SIXTH FRAMEWORK PROGRAMME

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NEEDS

New Energy Externalities Developments for Sustainability

INTEGRATED PROJECT

Priority 6.1: Sustainable Energy Systems and, more specifically,
Sub-priority 6.1.3.2.5: Socio-economic tools and concepts for energy strategy.

Deliverable D10.2 - RS2b

"Final report on sustainability assessment of advanced electricity supply options"

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1 Introduction

The EU Integrated Project NEEDS (New Energy Externalities Developments for Sustainability) has had objective of examining the sustainability of advanced electricity generation technologies for the four different countries of France, Germany, Italy and Switzerland in the year 2050. Within NEEDS, the central objective of Research Stream RS2b "Energy Technology Roadmap and Stakeholder Perspectives" has been to broaden the basis for decision support beyond the assessment of external costs and to extend the integration of the central analytical results generated by other Research Streams. This goal includes mapping the sensitivity of sustainability performance of technological options to stakeholder preference profiles by examining the robustness of technology ranking results under different stakeholder perspectives.

The baseline approach of total cost estimation for the advanced generation technologies was based on calculating and combining the direct (internal) and indirect (external) costs, based on information developed by other research streams and within RS2b. The second approach has been to use Multi-Criteria Decision Analysis (MCDA), combining specific technology characteristics related to sustainability with stakeholder preferences in a structured way.

The main efforts undertaken within RS2b have been to develop a framework for implementing such a MCDA approach. This has included

- developing a structured set of sustainability criteria, and surveying stakeholders on their appropriateness and acceptance,
- generating and then integrating environmental, economic and social indicators originating from RS2b and other research streams into a technology database for use in the MCDA process, including differentiation for the four NEEDS countries,
- performing a requirements analysis for the MCDA analysis methodology and a review of existing MCDA approaches,
- developing a range of new MCDA tools for ranking discrete alternatives (technologies, in the NEEDS context) and selecting the best for use,
- implementing an interactive, web-based interface for collecting stakeholder criteria preferences (and providing individualized technology rankings to each user), and
- collecting the individual user inputs and ranking results for analysis of overall patterns.

This report first discusses the background of and motivation for using multiple criteria for sustainability assessment v. using a single criterion (monetization, or total costs). It then discusses the overall structure of the methodology for sustainability assessment within the NEEDS project, including the selection of structured sustainability criteria and their approval by stakeholder surveys. The report then focuses on the multi-criteria analysis of sustainability within NEEDS, including the development and selection of new MCDA algorithms, their implementation for the survey of stakeholder preferences, the analysis of the survey response and results, and the conclusions for the relative sustainability and robustness of different technologies using MCDA as compared to total costs.

The reader is referred to other NEEDS reports for more complete descriptions of the development of sustainability criteria and their definitions, the first two stakeholder surveys on the acceptance of total costs and the sustainability criteria, a survey of the international uses of total costs for policy-making, the development of the environmental, economic and social indicators, their combination into the technology description database, and the mathematical description of the MCDA methodology. Here the emphasis in on the overall multi-criteria approach, analysis and results.

2 Background and Motivation

2.1 The electric sector planning problem

Deciding how to expand the electric generation sector is a difficult problem, even before issues related to sustainability are included. The reasons for this include -

- Complexity and size – Each generation technology includes a full energy chain from fuel extraction and transport to plant construction and operation to waste disposal and plant retirement. In addition, the sheer size of the electric utility sector means that decisions have large costs and impacts.
- Multiple criteria – Generation technologies have a range of economic costs and direct environmental burdens. Adding sustainability concerns means that an even wider range of environmental, economic and social criteria must be included.
- Multiple stakeholders – Different interest groups have much at stake to gain or lose, depending upon the choice of future technologies. These stakeholders include generators, system operators, large and small customers, utility regulators, and environmental regulators and activist groups.
- Inherent tradeoffs – Given the range of technologies currently and foreseeably available, there are no simple solutions that satisfy all criteria. Instead, there are inherent tradeoffs between different criteria, which different stakeholder value very differently.

Large, complex problems almost always have multiple stakeholders with different preferences across the broad range of multiple criteria. Because the problem is complex, there will not generally be a single optimum solution that satisfies everyone (if an optimum technical solution existed that satisfied everyone, it would no longer be a complex problem). And because the different stakeholders have different criteria preferences, they will prefer different solutions. This generally means that while stakeholder groups may be able to reach their own decisions, in the larger context there is no single decision-maker and choices are reached through a social or political process.

Because of the inherent conflicts between the multiple sustainability criteria considered, it is necessary to somehow combine these criteria in order to be able to prefer one technology over another, and thus construct a full preference ranking of the future generation options.

There are two major options for aggregating multiple criteria, which are -

- Total cost, and
- Multi-criteria decision analysis.

Actually, the NEEDS analysis of the future sustainability of the electricity sector has been simplified by limiting the future options considered to just generation technologies and their associated fuel cycles. These are very important, but once stakeholders have selected their top-ranked technologies they will also eventually need to consider how these technologies will interact with other options for the pre-existing power system, demand side efficiency and peak reduction, environmental regulation and system operating rules.

2.2 Total cost

Monetary cost has always been a basis for comparing very widely disparate commodities. In fact, the three basic economic functions of money are as 1) a medium of exchange, 2) a store of value and 3) a *numeraire,* or measure of comparative value (e.g. 1 EUR = x liters of gas = y oranges).

However, the direct or internal cost of electricity does not include indirect or external costs like the costs of health care due to air pollution. For this reason it is customary to define the total cost of a commodity as the internal cost plus the external cost, and this total cost is frequently used in public policy analysis and decision-making. However this approach incorporates some very significant assumptions. Money becomes *the* single metric or common denominator for all indicators, and it is assumed that *all* indicators can be monetized. In addition, only a single equivalent monetary value can be given to each indicator (e.g. human life, the environment, etc.).

The problem with this approach is that, by definition, external costs have no market where supply and demand can produce a market price. Nevertheless, it is assumed that somehow stakeholders can *agree* on the value of life, the environment, etc. Here there are two sub-problems.

In some cases there may be some plausible basis for monetization (willingness to pay, cost to control, damage cost, etc.), but the basis is controversial either in method or in the quantitative assumptions.

In other cases, the indicators may be entirely subjective, and hence any monetization is based purely on personal preference. These indicators include difficult, but potentially very important social aspects like social justice, perceived risk and risk aversion, resilience of the energy system and conflict potential (to name just some).

Thus, it is theoretically possible that any externality can be monetized, but in practice methodologies and valuation are often controversial, and the large amounts at stake and the wide differences between stakeholders mean that it is practically impossible for them all to agree on a single monetary value for any controversial indicator. A single decision-maker (usually the government) may choose and adopt a monetary value, but this imposes rather than promotes consensus. Nevertheless, it is certainly true that money is the single most useful and widely accepted common numerator, and cost-benefit analysis based on (total) costs has great attractions for guiding public policy.

This was supported by the NEEDS Survey 1, which used web-based survey software to ask stakeholders their opinions on the concept of external costs, their results and uses. It showed that in spite of the limitations, there is a general acceptance of the concept of externalities, of the internalