, the EU is able to strengthen the security of its energy supplies by considerably reducing import dependence. Similarly, the EU keeps its frontrunner role in renewables, which leads to the creation of some 3 million jobs until 2020 alone, mostly in biomass, wind and hydro technologies (Ragwitz et al., 2009). In addition, the renewables energy sector can generate a total value-added of around 1.1% of GDP until 2020, including export opportunities to countries with less developed renewables sectors.

3.2.4 Full Trade (FT 1/2) – Johannesburg Agreement

There is an emerging international consensus to tackle climate change globally in order to limit average global warming to no more than 2^{o}C above pre-industrial levels. In Johannesburg in December 2011, the world has decided by 2050 to reduce global GHG emissions by 50% compared to 1990 levels.

Two sub scenarios have been modeled: FT1 assumes two global markets for CO_2 emission allowances, one for Annex I countries (i.e. industrialized countries) and one for non Annex I countries (i.e. developing countries). FT2 assumes a fully integrated global market for CO_2 allowances.

This ambitious reduction target is achieved in the Global Climate Regime scenario of POLES, where global CO_2 emissions peak around 2020 and decrease considerably thereafter. As a result of global climate change mitigation efforts, CO_2 concentrations are stabilized at around 400 ppmv, which translates into a 50:50 chance of limiting global average temperature increase to 2^{o}C by the end of the century (IPCC, 2007). There are still serious climate change impacts but overall, they seem to be manageable. According to the IPCC, global impacts of climate change still include Greenland ice sheet melting and accelerating sea level rise leading to frequent coastal flooding. However, the risk of these events and the intensity of weather events may be lower, leading to fewer extremes than under other scenarios (Kundzewicz et al., 2009)

Large-scale transformation of ecosystems and degradation of coral reefs may also be avoided, but 100% of Arctic sea ice would likely still be lost. In addition, fewer people may be affected by climate change impacts. At such low temperature increases the net economic impacts in Europe are likely to be positive in the 2050s, considering agricultural yields and tourism, among others. For example, fewer weeks with good conditions for skiing each year (Kundzewicz et al., 2009) could be outweighed by increased demand for non-winter tourism (Ciscar et al., 2009). By 2085, water runoff in Europe might decrease by around 10%. Nevertheless, precipitation intensity will increase also for Europe, with extremes becoming more frequent than in the past.

3.3 Shock Scenarios

3.3.1 Price Shock

An increase in the price of oil and gas by a factor of three leads to a contraction of EU oil and gas consumption of around 10-20% in the short term (2020), but to diminishing impacts in the longer term (2050). High prices for fossil fuels promote the application of nuclear energy with a positive effect on long term CO_2 emissions.

BL

Under the Baseline scenario, this leads to a contraction of EU primary energy consumption of 8% in the short term (2020) and 7% in the long term (2050) compared to the situation without the shock. Combining this price shock with a significant replacement of fossil based electricity with nuclear, CO_2 emissions levels in the EU could be considerably lower (-10% in 2020 and -17% in 2050) than in the absence of the shock.

MT

The “oil and gas shock” of tripling prices in 2015 would lead to a contraction of the EU primary energy consumption by 8% in the short term (2020) and by 5% in the long term (2050) compared to the same scenario without the price shock. The shock would ultimately lead to CO_2 emission levels in the EU being lower (-10% in 2020 and -14% in 2050) than otherwise, due to the boost of nuclear in the power-generation mix.

EA

The “oil and gas shock” of tripling prices in 2015 scenario would thus cause a contraction of the EU primary energy consumption by 6% in the short term (2020) and only by 3% in the long term (2050) compared to a situation without the shock. As expected, the price shock would ultimately lead CO_2 emission levels in the EU to be lower (-8% in 2020 and -6% in 2050) than otherwise, due to the boost of nuclear in the power-generation mix.

FT (not explicitly shown)

Due to a lower dependence on fossil fuels, an oil price shock has less impact on long-run demand for oil and gas than in previous scenarios.

3.3.2 Nuclear accident

The second shock is a nuclear accident in the year 2015, which leads to a moratorium on new nuclear power plants after 2015 and a progressive phase-out of existing plants. Until 2020 this has no significant effects on nuclear production in Europe, but reduces nuclear production significantly until 2050. An increase in the share of fossil fuels leads to increasing CO_2 emissions in the long term, as compared to a situation without a preceding nuclear accident.

BL

Under the Baseline scenario, the resulting nuclear production shows no significant differences in the short term (2020), but is halved in 2050. This has important implications for the EU electricity mix. A rising share of fossil fuels (coal & gas) linked with an increasing penetration of carbon capture and sequestration (CCS) technologies leads to an increase in EU CO_2 emissions of 3% by 2050, compared to the situation without a nuclear accident.

MT

The “nuclear accident” exercise, on the other hand, would squeeze primary nuclear energy production in this scenario to less than a third of its initially projected level in 2050. The share of fossil fuels (coal & gas) including CCS would therefore be higher, resulting in the EU’s total CO_2 emissions in 2050 to be 7% higher than they would be otherwise.

EA (not explicitly shown)

The results of the “nuclear accident” simulation exercise are also in line with those of the previous scenario, showing a long term reduction of the share of nuclear energy in the energy mix. The increasing use of fossil fuels, which serve as a substitute for some of the nuclear energy, leads to increases in long term CO_2 emissions despite available CCS technologies.

FT

Given that CCS technologies and nuclear energy play a substantial role in this low-carbon energy scenario, both the non-deployment of CCS and a nuclear accident in the year 2015 have larger impacts on CO_2 emissions than in the previous two scenarios.

3.3.3 No CCS

The third shock takes into account that deployment of CCS may never occur due to barriers to safe and cost effective deployment. Although this will decrease the use of fossil fuels (and increase nuclear production), CO_2 emissions are expected to increase in the long-term because they are not abated in the absence of CCS.

BL (not explicitly shown)

However, since CCS plays no role in the Baseline scenario, this “shock” does not alter results in the short or long term.

MT

The third exercise, which assumes that CCS technologies fail to become deployed on a large scale, shows that although the level of electricity consumption of the EU27 would hardly change, there would be considerable shifts in the electricity mix. The use of fossil fuels would decrease, while nuclear would replace CCS with almost no impact on renewables. The result are electricity CO_2 emissions, which are 14% higher in 2050 than in the same scenario without this “CCS shock”. Consequently, total CO_2 emissions in the EU would be 5% higher than otherwise in 2050.

EA

Without the availability of CCS technologies, i.e. in the context of the third simulation exercise, nuclear energy becomes more prominent in the EU’s electricity mix at the expense of fossil fuels. However, because the CO_2 emissions of the remaining fossil fuels are unabated, electricity CO_2 emissions will be 43% higher in 2050 than initially projected. Consequently, total CO_2 emissions in the EU would be 11% higher than otherwise in 2050.

FT

Given that CCS technologies and nuclear energy play a substantial role in this low-carbon energy scenario, both the non-deployment of CCS and a nuclear accident in the year 2015 have larger impacts on CO_2 emissions than in the previous two scenarios.

4 Indicators

The development of the indicator set is a decisive step for the quality of an MCDA. The set of indicators should comprehensively cover all aspects of the decision problem with as little as possible overlap to avoid double counting.

Another important step is to carefully design the tree structure. (The tree used in this project is shown in Figure 1, chapter 2). As each of the branches is normalized separately on each level, the stakeholder can only chose the relative weights of the sub-criteria; the total weight is determined by the node above the sub-criteria.

The tree structure allows e.g. to set the importance of the main dimensions of the MCDA, i.e. security of supply, environment, economical and social criteria independently of the number of criteria within each category. Through this tree structure it is possible to selectively cover some categories in more detail with more indicators and even allow overlap between indicators (e.g. CO_2 EU27 and CO_2 world).

In the SECURE project, the focus of the work was on supply security. This aspect was therefore quantified using the highest number of indicators, allowing for a detailed study of influences of supply security.

Supply security is a function of the entire energy system; it can be said that in general a more diverse energy mix should improve supply security. The same argument applies also within single energy chains such as the oil chain, where a higher number of possible trading partners and a more homogenous distribution of resources decreases risk from various hazards such as geopolitical issues, market distortions through the formation of monopolies or physical threats such as blocked transport routes (GRCF, 2010). The quantification of such hazards, i.e. their probabilities in long term scenarios is naturally very difficult, particularly where political factors are involved. In the SECURE project it was instead decided to focus on the vulnerability of the energy system by quantifying several diversity indicators, such as the import diversity for the entire energy system of the EU27 as well as diversity for the key fossil resources oil, gas and coal.

Other possible hazards such as underinvestment due to uncertainty of future demand, regulatory uncertainty or uncertainty about the technological development cannot be implemented based on the POLES model. Within SECURE this problem was addressed by introducing external shocks such as a sudden jump in fossil fuel prices, a nuclear accident forcing the phase out of this technology in the model and the non availability of CCS technologies. This approach allows again to test the vulnerability of the entire energy system towards such possible shocks though it would be of high interest to address the probability that these scenarios take place and explore the underlying reasons for the shock. (I.e. CCS technology could become infeasible for technical, economical or political reasons).

Table 2 gives an overview of the indicators chosen for the SECURE MCDA. The indicators represent the three pillars of sustainability, i.e. environmental, economical and social aspects in addition to the indicators for security of supply.

Other than for the security of supply criteria, for the sustainability criteria only a limited number of criteria could be chosen. The criteria were derived from work performed within the large project NEEDS (Hirschberg, Bauer, Burgherr, Dones, Schenler, et al., 2008), where the sustainability dimensions were explored in detail with 36 indicators, quantified for 26 different electricity generation technologies. The complete list of indicators developed for the NEEDS project can be found in Table 8 in the appendix. The SECURE MCDA on the other hand compares entire policy scenarios, meaning that the outputs of the model are aggregated over various technologies to the level of entire energy chains. The indicators for SECURE were therefore chosen to be representative for the behavior of the chain in the respective dimension.

Except for the social aspects, the indicators are based directly on the modeling results of the POLES model, the available outputs therefore present another boundary condition on the choice of indicators.

All indicators are quantified for all scenarios described in chapter 3.

Criteria / Indicator	Description	Unit	Source
ENVIRONMENT	Environment related criteria and indicators		
CO_2 Emissions World	Worldwide CO_2 emissions per capita	t CO_2 / capita	POLES
CO_2 Emissions EU 27	EU 27 CO_2 emissions per capita	t CO_2 / capita	POLES
ECONOMY	Economy related criteria and indicators		
Energy Expenditure World	Worldwide energy expenditure per Gross Domestic Product (GDP)	USD / GDP	POLES
Energy Expenditure EU 27	EU 27 energy expenditure per Gross Domestic Product (GDP)	USD / GDP	POLES
SOCIAL	Socially related criteria and indicators		
Severe Accidents	Risk from severe accidents		
Average Number of Fatalities	Cumulated expected number of fatalities from severe (≥5 fatalities) accidents worldwide in fossil (coal, oil, gas), hydro and nuclear energy chains	Fatalities / year	PSI
Consequences of Worst Accident	Maximum fatalities from severe (≥5 fatalities) accidents worldwide in fossil (coal, oil, gas), hydro and nuclear energy chains	Fatalities	PSI
Oil Spills	Oil spill risk is assumed to scale linearly with the amounts of oil used, so the indicator scales with the amount of oil used globally	Mtons	PSI
Terrorism Risk	Cumulated terrorism risk for EU 27, based on attack scenarios for a European Pressurized Reactor (EPR), hydropower dam, refinery and Liquefied Natural Gas (LNG) Terminal	Fatalities	PSI
SECURITY OF SUPPLY	Security of Supply related criteria and indicators		

Criteria / Indicator	Description	Unit	Source
Diversity EU 27 Consumption	Shannon-Wiener diversity index of EU 27 gross inland energy consumption (Mtoe) for the different energy carriers	Factor	POLES
Share of energy imports EU 27	Ratio of Primary Production (Mtoe) / Gross Inland Consumption (Mtoe) in EU 27	Factor	POLES
Diversity of Resources	Shannon-Wiener diversity index of net exporters from 23 world regions in oil, gas and coal markets		
Diversity World Oil Market	Shannon-Wiener diversity index of net oil exporters (Mtoe) from 23 world regions in POLES	Factor	POLES
Diversity World Gas Market	Shannon-Wiener diversity index of net gas exporters from 23 world regions in POLES	Factor	POLES
Diversity World Coal Market	Shannon-Wiener diversity index of net coal exporters from 23 world regions in POLES	Factor	POLES

Table 2 Overview over the MCDA indicators

4.1 Environment

POLES provides CO_2 per capita emissions as the main environmental indicator. For the MCDA both CO_2 emissions in the EU27 and in the world are taken into account. The user of the MCDA can thus decide which emission he deems more relevant. Figure 7 shows the results for all scenarios.

Of course CO_2 emissions are not the only impact of energy production on the environment, however in comparing CO_2 policy options they are a central measure of environmental impact. Another environmental aspect is covered through the oil spill risk indicator that can be found under severe accidents in the social category.

The main missing component are the emissions of major pollutants (SO_x, NO_x and particulate matter (PM)) and their effects. Unfortunately, these emissions are not calculated by POLES. They are partially correlated with CO_2-emissions being associated with fossil technologies. As discussed later, inclusion of such emissions would further strengthen the overall conclusions of the present work.

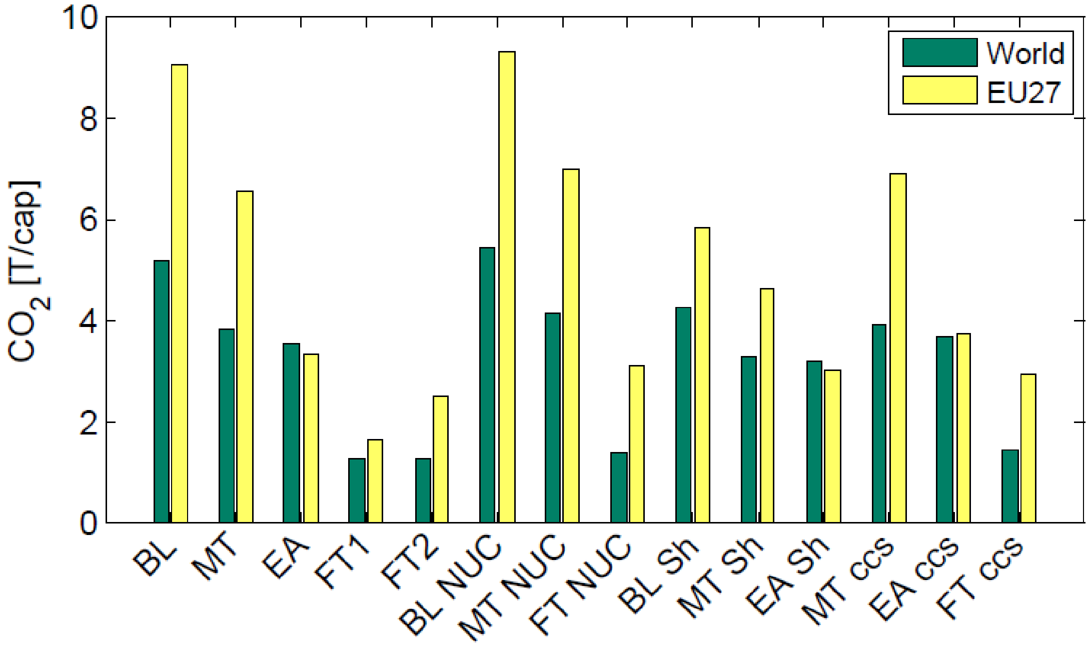

Figure 7 CO_2 per capita, EU 27 and worldwide, 2050

Clearly visible is the effect of the progressively stringent CO_2 policies in the basic scenarios, i.e. stronger CO_2 policies work to reduce the emissions of CO_2. Both the nuclear accident and the no-ccs shock scenarios lead to increased emissions compared to the respective basic scenario, by between 3 to 12 % for global CO_2 emissions, while in the price shock in fossil fuels leads to lowered emissions of CO_2 compared to the respective basic scenario by 10 to 20%.

4.2 Economical aspects

POLES provides energy expenditure as main economic indicator. For the MCDA both energy expenditure in the EU27 and in the world are taken into account. The user of the MCDA can thus decide which he deems more relevant. Figure 8 shows the results for all scenarios.

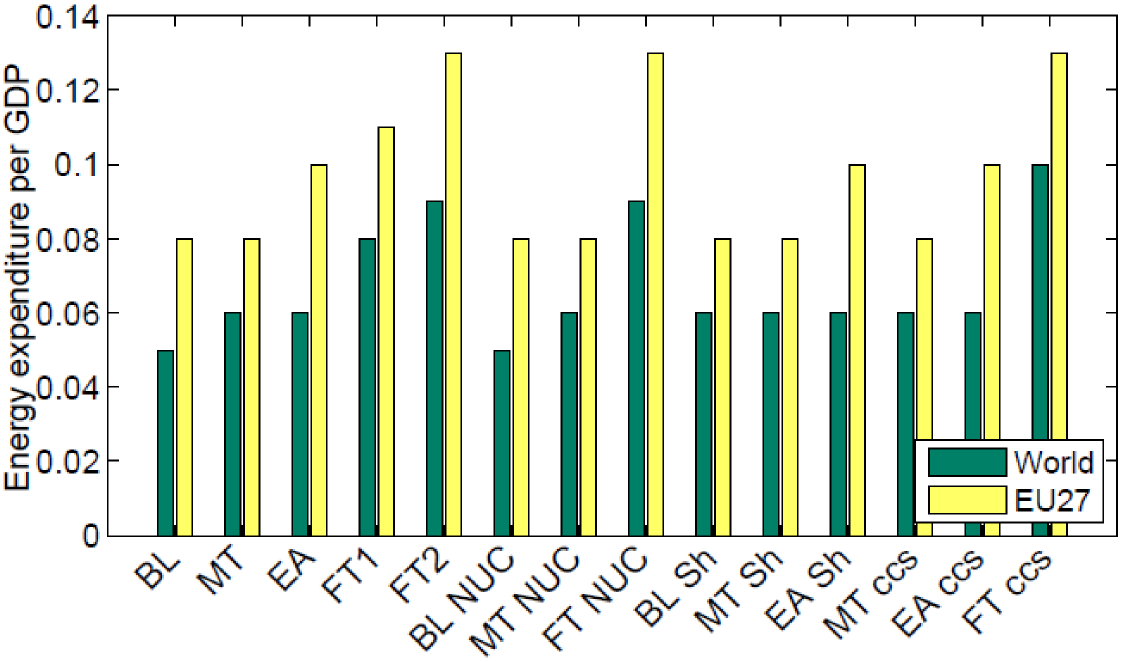

Figure 8 Energy expenditure per GDP, EU 27 and worldwide, 2050

As can be seen from Figure 8, the total expenditure on energy per GDP grows with more stringent CO_2 policies. The nuclear shock increases energy expenditure in both the EU and the world by 4% for the MT case , the effect on both the baseline case and the FT case are smaller. A more pronounced effect is seen from the price shock, expendidure in the baseline and MT case increases by 6% for the world, the EA scenario shows less impact with a 3% increase globally.

The CCS shock has no impact in the MT and EA case, but accounts for a 3% increase in expenditure in the FT scenario both globally and on an EU level.

4.3 Social indicators

Two groups of social indicators were quantified for the MCDA: terrorism risk and severe accidents, comprising again three indicators measuring the average number of fatalities from severe accidents, the consequences from worst case accidents and the risk of oil spills.

The chosen indicators focusing on risks may be considered as a surrogate for the missing broader set. Implicitely they reflect the overall limited social acceptance of fossil energy sources, the controversies associated with nuclear power, i.e. low expected risk but high aversion potential due to the possibility of accidents with high consequences, and high acceptance of most renewables (though not necessarily always at the local level).

Other possible social indicators that were taken into account in the sustainability project NEEDS such as political aspects or indirect influences of energy production on the residential environment were beyond the scope of SECURE and are not considered in the POLES model.

4.3.1 Severe Accidents

Details about the quantification of accident risk can be found in a separate deliverable (Burgherr, Eckle, & Hirschberg, 2010).

Average number of fatalities

For the "average number of fatalities", the expected number of fatalities from severe accident with five or more fatalities is calculated per Mt_{oe} for the different energy chains, i.e. coal, gas, oil, nuclear and hydro power. These values are then multiplied by the respective amount of energy in the different scenarios.

	Expected fatalities per M_{toe}	"maximum accident"	
Coal	0.17	434	Immediate fatalities
Gas	5*10-2	234	Immediate fatalities
Oil	0.16	2700	Immediate fatalities
Nuclear	10-5	28000	Latent fatalities
Hydro	10-2	10000	Immediate fatalities

Table 3 Quantification of severe accident indicators

The results are shown in Figure 9. As expected number of fatalities from severe accidents is highest for coal and oil, the scenarios in which the share of coal and oil is reduced most through CO_2 policies perform best. This also leads to a decerase in expected fatalities with the price shocks as the use of fossil fuels is decreased and consequently to an increase with the nuclear shock. The increase due to the nuclear shock scenario is most pronounced in the FT scenario, by 21%, however in absolute numbers it is still lower than in the other scneraios. The CCS shock leads to s decrease in expected fatalities by 40% in the FT CCS shock compared to the basic FT scenario and to almost no effect in the MT and EA scenarios.

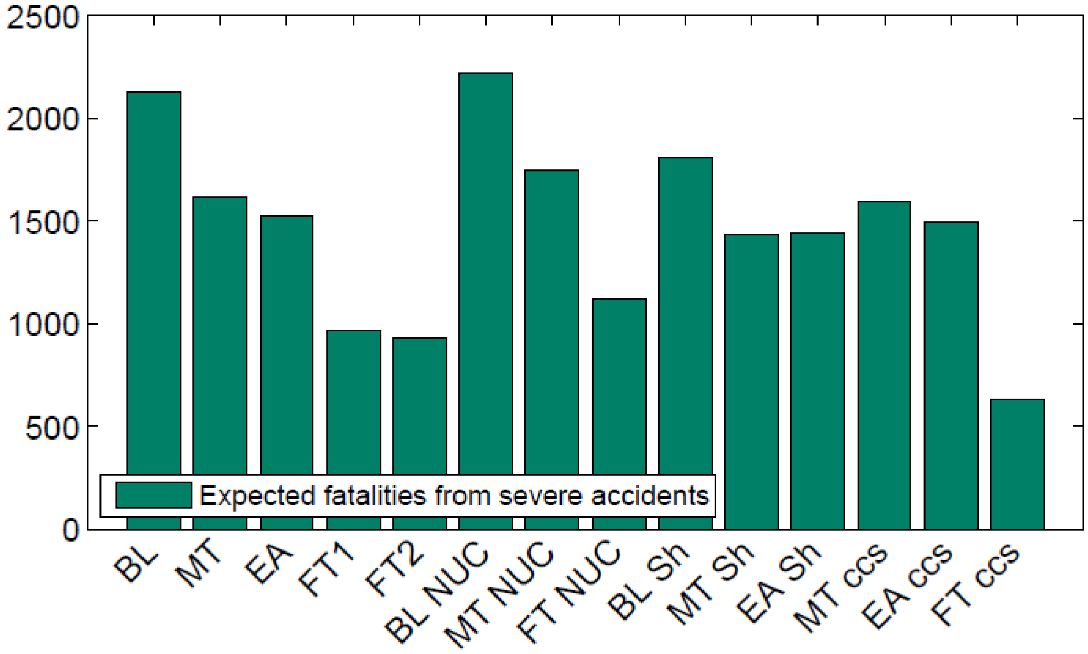

Figure 9 Expected fatalities from severe accidents in 2050 per year worldwide

Consequences of worst case

For the consequences of a worst case accident, the fatalities for a maximum accident as given in Table 3 are multiplied by the respective *amount* of energy in the different scenarios. Figure 10 shows the numbers scaled with the *share* of energy used in the respective chain in the different scenarios.

The maximum accident for the fossil fuels oil, gas and coal is the worst historic accident that has happened in the respective energy chain. For hydropower the maximum accident is taken from the worst case scenario in a probabilistic safety assessment of a dam in Switzerland, where the dam breaks without pre warning. In the case of nuclear power again the worst case of a probabilistic safety assessment was taken, calculated for a European pressure reactor in France. It needs to be emphasized that the respective probabilities of these “worst case” events were not taken into account for this indicator. Due to the large share of nuclear power in this scenario the FT CCS shock scenario performs worst for this indicator. The nuclear shock scenarios consequently have the best performance on this indicator.

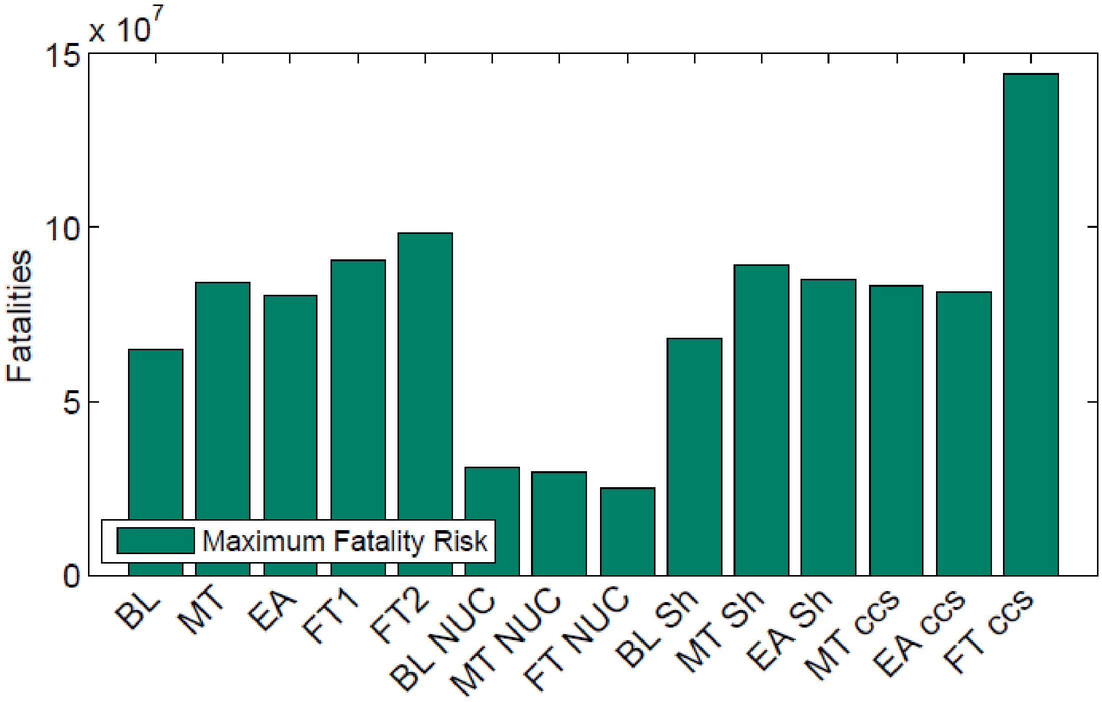

Figure 10 Maximum fatality risk from severe accidents in the coal, oil, gas, nuclear and hydro power chain.

Oil Spills

As a proxy for the risk of oil spills the global use of oil in the different energy chains was taken to calculate the indicator. To calculate the indicator the amounts of oil used globally in each scenario were were taken and subsequently normalized to the value of the scenario with maximum oil use and the scale inverted. The world oil production in the different scenarios is shown in Figure 1.

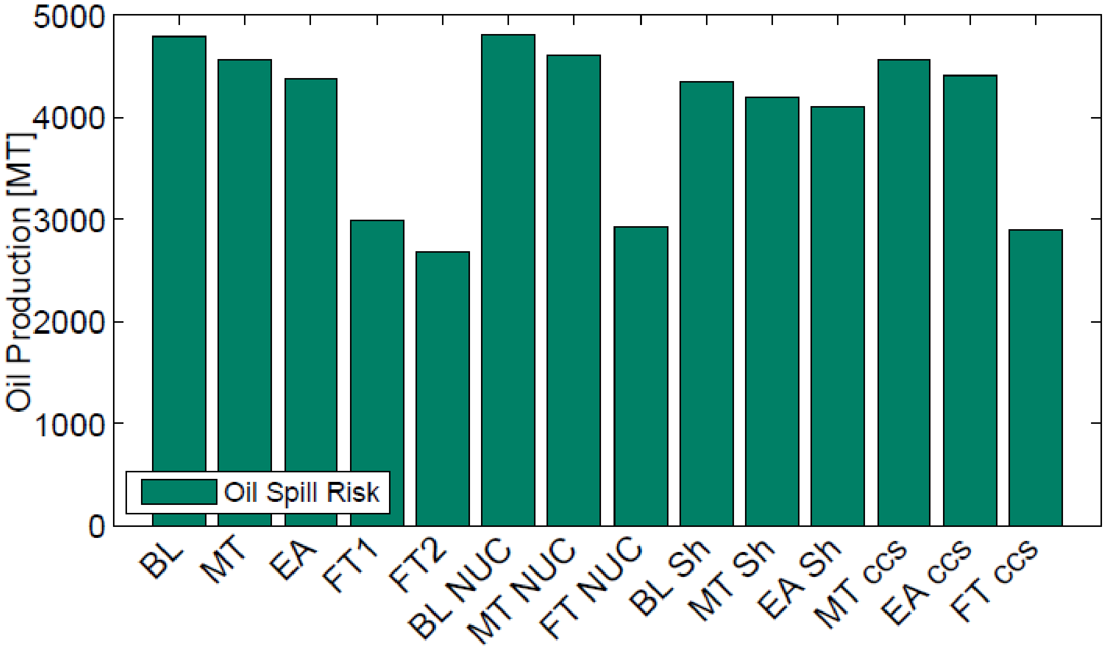

Figure 11 Oil production in the different scenarios worldwide, 2050 as a proxy for the risk of oil spills

The price shocks lead to a decrease by between 6 and 9%, while the nuclear and CCS shocks lead to an increase.

4.3.2 Terrorism Risk

Details about the quantitative, PSA-based methodology that was developed to quantify terrorism risk can be found in (Eckle, Burgherr, & Hirschberg, 2010)[3].

The indicator uses the total fatality risk that was calculated for single installations in the oil, gas, nuclear and hydropower chain. The risk for the oil chain is calculated as the risk per year for fatalities caused by a potential attack on a refinery in the USA.

The risk for the oil chain is calculated as the risk per year for fatalities caused by a potential attack on a refinery. For the gas chain, the risk is calculated as the risk per year for fatalities caused by a potential attack on an LNG terminal located in Belgium.

For the nuclear chain it is calculated as the risk per year for fatalities caused by a potential attack on an EPR (European Pressurized Reactor) located in the USA. The fatalities include both immediate and latent fatalities. The risk for the hydro chain is calculated as the risk per year for fatalities caused by a potential attack on a hydro power dam located in the USA.

The risk is then multiplied with the primary production in the EU27 in the respective chain and aggregated over all chains.

The results are given in Figure 12.

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[3] The executive summary of this report is publicly available

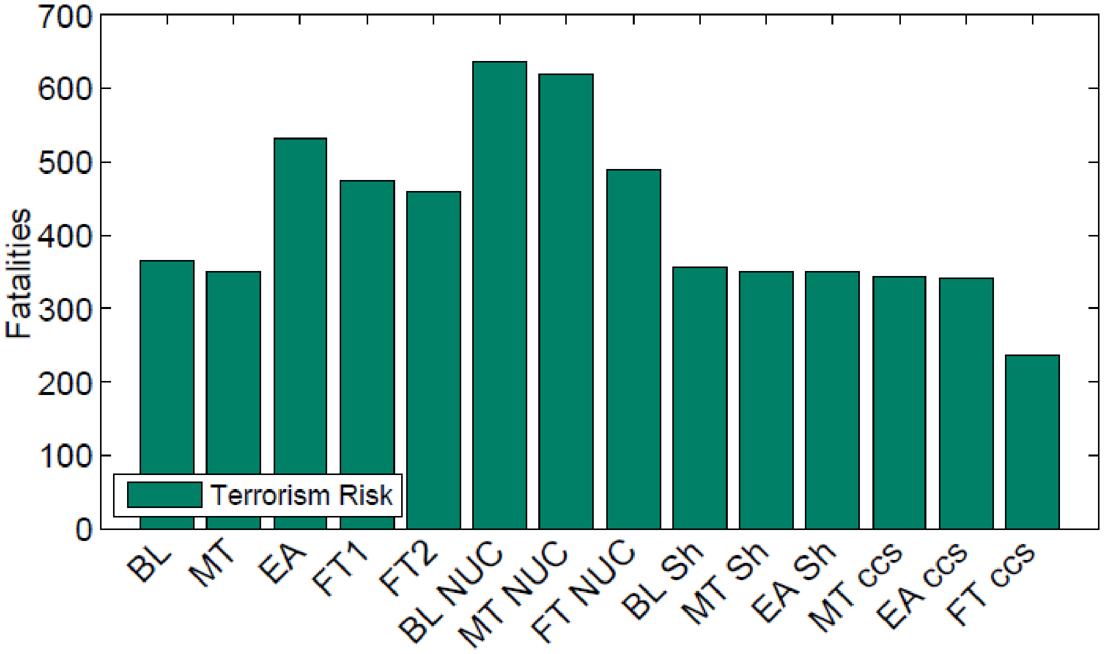

Figure 12 Terrorism risk 2050, fatalities from potential attacks on energy installations

4.4 Security of supply

Three main criteria used to measure security of supply were:

The diversity of EU 27 domestic consumption.

The dependence of the EU 27 on energy imports

The worldwide diversity of the fossil fuel markets

4.4.1 Shannon Wiener diversity index

The Shannon-Wiener diversity indicator (SWN) (Magurran, 1988) is used to measure the diversity of EU 27 domestic consumption and the worldwide diversity of the fossil fuel markets. The indicator is zero for a single contributor and approaches one with more contributors as well as with more even shares (Spellerberg & Fedor, 2003; "Wikipedia - Shannon Wiener index," n d). The indicator is calculated as follows:

$$SWN = -\sum_{i=1}^{S} (p_i \log p_i) - [(S-1)/2N]$$

Where N is the total, S is the number of contributors and p_i is the share of contributor i.

For example for oil export distribution diversity:

N: total of oil on market

S: number of countries/regions exporting

pi: Resource amount in a given country/ N

4.4.2 Diversity of EU 27 domestic consumption

This indicator calculates the SWN diversity indicator of the gross inland consumption (Mtoe) calculated in POLES. The results for the different scenarios are shown in Figure 13.

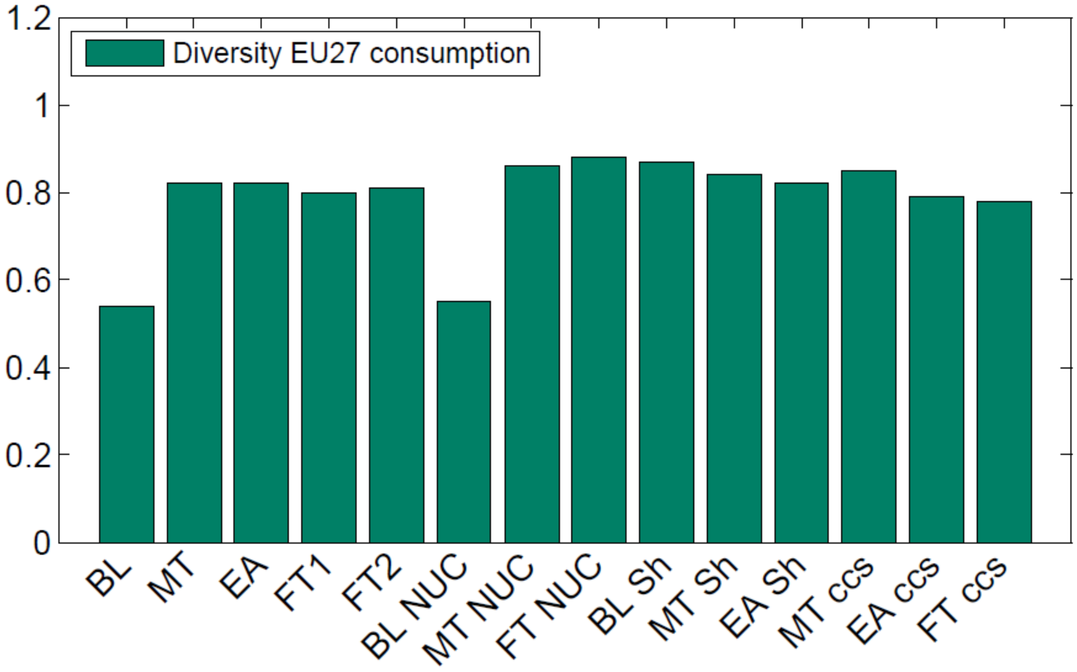

Figure 13 Diversity domestic energy consumption in the EU 27 2050

4.4.3 Share of energy imports EU 27

This indicator measures the share of energy imports of the total energy consumed in the EU 27, as a measure of the dependency of the EU 27 on energy imports. The results are shown in Figure 14.

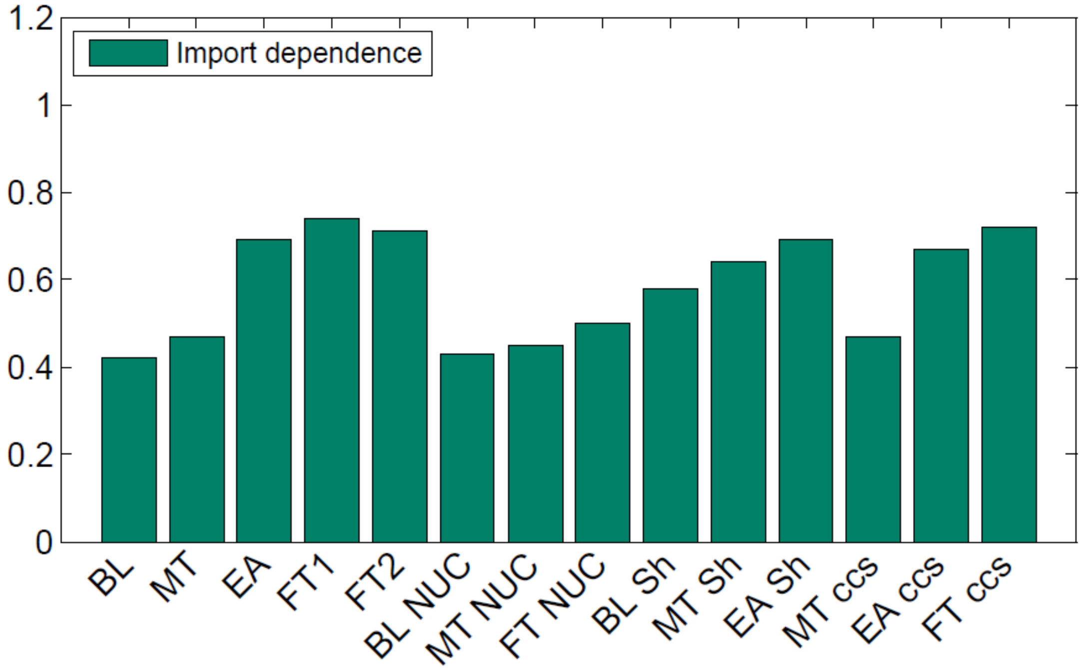

Figure 14 Import dependence EU2: Primary production / consumption in the EU27

More stringent CO_2 policies increase the ratio between domestically produced energy vs energy imports in the EU27. The price shock decreases imports and thus improves this indicators, however this effect is only pronounced for the BL and MT case, while for the EA case only a 1% improvement in the ratio is seen. The CCS shock has now profound influence on this ratio, with changes ranging from + 3% to -3%. The nuclear shock leads to a pronounced decerase by 30% in the FT case, in the other cases the changes are in the region of 5%.

4.4.4 Diversity of Resources

As the information about resources is not directly available from POLES, instead the worldwide market concentration is measured for oil, coal and gas.

POLES splits the world in 23 regions, from these regions, the number of net exporters in oil/gas/coal is selected, and subsequently a SWN is calculated according to the respective net exports.

The result is shown in Figure 15.

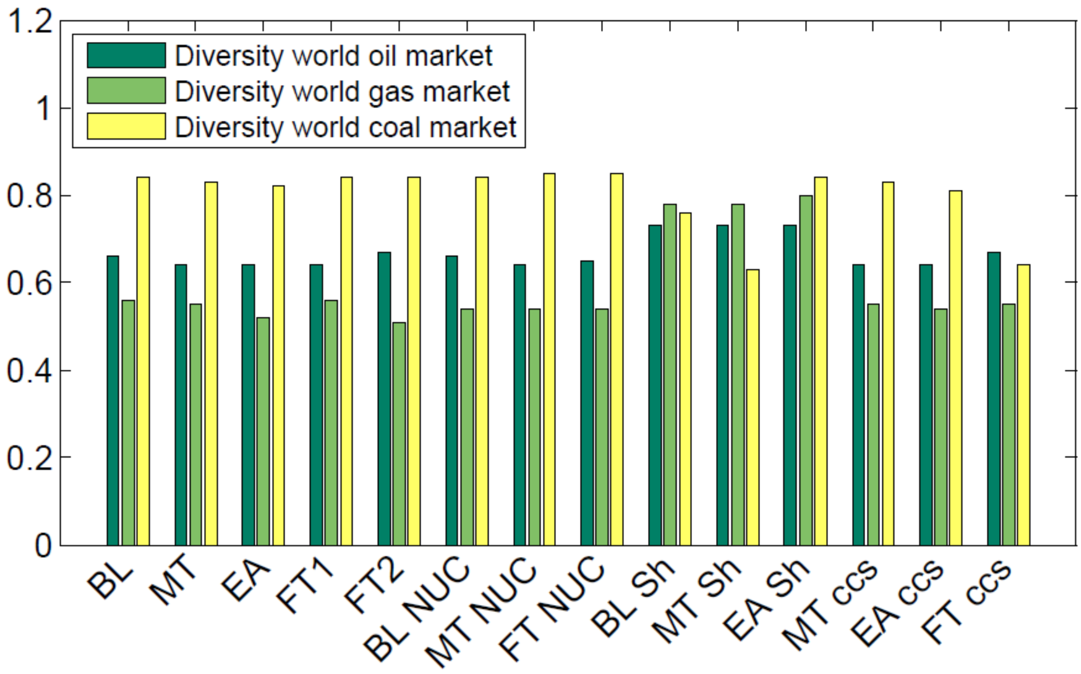

Figure 15 Diversity of global fossil resources in 2050 measured as diversity of net exporters.

The diversity indicator for all three fossil fuel markets is only very weakly dependent on the CO_2 policy. Clear effects are however visible in the price shock scenarios, that improve the diversity indicator in 2050 significantly for oil and gas. For the MT scenario at the same time the diversity indicator for the coal market is reduced by 25%.

4.5 Scaling for MCDA

13 indicators were calculated based on the POLES model as well as additional inputs such as the indicators, for severe accident and terrorism risk that were analyzed in WP 5.7 of SECURE (Burgherr, Eckle, & Hirschberg, 2011). For the MCDA, all indicators need to be on a scale from zero to one, where zero means worst performance and one best. Some indicators such as the diversity indicators (see below) are naturally on this scale, others need to be scaled accordingly.

The indicators where a higher number means a worse performance are: CO_2 emissions, energy expenditure and all social indicators. The security of supply indicators are all Shannon Wiener diversity indicators, where zero means lowest diversity and one highest diversity, so they don't need to be scaled.

For the scaling of the other indicators, the indicator values of all scenarios v_{ij} are first normalized to the maximum (i.e. worst performance) of all scenarios so that the scale is mapped to the interval between zero and one. The scale is then flipped so that a higher value means better performance by subtracting each indicator value from one. See also chapter 2.1.

Figure 16 - Figure 19 give an overview over the scaled indicators.

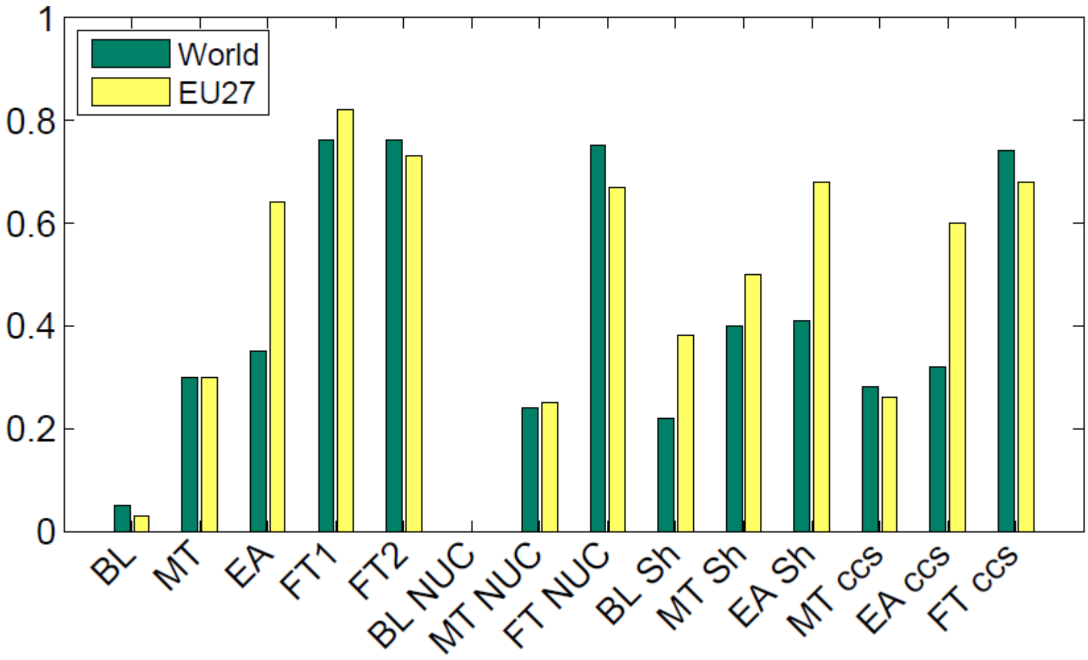

Figure 16 Environmental indicators: CO_2 emissions world and EU 27

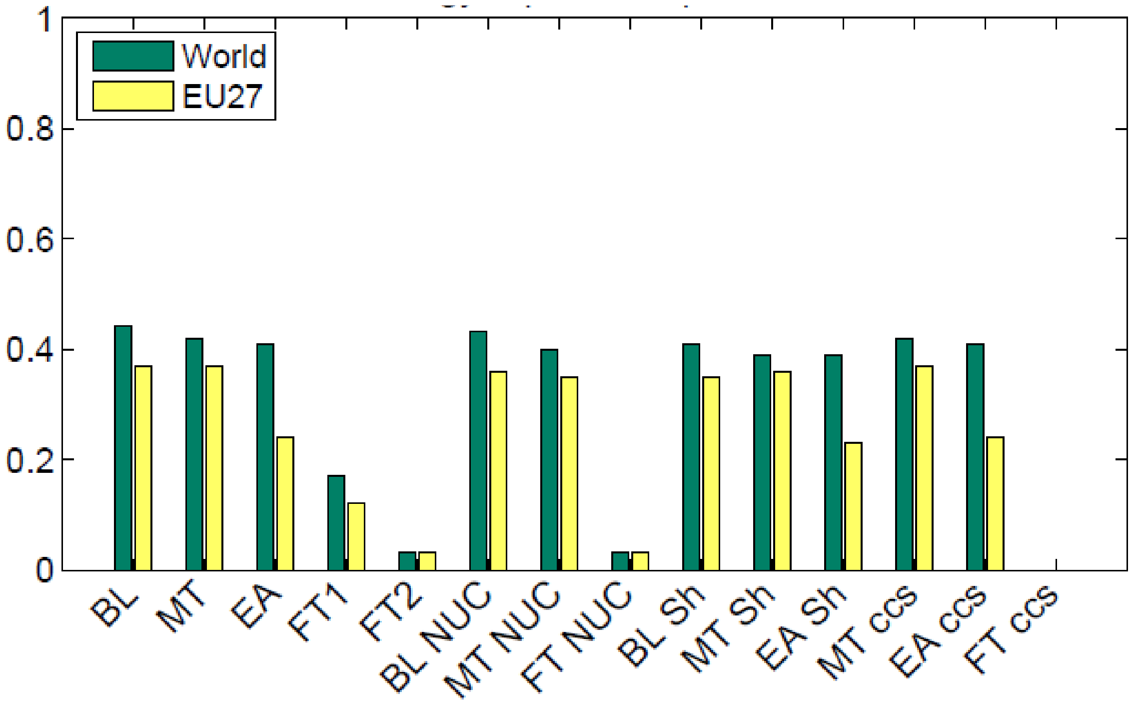

Figure 17 Economic indicators: Energy expenditure world and EU 27

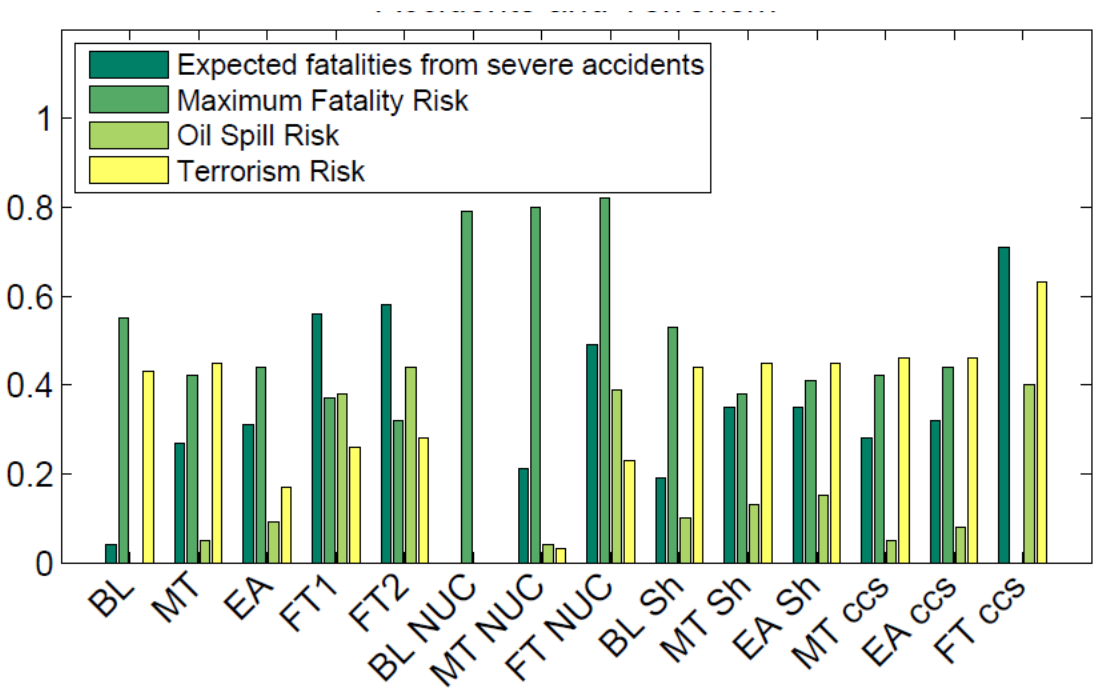

Figure 18 Social indicators, Accidents and terrorism

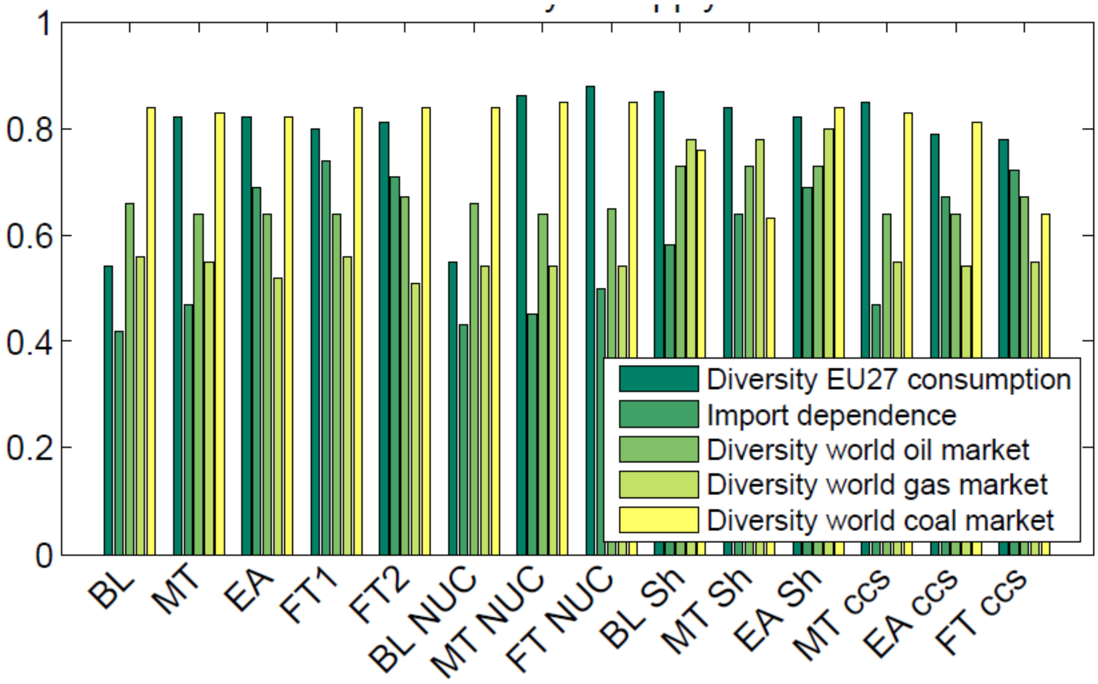

Figure 19 Security of supply indicators

5 Interactive online tool

The interactive online SECURE MCDA tool that has been developed by PSI can be accessed under www.secure-mcda.net. The aim of this tool is three fold:

It provides information on the project and in particular on the policy scenarios that have been developed for SECURE and thus helps to communicate the findings of the SECURE project to the public and in particular different stakeholder groups.

Second it gives the user the opportunity to perform the MCDA using their personal preferences in an interactive process, where the preferences can be revised iteratively. Through this iterative process the user can identify the driving criteria that affect the total performance of the different scenarios.

The third purpose of this online tool is that constitutes a survey that allows an analysis how preference profiles relate to the different stakeholder groups.

5.1 Technical implementation

Figure 20 shows the functional structure of the webpage. Except for the general homepage that gives a brief overview over the page, the user is required to sign up and subsequently login to access the full functionality.

During the sign up procedure the user is asked to provide additional voluntary information such as age group, country of residence, level of formal education and stakeholder group, that is saved in a database and can be used to correlate stakeholder preference profiles to the

After login, the user has access to the MCDA i.e. the core functionality of the website as well as additional information pages giving details on the project, methodology and indicators.

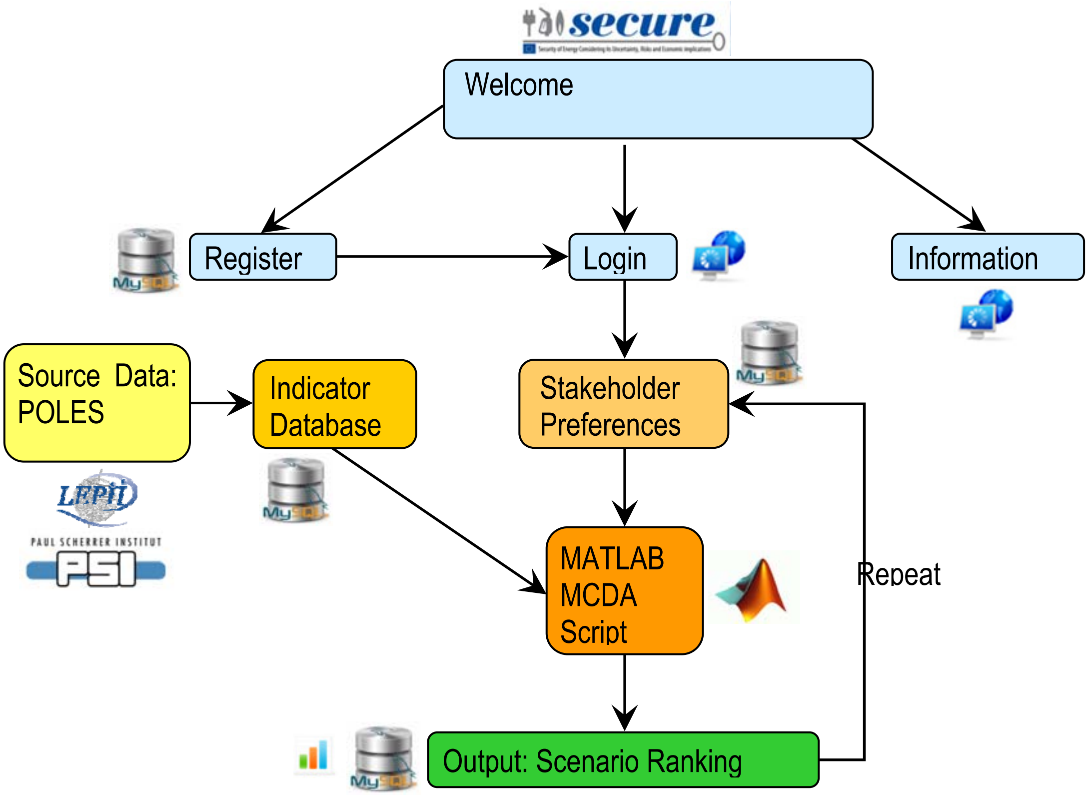

Figure 20 Functional structure of the MCDA web tool

6 MCDA results

Table 4 and Table 5 give an overview over all normalized indicator values as described in chapter 4. In addition Figure 21 gives a graphical overview. From these indicator values the final ranking of the scenarios is calculated by weighting each indicator according to the preferences of a stakeholder.

To analyze the behavior of the MCDA in this chapter two approaches are used: Chapters 6.1 to 6.7 show a number of profiles chosen to test few representative cases. In chapter 6.8 possible profiles are sampled systematically to test the sensitivity of the results to changes in the preferences.

FINAL INDICATORS 2050	BL	MT	EA	FT1	FT2
GHG world	0.05	0.30	0.35	0.76	0.76
GHG EU27	0.03	0.30	0.64	0.82	0.73
Diversity EU27 consumption	0.54	0.82	0.82	0.80	0.81
Share of energy imports EU27	0.42	0.47	0.69	0.74	0.71
Diversity world oil market	0.66	0.64	0.64	0.64	0.67
Diversity world gas market	0.56	0.55	0.52	0.56	0.51
Diversity world coal market	0.84	0.83	0.82	0.84	0.84
Energy expenditure world	0.44	0.42	0.41	0.17	0.03
Energy expenditure EU27	0.37	0.37	0.24	0.12	0.03
Average number of fatalities	0.04	0.27	0.31	0.56	0.58
Consequences of worst accident	0.55	0.42	0.44	0.37	0.32
Oil Spills	0.00	0.05	0.09	0.38	0.44
Terrorism risk	0.43	0.45	0.17	0.26	0.28

Table 4 Indicator data for main scenarios

FINAL INDICATORS 2050	BL Nuc	MT Nuc	FT Nuc	BL Sh	MT Sh	EA Sh	MT ccs	EA ccs	FT ccs
GHG world	0.00	0.24	0.75	0.22	0.40	0.41	0.28	0.32	0.74
GHG EU27	0.00	0.25	0.67	0.38	0.50	0.68	0.26	0.60	0.68
Diversity EU27 consumption	0.55	0.86	0.88	0.87	0.84	0.82	0.85	0.79	0.78
Share of energy imports EU27	0.43	0.45	0.50	0.58	0.64	0.69	0.47	0.67	0.72
Diversity world oil market	0.66	0.64	0.65	0.73	0.73	0.73	0.64	0.64	0.67
Diversity world gas market	0.54	0.54	0.54	0.78	0.78	0.80	0.55	0.54	0.55
Diversity world coal market	0.84	0.85	0.85	0.76	0.63	0.84	0.83	0.81	0.64
Energy expenditure world	0.43	0.40	0.03	0.41	0.39	0.39	0.42	0.41	0.00
Energy expenditure EU27	0.36	0.35	0.03	0.35	0.36	0.23	0.37	0.24	0.00
Average number of fatalities	0.00	0.21	0.49	0.19	0.35	0.35	0.28	0.32	0.71
Consequences of worst accident	0.79	0.80	0.82	0.53	0.38	0.41	0.42	0.44	0.00
Oil Spills	0.00	0.04	0.39	0.10	0.13	0.15	0.05	0.08	0.40
Terrorism risk	0.00	0.03	0.23	0.44	0.45	0.45	0.46	0.46	0.63

Table 5 Indicator data for shock scenarios

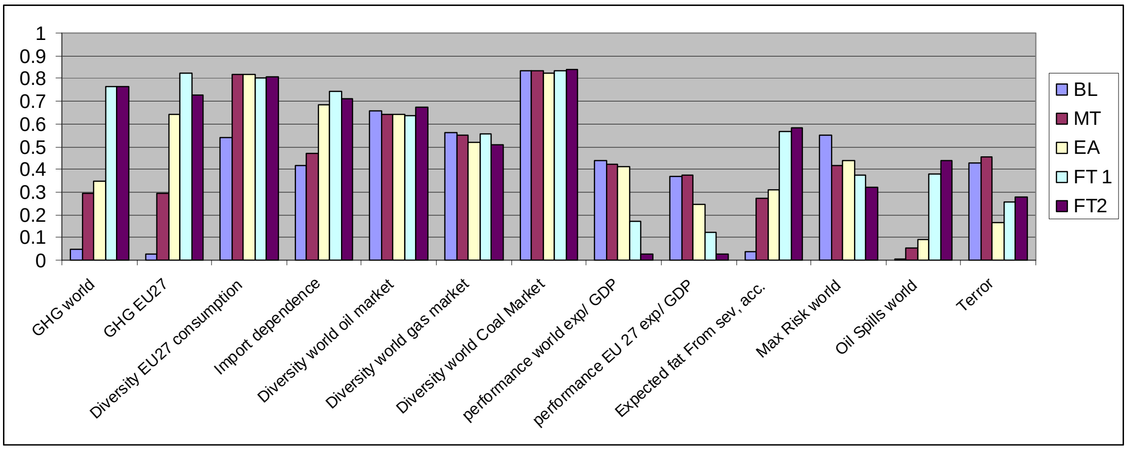

Figure 21 Indicator values for the main scenarios

For the example profiles, the preference inputs are given as graphical bars in the indicator tree in the same way as in the interactive online tool, allowing for a quick overview of the chosen preferences. It should be kept in mind that the relative weights count, i.e. setting all bars to five is the same as setting all bars to ten or one. The scale goes from zero, unimportant where the bar is empty to ten, very important where the bar is fully colored.

When contemplating the results, the focus should be on the performance on the base set of scenarios (BL, MT, EA, FT1 and FT2). The shock scenarios represent special sensitivity cases. Some of these scenarios can perform relatively well in MCDA under specific preference profiles. Nevertheless, such scenarios should not be considered to be desirable due to serious consequences for the society, partially not addressed in the underlying models used in the secure project.

6.1 Neutral profile

In this profile all preference inputs are set to five, representing a neutral profile.

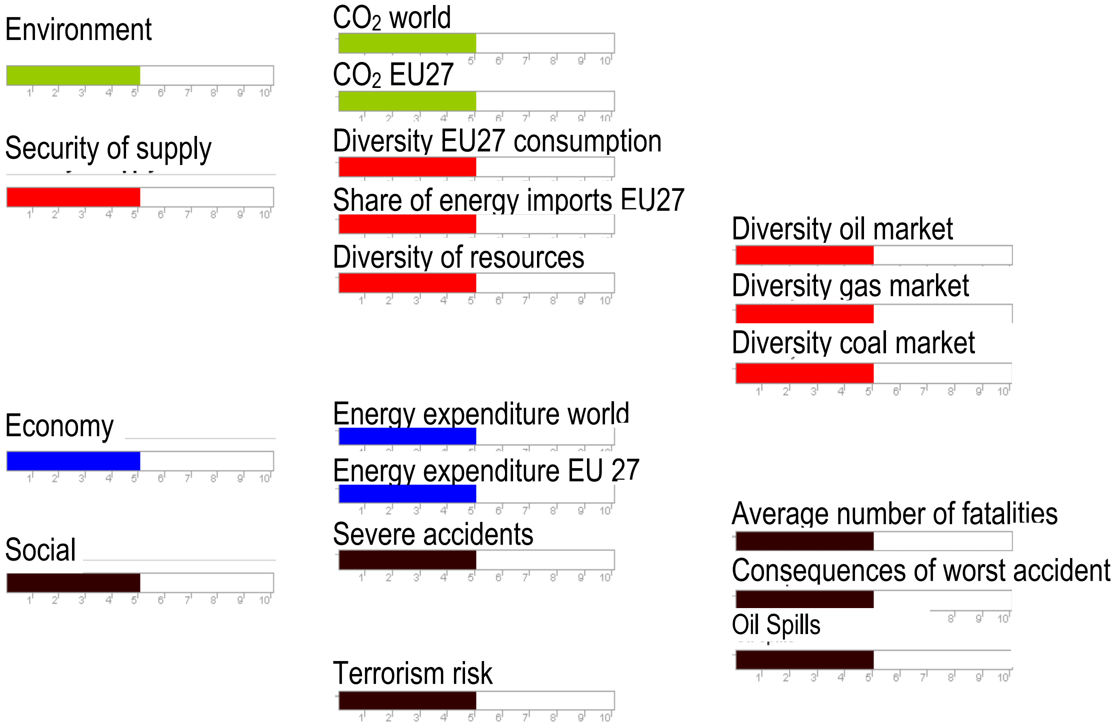

Figure 22 Neutral preference profile

The result of the neutral profile is shown in Figure 23, the legend for the colored bars is given in Figure 24 for all result graphs.

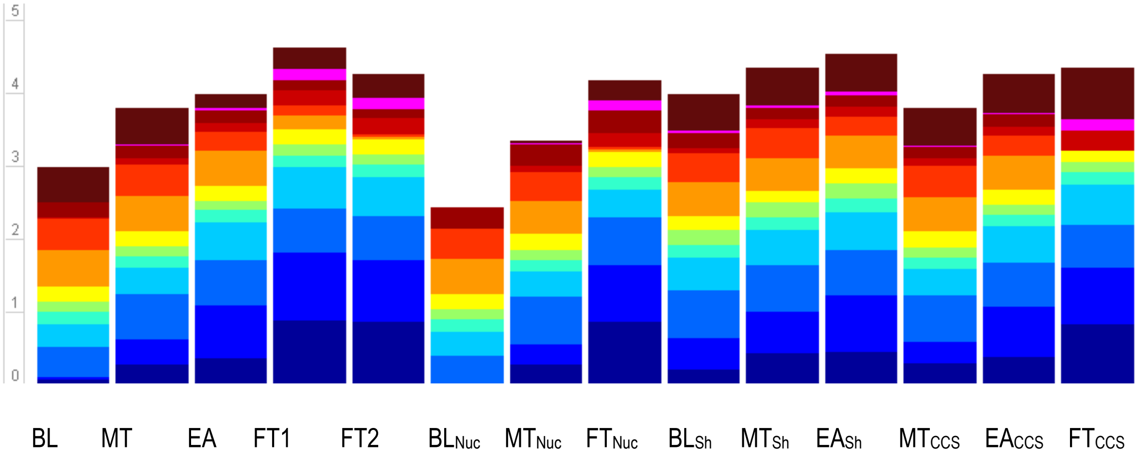

Figure 23 Result of the neutral preference profile

🟦 CO2 world
🟦 CO2 EU 27
🟦 Diversity EU27 consumption
🟦 Share of imported energy EU27
🟩 Diversity world oil market
🟩 Diversity world gas market
🟨 Diversity world coal market
🟧 Energy expenditure word
🟥 Energy expenditure EU27
🟥 Average number of fatalities
🟥 Consequences of worst accident
🟪 Oil spills
🟫 Terrorism

Figure 24 Legend for all results graphs

In a neutral profile, among the basic scenarios, the performance increases with more stringent CO_2 policies. The nuclear shock performs worse than the related basic scenarios, the price shock on the other hand even outperforms the basic scenarios under this preference profile.

6.2 Balanced case

Compared to the neutral profile shown in 6.1 for this case the preferences for the two lower levels were modified:

As the final aim of the analyzed policy scenarios is the reduction of global emissions, world wide emissions are emphasized over the emissions in the EU27.

From the security of supply criteria, those with larger differences between the different scenarios are weighted with higher values to clearly discriminate between the scenarios.

For the economical criteria again a higher weight is placed on the world energy expenditure, thus emphasizing measuring the cost of the entire system and not just the additional cost inside the EU27.

Among the social criteria, accident and terrorism risk are weighted equally, while within the accident branch the highest weight is placed on average number of fatalities, i.e. the expected consequences of accidents. Taking a very rational view, consequences of the worst accident are weighted down as this number represents the consequences of quite unlikely events not weighted by their respective probabilities. This value thus represents more a measure of risk aversion.

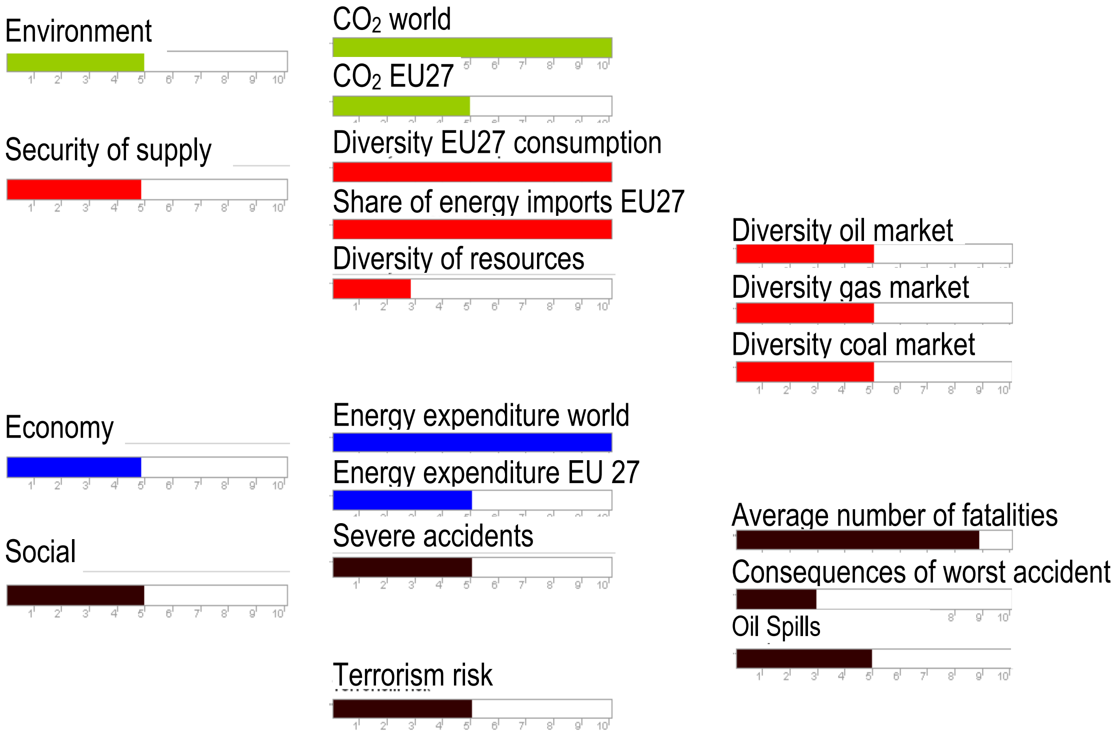

Figure 25 Balanced / differentiated profile

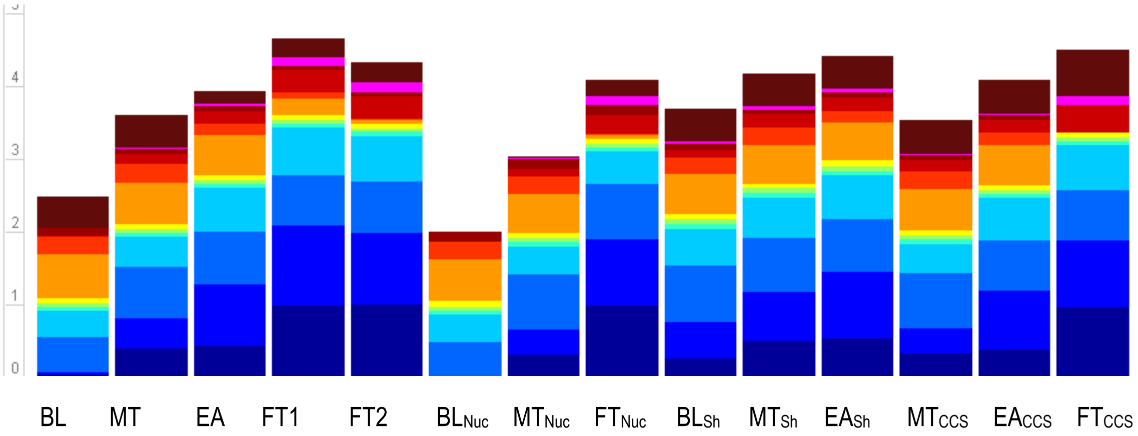

Figure 26 Result of the balanced/differentiated profile

The changes in the lower level affect the ranking only slightly, within the basic scenarios, the ranking remains FT1 first, then FT2, EA, MT and BL. The nuclear shock leads to a worse performance, while under the price shock the overall performance is better and in the CCS similar to the respective basic scenario.

6.3 Environmentally centered case

For this profile the prferences in the two lower levels are kept as in 6.2. In addition, the environmentally centered profile places 77% of the weight on the environmental indicators as shown in Figure 27. The result is shown in Figure 28.

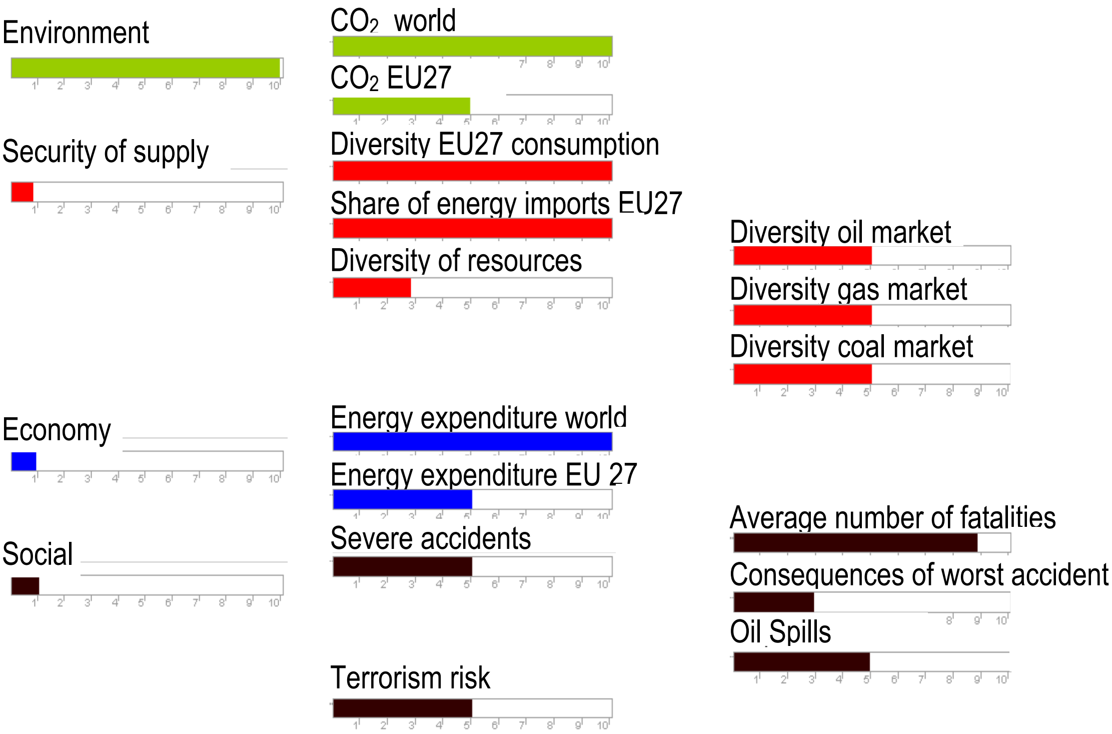

Figure 27 environmentally centered profile

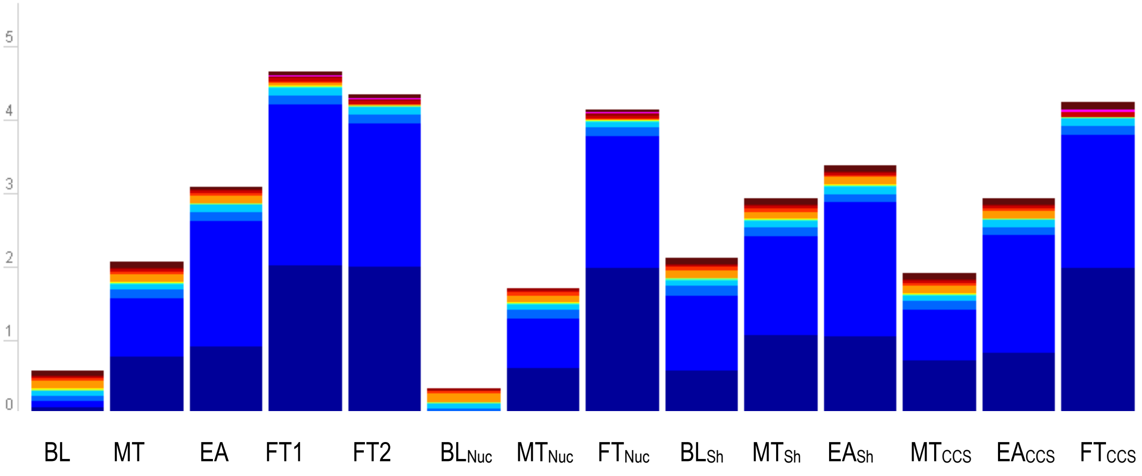

Figure 28 Result of the environmentally centered profile

Unsurprisingly, the scenarios perform better with increasingly stringent CO_2 policy. The price shocks lead to a better performace of the scenarios compared to their corresponding basic scenarios due to the decreased use of fossil fuels. The nuclear shock decreases performance mainly for the the BL and MT case while the CCS shock has no strong influence under this preference profile.

6.4 Economy centered case

In the economy centered profile (Figure 29), the expenditure on energy is the main focus of the preference profile. The preferences in the lower two levels are the same as in the previous example.

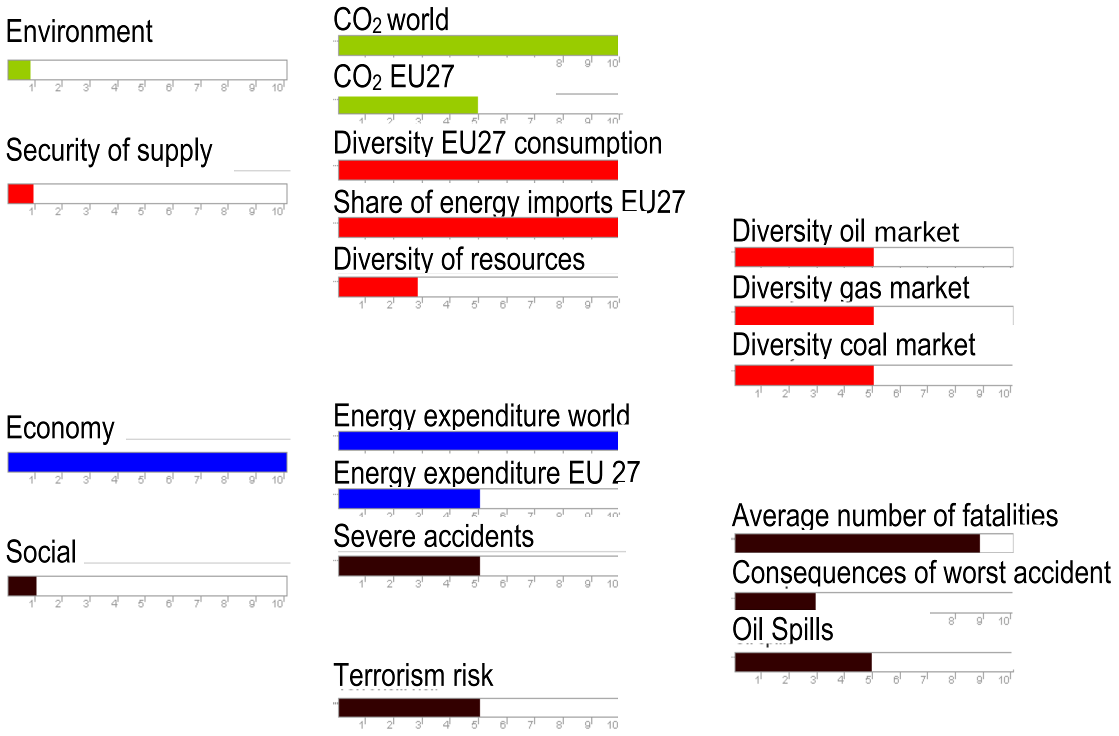

Figure 29 economy centered profile

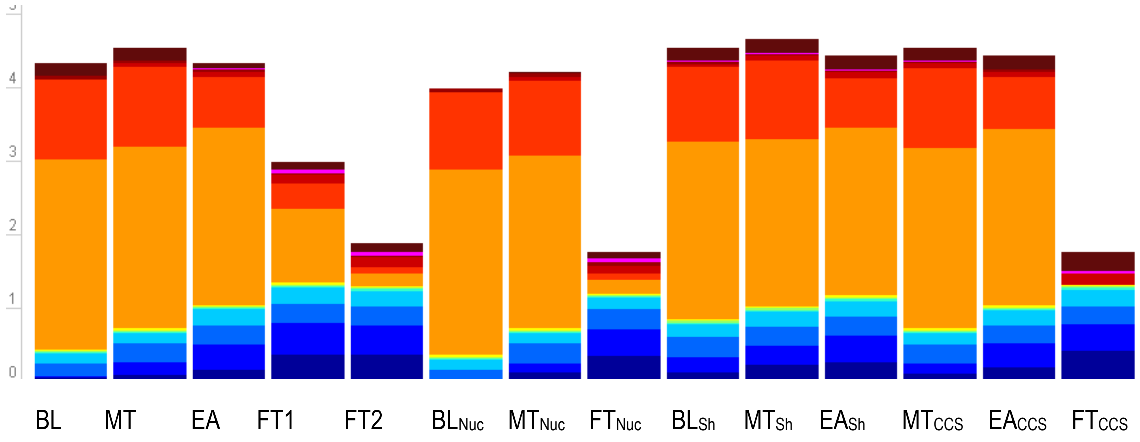

Figure 30 Result of the economy centered profile

This preference profile favors scenarios with no or weak CO_2 policies (see Figure 30). The shocks have no large influence in this case, the FT shocks perform similar to the FT2 scenario.

6.5 Socially centered case

In the socially centered profile (see Figure 31), accidents and terrorism risk are in the focus of the preference profile.

The preferences in the lower two levels are the same as in the previous example. This preference profile favors scenarios with reduced use of fossil fuels (see Figure 32), i.e. the FT scenarios and fossil fuel price shock scenarios.

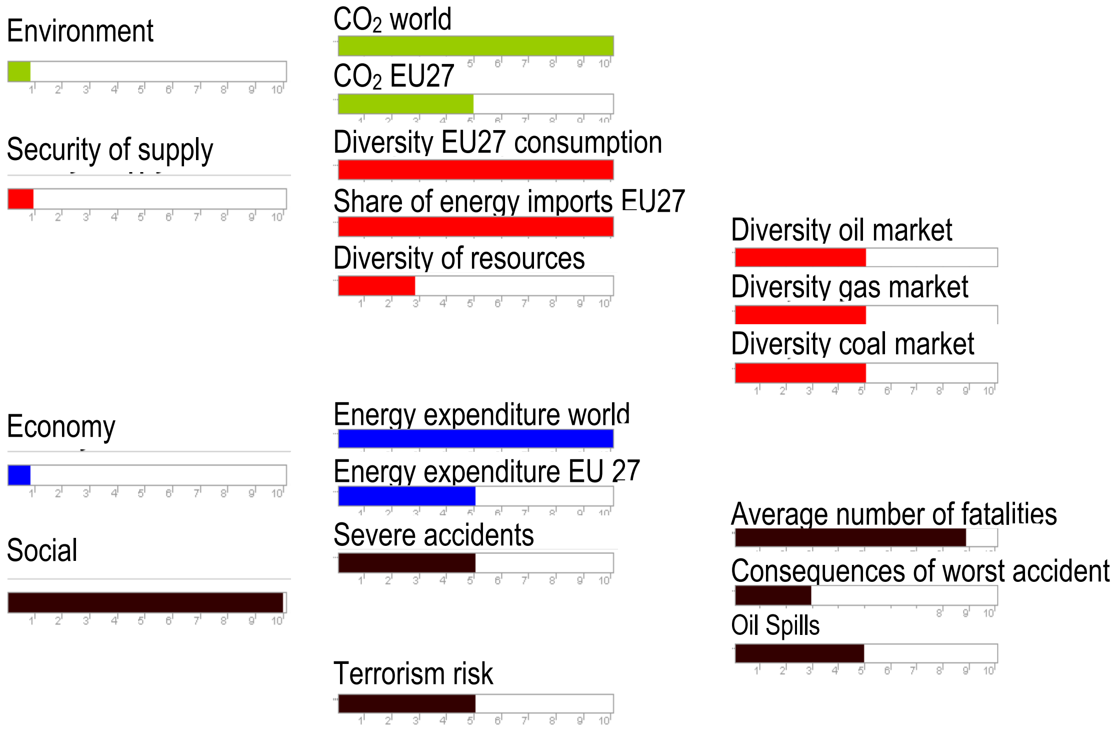

Figure 31 socially centered profile

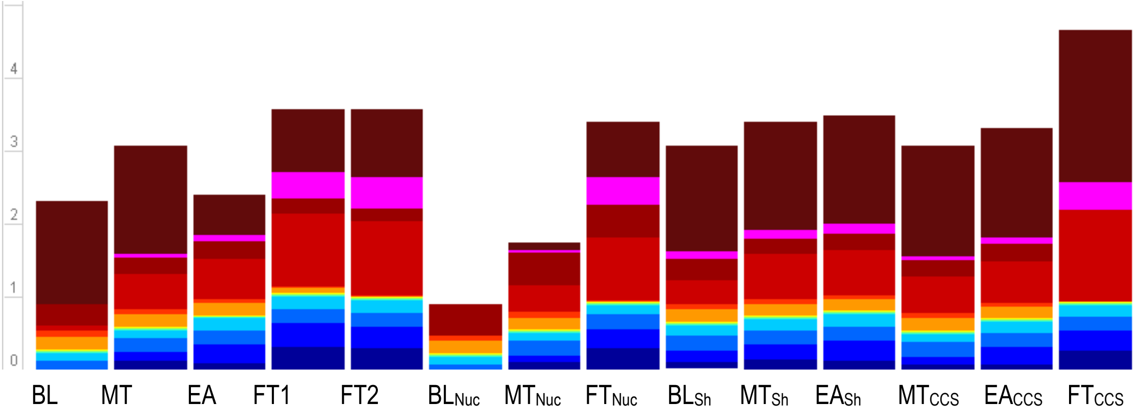

Figure 32 Result of the socially centered profile

Under the socially centered profile, the differnces within the group of basic scenarios is less pronounced than in the previous tests. An improvement with more stringent CO_2 policies is visible here as well. The nuclear shock significantly decreases performance for the weak policy scenarios, wahile the price shock offers a slight improvement over the basic scenarios. The CCS shock affects mainly the FT scenario and improves performance.

6.6 Security of Supply centered case

The scenarios that perform worst if security of supply is considered the most important (see Figure 33) are the scenarios with no or weak CO_2 policies (see Figure 34). The reason is the larger share of fossil energy use in this case. Import dependence decreases with progressively stronger CO_2 policies, the diversity indicator is particularly low in the baseline scenario. The preferences in the lower two levels are the same as in the previous example.

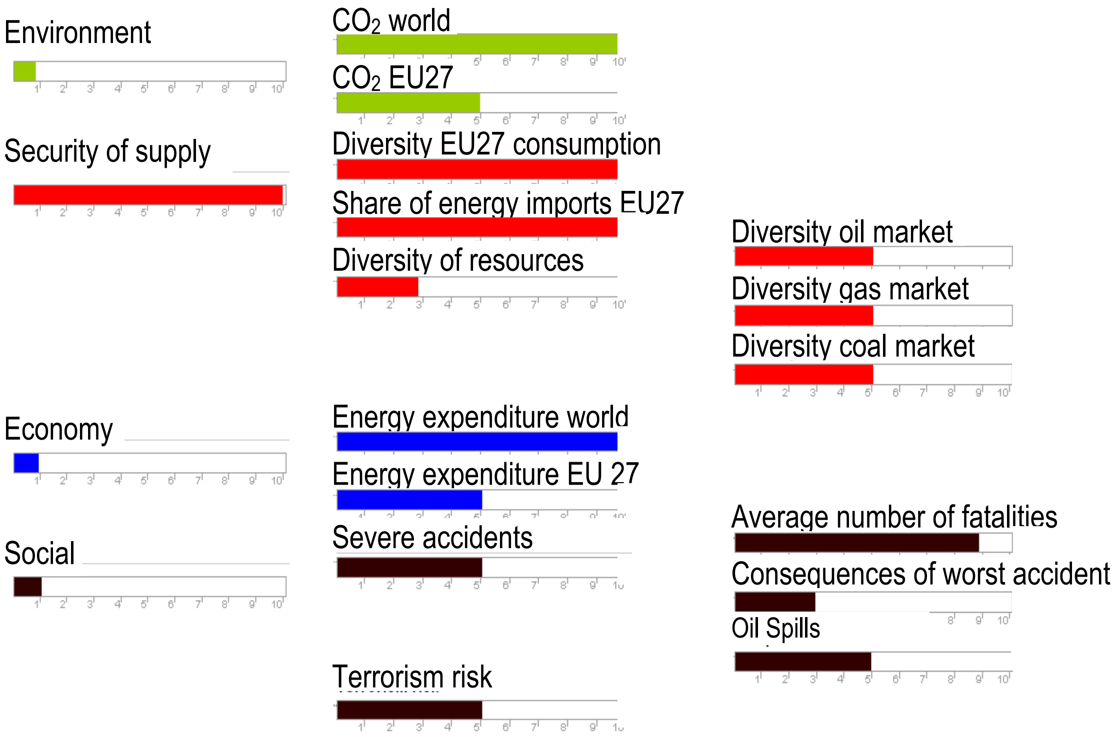

Figure 33 security of supply centered profile

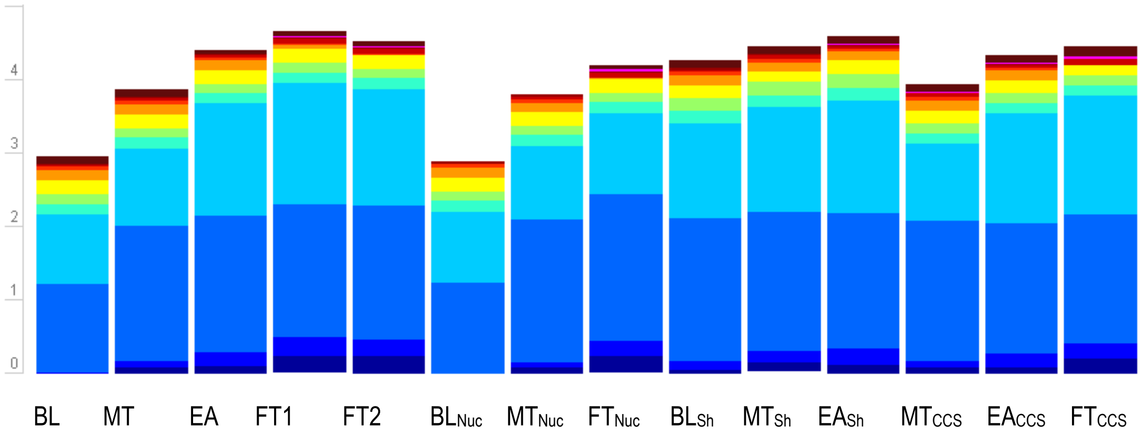

Figure 34 Result of the security of supply centered profile

Again performance improves with more stringent CO_2 policies, the nuclear shock slightly decreases performance under this preference profile while the price shock leads to an improvement. The CCS shock does not affect the performace of the scenarios significantly.

6.7 When is the baseline scenario ranked top?

An interesting question is under which preference profile the baseline scenario can outperform all other scenarios. It will be shown in chapter 6.8 that if a neutral profile is assumed for the two lower levels of the tree, there is no combination of weights on the uppermost level that leads to the baseline scenario being ranked top. The only indicators for which this scenario performs better than all other scenarios are the “consequences of worst accident” and less pronounced “energy expenditure”. As the following example shows (see Figure 35), a strongly biased profile emphasizing these indicators over all other indicators results in the baseline scenario performing best (see Figure 36).

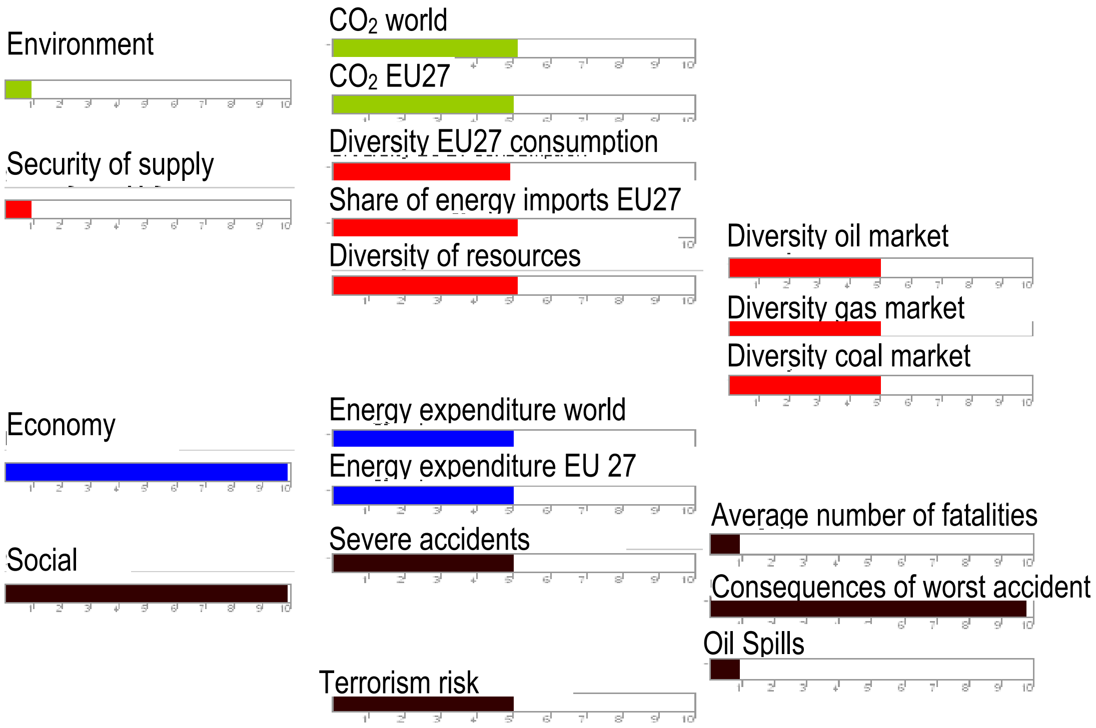

Figure 35 Baseline top profile

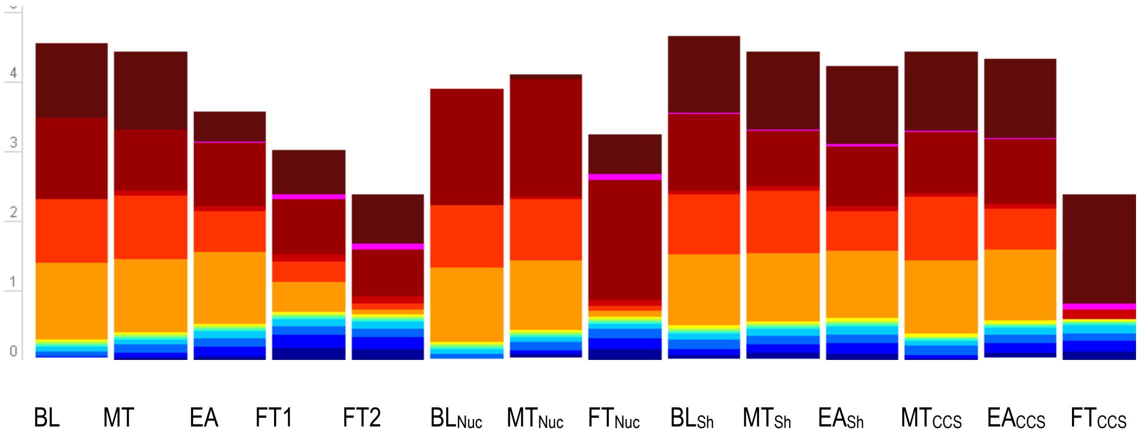

Figure 36 Results of baseline top

6.8 Systematic exploration of preference profiles

One possibility that MCDA offers is to explore the robustness of the scenario rankings by systematically trying out all preference profiles. This approach is computationally intensive, as with thirteen indicators and ten values per indicator, this would amount to 10^{14} possible combinations. To get an overview over the general behavior it is however sufficient to vary only the preferences on the highest level, while the preferences at the second and third level in the hierarchical tree are kept neutral at the same value. (Recall that the absolute level is not important as only relative values within a branch influence the result).

The preferences on the uppermost level are then varied in steps of one between one and ten, resulting in a total of 10^4=10000 possible preference profiles. Here again these profiles are not all different, as different absolute values result in the same relative preference profile. The reason for this is that due to the normalization only the ratios between the nodes on the same level are important. E.g. the two settings on the top level (1,2,3,2) and (2,4,6,4) correspond to the same profile as both sets are normalized to their sum, leading to the identical weights of (0.125, 0.25, 0.375, 0.25).

This double counting results in an higher emphasis on balanced profiles compared to extreme profiles in the total set of sampled preference profiles. I.e. there are ten possibilities to express a neutral profile, i.e. (1,1,1,1) , (2,2,2,2), (3,3,3,3) etc, but only one way to express that the first criterion is ten times as important as all others, i.e. (10, 1, 1, 1).

To illustrate this feature, Figure 37 shows an example. We assume two hypothetical weights w_1 and w_2 with possible settings from 1 to 10. Possible combinations of weights then range from (1,1) to (10,10). If the ratio between w_1 and w_2 is calculated for every combination, the values rank from 1/10=0.1 to 10/1=10. However not all ratios appear with the same frequency, there are considerably more balanced profiles with a ratio close to 1 than extreme profiles.

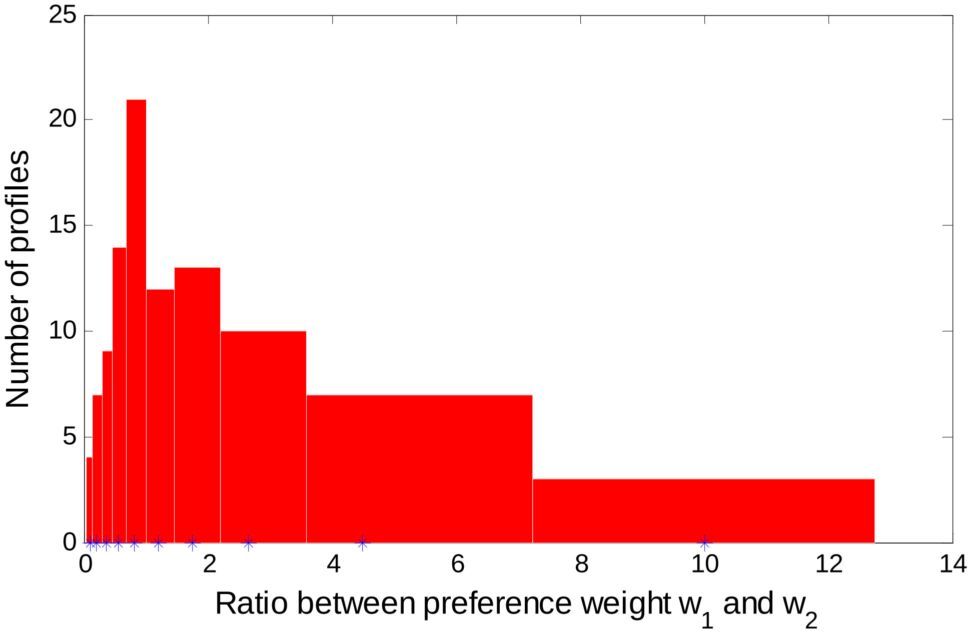

Figure 37 Histogram of the number of profiles with a given ratio of chosen weights considered by sampling the preferences for two indicators from 1:10. Possible ratios range from 0.1 to 10. There are more balanced profiles with a ratio between the preferences around 1 than extreme profiles. Blue stars mark the bin center.

Still this method gives an indication about the relative robustness of the place in the ranking of the different scenarios. An overview is given in Table 6.

Under the condition of neutral settings in the second and third level of the tree, the scenario that comes out on top for most profiles is the FT1 scenario. The baseline scenario on the other hand is never ranked top and in 89% of cases performs worst. The overall ranking is thus FT1, FT2, EA, MT and BL.

	BL	MT	EA	FT1	FT2
Rank 1	0%	14%	3%	84%	0%
Rank 2	2%	9%	18%	7%	63%
Rank 3	2%	17%	64%	6%	11%
Rank 4	7%	60%	14%	3%	16%
Rank 5	89%	0%	1%	0%	10%

Table 6 Rankings for the basic scenarios, percentage values are rounded, zeros are omitted

Table 7 shows the result for the same exercise for all scenarios, including the shocks. This table shows an important feature of the scenarios: while the FT scenarios perform very well under the conditions given for the main scenarios, their performance is highly affected by the CCS and nuclear shocks that were introduced to test the sensitivity of the scenarios.

The price shocks on the other hand seem to improve the overall performance of the scenarios compared to the main scenarios, i.e. while the basic EA scenario is never top ranked under the evaluated profiles, the price shock EA scenarios is ranked top in 27% of tested profiles.

WS	BL	MT	EA	FT1	FT2	BL Nuc	Mt Nuc	FT Nuc	BL Sh	MT Sh	EA Sh	MT ccs	EA cs	FT ccs
Rank 1				45%						13%	27%			14%
Rank 2				18%	8%				3%	18%	36%			17%
Rank 3				11%	21%			1%	13%	20%	12%	1%	5%	14%
Rank 4		1%	5%	4%	14%			18%	5%	9%	6%	3%	24%	11%
Rank 5		4%	7%	4%	9%			16%	8%	5%	19%	7%	14%	7%
Rank 6		9%	7%	3%	9%			8%	9%	32%		5%	13%	4%
Rank 7	2%	10%	13%	4%	8%			10%	4%	2%		6%	36%	5%
Rank 8	1%	6%	36%	6%	2%		2%	9%	17%			7%	7%	6%
Rank 9	2%	8%	16%	2%	5%		7%	7%	40%			7%		6%
Rank 10	5%	57%	3%	2%	12%	1%	3%	4%	1%			9%		4%
Rank 11	2%	4%	11%	1%	3%	2%	3%	13%				55%		5%
Rank 12	7%		1%		6%	1%	77%	6%						3%
Rank 13	81%				3%		8%	6%						1%
Rank 14					1%	95%		3%						1%

Table 7 Rankings for all scenarios, percentage values are rounded, zeros are omitted

The systematic variation of the preferences also allows to analyze the MCDA in reverse, i.e. to find profiles that lead to a certain ranking. The highest level of the tree allows to set the 4 criteria (environment, security of supply, economy and social) with weight combinations (w_1, w_2, w_3, w_4). Again the lower levels of the tree are set to a neutral profile, i.e. all to the same value. The highest rank that the baseline scenario can achieve under this condition is rank two.

The question is now, which preference profiles lead to the Baseline scenario achieving this rank two? To answer this we look at the respective weight combinations and simply count the frequency of each of the weights. The result is shown in Figure 38.

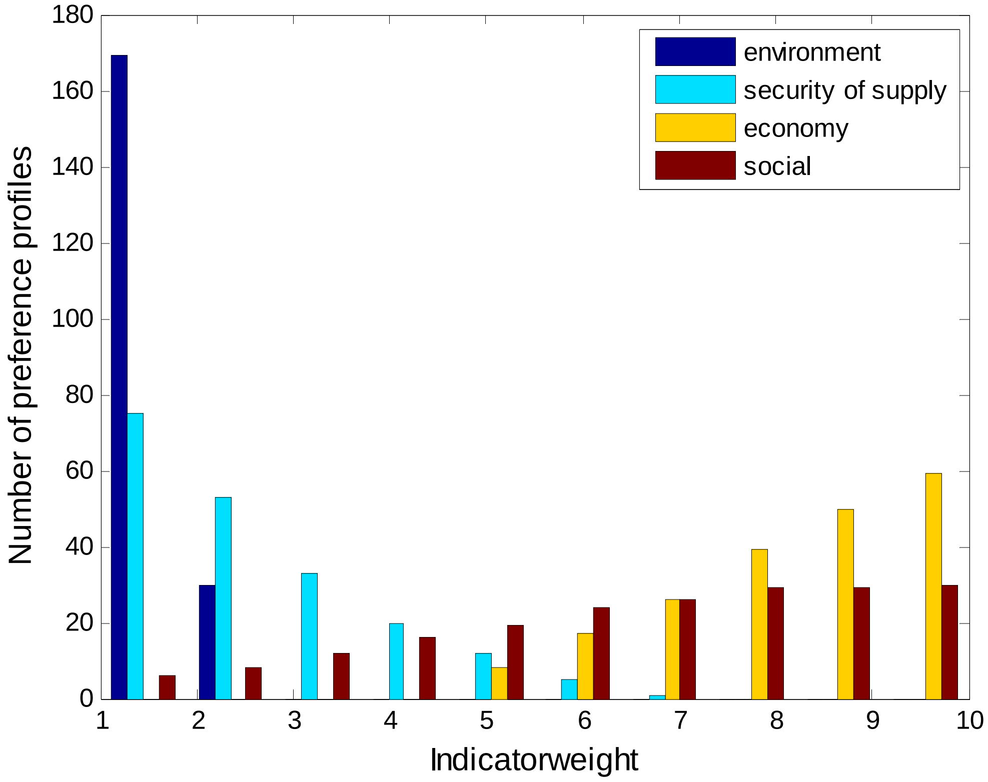

Figure 38 Preference profiles that lead to the highest possible rank of the baseline scenario (i.e. rank 2) when varying the top level preferences with a neutral profile in the lower levels of the tree.

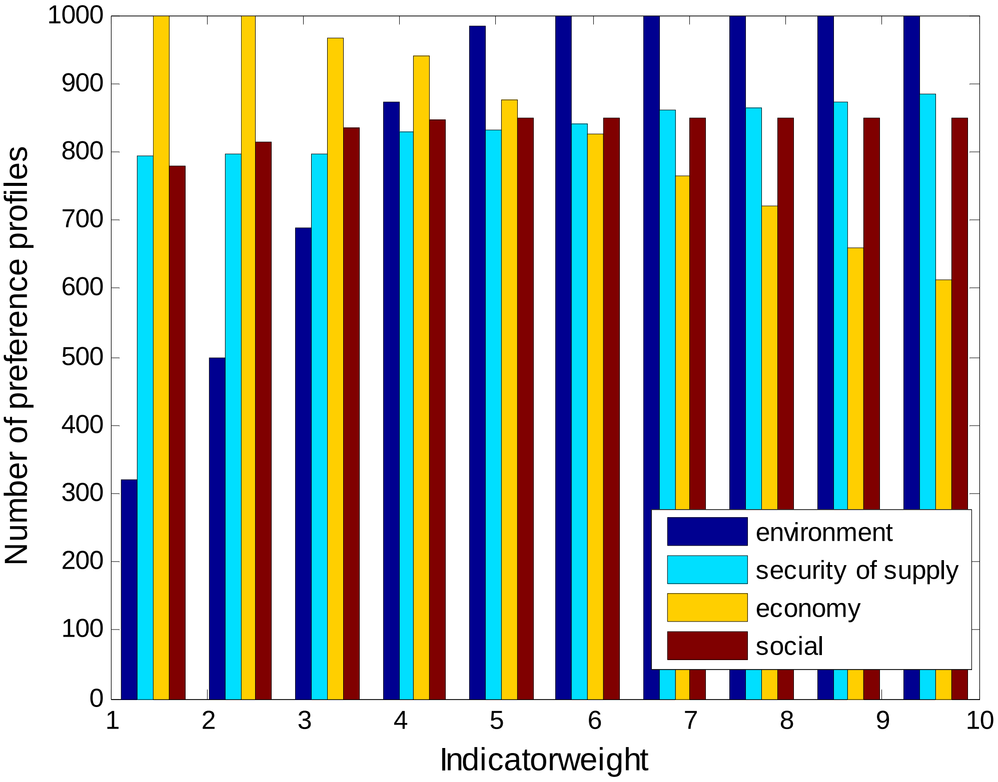

Figure 39 Relative distribution of indicator weights of the main categories for FT1 ranked first.

This graph clearly shows that a high ranking of the baseline scenario requires an emphasis on economic and social criteria while in particular the weight of the environmental indicators must be chosen very low, i.e. one or two. Figure 38 shows the same data but for the case where FT1 is top ranked. The economic and social criteria can assume any weight with from one to ten while a de-emphasis of economic criteria and an emphasis on the environment is shown to lead to a high ranking of FT1.

7 Summary and Conclusions

Multi-criteria Decision Analysis (MCDA) was employed in the SECURE Project to evaluate the various energy supply scenarios generated by the POLES model. The MCDA approach allows decision-makers and stakeholders to address simultaneously and in a structured manner the often conflicting economic, ecological and social criteria, account for the impact of subjective preferences and apply the necessary trade-offs. The associated process leads to increased understanding of the strengths and weaknesses of technologies and scenarios and identification of most robust options, and helps to guide the debate on controversial energy issues. The results obtained in the SECURE project point to policies that are most robust with respect to the balance between sustainability and security of supply.

The four families of scenarios, as generated by POLES were analyzed. The main focus was on the base scenario set but also shock scenarios were addressed. The following steps were implemented:

Establishing a structured and hierarchical set of evaluation criteria with associated indicators.

Assembling quantitative indicators characterizing the performance of the different scenarios. Most indicators originated directly from POLES while some (risk indicators) were generated in a dedicated task.

Selecting a suitable MCDA-method and tool.

Carrying out the MCDA using a variety of stakeholder profiles encountered in the energy debate.

Analyzing the results with the goal to identify specific patterns.

Compared to earlier MCDA-applications the criteria set covering the three dimensions of sustainability (environment, economy and social), was extended by explicit representation of security of supply.

Totally 13 indicators were employed, thereof two environmental (CO_2-emissions world-wide and CO_2-emissions in EU-27), two economic (energy expenditure world-wide and energy expenditure in EU-27), four risk-related social (expected severe accident risks, consequences of worst accidents, oil spill risks and risk of terrorist threat) and five for security of supply (diversity of EU-27 energy consumption, energy import dependence of EU-27, and diversity of oil, gas and coal world supply markets).

The following conclusions could be drawn from the analysis

No single scenario meets all sustainability and security of supply criteria used in SECURE; thus, trade-offs are inevitable,

Given balance between environmental, economic, social and security of supply criteria, the global regime climate regime scenarios (without shocks) perform best while the baseline scenario is consequently worst.

This result is with two exceptions quite stable with respect to the variations of preferences. The exceptions are economy-centered profiles and/or high importance assigned to the aversion towards worst consequences of severe accidents. The earlier issue is mitigated by the fact that within the SECURE project it was not possible to account for costs of avoided health and environmental damages due to reduced use of fossil energy carriers (i.e. for avoided external costs). Based on earlier experiences the cost of such damages may match or even outweigh the increased overall costs of systems employing to a large extent environmentally friendly technologies.

There are clear synergies between protection of climate and security of supply. Meeting ambitious GHG-emission reduction goals by means of successful decarbonisation of the energy supply system through expansion of renewables, nuclear and CCS, combined with very extensive efficiency improvements, is also highly beneficial for security of supply.

The sensitivity of the scenarios to shocks also depends on the preference profiles, for each basic scenario, performance under some indicators becomes worse while under other indicators it improves.

The MCDA implemented in SECURE was mainly based on the results of the model POLES limiting the scope of indicators that could be calculated to be used in the MCDA. In particular the number of indicators measuring sustainability was very limited if compared to the earlier project NEEDS. To achieve a more nuanced assessment of the trade offs between the scenarios it would desirable to take issues outside the scope of POLES into account. This may for example include social issues like the creation of jobs or additional environmental indicators such as impacts of pollution, wastes and land use.

Also in the core focus of SECURE - energy security - it would be desirable to go beyond measuring the vulnerability of the energy system with diversity indicators and instead directly quantify hazards to energy supply such as geopolitical issues or risks to the energy infrastructure.

Another important aspect that should be taken into account to achieve a more complete picture of energy security are the specific risks and benefits of the increasing share of power generated from the various renewable energy sources in the electricity supply system.

Acknowledgements

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Appendix

Table 8 Criteria for a comprehensive assessment of sustainability of electricity generation options developed for the NEEDS project (Hirschberg, Bauer, Burgherr, Dones, Schenler, et al., 2008)

Hierarchy level	Criteria name (short name)	Description	Best value = min. or max.	Unit
1	ENVIRONMENT	Environment related criteria Source: NEEDS Research Streams 1a & 2b, using Life Cycle Analysis (LCA)		
1.1	RESOURCES	Resource use (non-renewable)		
1.1.1	Energy	Energy resource use in whole life-cycle		
1.1.1.1	Fossil fuels	This criterion measures the total primary energy in the fossil resources used for the production of 1 kWh of electricity. It includes the total coal, natural gas and crude oil used for each complete technology chain. Note: Using coal fired technologies as an example; the total primary energy also includes the energy from oil used in transportation as well as from natural gas in the electricity mix used for mining and processing.	min	MJ/kWh
1.1.1.2	Uranium	This criterion quantifies the primary energy from uranium resources used to produce 1 kWh of electricity. It includes the total use of uranium for each complete electricity generation technology chain.	min	MJ/kWh

Hierarchy level	Criteria name (short name)	Description	Best value = min. or max.	Unit
1.1.2	Minerals	Mineral resource use in whole life-cycle		
1.1.2.1	Metal ore	This criterion quantifies the use of selected scarce metals used to produce 1 kWh of electricity. It is based on the Life Cycle Impact Assessment method "CML 2001". The use of all single metals is expressed in antimony-equivalents, based on the scarcity of their ores relative to the reference ore (antimony).	min	kg(Sb-eq.)/kWh
1.2	CLIMATE	Potential impacts on the climate		
1.2.1.1	Carbon dioxide emissions (CO_2 emissions)	This criterion includes the total for all different greenhouse gases expressed in kg of CO_2 equivalent for each electricity generation technology. It addresses the potential negative impacts of global climate change caused by the greenhouse gases from the production of 1 kWh of electricity.	min	kg(CO_2-eq.)/kWh
1.3	ECOSYSTEMS	Potential impacts to ecosystems		
1.3.1	Normal operation (Normal op.)	Ecosystem impacts from normal operation		
1.3.1.1	Biodiversity	This criterion quantifies the loss of species (flora & fauna) due to the land used to produce 1 kWh of electricity. The "potentially damaged fraction" (PDF) of species is multiplied by land area and years for each complete	min	PDF*m^2*a/kWh

Hierarchy level	Criteria name (short name)	Description	Best value = min. or max.	Unit
		electricity generation technology chain.		
1.3.1.2	Ecotoxicity	This criterion quantifies the loss of species (flora & fauna) due to ecotoxic substances released to air, water and soil to produce 1 kWh of electricity. The "potentially damaged fraction" (PDF) of species is multiplied by land area and years for each complete electricity generation technology chain.	min	PDF*m^2*a/kWh
1.3.1.3	Air pollution	This criterion quantifies the loss of species (flora & fauna) due to acidification and eutrophication caused by pollution from production of 1 kWh of electricity. The "potentially damaged fraction" (PDF) of species is multiplied by land area and years for each complete electricity generation technology chain.	min	PDF*m^2*a/kWh
1.3.2	Severe accidents (Severe acc.)	Ecosystem impacts in the event of severe accidents		
1.3.2.1	Hydrocarbons	This criterion quantifies large accidental spills of hydrocarbons to the environment, which can potentially damage affected ecosystems. It considers severe accidents only, i.e. releases of at least 10000 tonnes.	min	t/GWeyr
1.3.2.2	Land	This criterion quantifies land contaminated due to accidents	min	km^2/GWeyr

Hierarchy level	Criteria name (short name)	Description	Best value = min. or max.	Unit
	contamination (Land contam.)	releasing radioactive isotopes. The land area contaminated is estimated using Probabilistic Safety Analysis (PSA). Note that this indicator is restricted to the nuclear electricity generation technology chain.		
1.4	WASTE	Potential impacts due to waste		
1.4.1.1	Chemical waste	This criterion quantifies the total mass of special chemical wastes stored in underground repositories due to the production of 1 kWh of electricity. It does not reflect actual damage to humans or nature and does not reflect the confinement time required for each repository.	min	kg/kWh
1.4.1.2	Radioactive waste (Rad. waste)	This criterion quantifies the volume of low, medium and high level radioactive wastes stored in underground repositories due to the production of 1 kWh of electricity. It covers each complete electricity generation technology chain and does not reflect actual damage to humans or nature. It also does not reflect the confinement time required for the repository.	min	m^3/kWh

2	ECONOMY	Economy related criteria Source: NEEDS Research Stream 2b contributors for different technologies.		

Hierarchy level	Criteria name (short name)	Description	Best value = min. or max.	Unit
2.1	CUSTOMERS	Economic effects on customers		
2.1.1.1	Generation cost (Gen. Cost)	This criterion gives the average generation cost per kilowatt-hour (kWh) for each technology, including the capital cost of the plant, (fuel), and operation and maintenance costs. It is the cost to the utility of generating electricity and not the end price that the customer must pay.	min	EUR/MWh
2.2	SOCIETY	Economic effects on society		
2.2.1.1	Direct jobs	This criterion gives the amount of employment directly related to building and operating the generating technology, including the direct labour involved in extracting or harvesting and transporting fuels (when applicable). Indirect labour (e.g fabricating plant components) is not included. The employment is measured in terms of man-years of labour and averaged over the generation, i.e. units are person-years/GWh.	max	Person-years/GWh
2.2.1.2	Fuel autonomy	Utility companies and the societies they serve may be vulnerable to interruptions in service if imported fuels are unavailable due to economic or political problems related to energy resource availability. This measure of vulnerability is based on expert judgment (of related factors), including whether a resource is domestic or imported,	max	Ordinal

Hierarchy level	Criteria name (short name)	Description	Best value = min. or max.	Unit
		renewable or finite, and the relative size of different finite resources.		
2.3	UTILITY	Economic effects on utility company		
2.3.1	Financial	Financial impacts on utility		
2.3.1.1	Financing risk	Utility companies can face a considerable financial risk if the total cost of a new electricity generating plant is very large compared to the overall size of the company. These risks can require forming necessary partnerships with other utilities or raising capital through financial markets.	min	Million EUR, NPV (NPV = Net Present Value)
2.3.1.2	Fuel sensitivity	The fraction of fuel cost to overall generation cost can range from zero (solar PV) to low (nuclear power) to high (gas turbines). This fraction therefore indicates how sensitive the generation costs would be to a change in fuel prices.	min	Factor
2.3.1.3	Construction time (Constr. Time)	Once a utility has started building a plant it is vulnerable to public opposition, resulting in delays and other problems, driving up the total cost. This indicator therefore gives the expected plant construction time in years. Time required for planning and regulatory approval is not included, as the bulk of spending occurs after the start of	min	Years

Hierarchy level	Criteria name (short name)	Description	Best value = min. or max.	Unit
		construction.		
2.3.2	Operation	Factors related to a utility company's operation of a technology.		
2.3.2.1	Marginal cost	Generating companies “dispatch” or order their plants into operation according to their variable cost, starting with the lowest cost baseload plants up to the highest cost plants at peak load periods. This variable (or dispatch) cost is the cost to run the plant, without the cost to build it. It is equal to the average fuel cost plus variable operation and maintenance costs per kilowatt-hour.	min	EUR-cents/kWh
2.3.2.2	Flexibility	In order to plan the operation of their generating plants at least a day in advance, utilities need forecasts of generation they cannot control (renewable resources like wind and solar), and the necessary start-up and shut-down times required for the plants they can control. This indicator combines these two measures of planning flexibility, based on expert judgment, including the logarithmic nature of planning time (the difference between 1 and 2 hours advance notice is more important in planning than the difference between 11 and 12 hours).	max	Ordinal
2.3.2.3	Availability	All technologies can have plant outages or partial outages (less	max	Factor

Hierarchy level	Criteria name (short name)	Description	Best value = min. or max.	Unit
		than full generation), due to either equipment failures (forced outages) or due to maintenance (unforced or planned outages). This indicator tells the fraction of the time that the generating plant is available to generate power. Partial outages are accounted for by making an annual average equivalent availability factor, equal to the expected possible annual generation divided by maximum annual generation at full power.		
3	SOCIAL	Socially related criteria Source: NEEDS Research Stream 2b survey of social experts for most indicators (indicated by ordinal scale for units). Quantitative risk measures based on PSI risk database.		
3.1	SECURITY	Social Security		
3.1.1	Political continuity (Pol. Continuity)	Political continuity		
3.1.1.1	Secure supply	This criterion refers to the market concentration of energy suppliers in each primary energy sector that could lead to economic or political disruption. It is based on expert judgement.	min	Ordinal scale
3.1.1.2		The criterion is based on the	min	Ordinal scale

Hierarchy level	Criteria name (short name)	Description	Best value = min. or max.	Unit
	Waste repository (Waste repos.)	possibility that an infrastructure of storage facilities will not be available in time to take deliveries of waste materials from the fuel chain, including from the fuel supply, plant construction, operation and decommissioning of the plant.		
3.1.1.3	Adaptability	The criterion refers to the technical characteristics of each electricity generation technology that may make it flexible in implementing technical progress and innovations.	max	Ordinal scale
3.2	POLITICAL LEGITIMACY (Political Legit.)	Political legitimacy		
3.2.1.1	Conflict	The indicator refers to conflicts that are based on historical evidence. It is related to the characteristics of energy systems that trigger conflicts.	min	Ordinal scale
3.2.1.2	Participation	This criterion is based on the fact that certain types of technologies require public, participative decision-making processes, especially for construction or operating permits or licenses.	min	Ordinal scale
3.3	RISK	Risk		
3.3.1	Normal risk	Normal operation risk Source: NEEDS Research Stream 2b for life cycle risk data		
3.3.1.1		This criterion is based on the	min	YOLL/kWh

Hierarchy level	Criteria name (short name)	Description	Best value = min. or max.	Unit
	Mortality	increased rate of mortality due to normal operation of the electricity generation technology and its associated energy chain. It is measured in the years of life lost (YOLL) by the entire population, compared to the expected lifetimes without the technology in question.		
3.3.1.2	Morbidity	This criterion is based on the increased rate of sickness or morbidity due to normal operation of the electricity generation technology and its associated energy chain. It is measured in the years of life affected by disabilities (disability adjusted life years, or DALY) suffered by the entire population, compared to their expected health without the technology in question.	min	DALY/kWh
3.3.2	Severe accidents (Sev. Accidents)	Risk from severe Accidents Source: NEEDS Research Stream 2b for severe accident data		
3.3.2.1	Accident mortality (Acc. Mortality)	This criterion is based on the number of fatalities expected for each kWh of electricity that occur in severe accidents with 5 or more deaths per accident for a particular electricity generation technology chain.	min	Fatalities/GWeyr
3.3.2.2	Maximum fatalities	This criterion is based on the maximum number of fatalities that are reasonably credible for a single accident for a particular	min	Fatalities/accident

Hierarchy level	Criteria name (short name)	Description	Best value = min. or max.	Unit
	(Max. fatalities)	electricity generation technology chain.		
3.3.3	Perceived risk	Perceived risk		
3.3.3.1	Normal operation	This criterion is based on citizens' fear of negative health effects due to normal operation of the electricity generation technology.	min	Ordinal scale
3.3.3.2	Perceived accidents (Perceived acc.)	This criterion is based on citizens' perception of risk characteristics, including whether they can control the risk personally, whether the potential damage is small or catastrophic, and their familiarity with the risk.	min	Ordinal scale
3.3.4	Terrorism	Risk of terrorism		
3.3.4.1	Terror-Potential	This criterion indicates the potential for a successful terrorist attack on a specific technology, based on its vulnerability, the potential damage and public perception of risk.	min	Ordinal scale
3.3.4.2	Terror-Effects	This criterion concerns the potential likely consequences of a successful terrorist attack. The criterion implicitly addresses the aversion towards low-probability high-consequence accidents.	min	Expected number of fatalities
3.3.4.3	Proliferation	This criterion represents the potential for misuse of technologies or substances present in the nuclear electricity	min	Ordinal scale

Hierarchy level	Criteria name (short name)	Description	Best value = min. or max.	Unit
		generation technology chain, based on both their presence and the risk of such misuse or diversion.		
3.4	RESIDENTIAL ENVIRONMENT (Residential env.)	Quality of the residential environment		
3.4.1.1	Landscape	This criterion is based on the overall functional and aesthetic impact on the landscape of the entire infrastructure related to each electricity generation technology chain, including mines, transmission lines or pipelines, structures, etc. Note: Excludes traffic.	min	Ordinal scale
3.4.1.2	Noise	This criterion is based on the amount of noise caused by the generation plant, as well as transport of materials to and from the plant (e.g. trucking of fuel and/or waste).	min	Ordinal scale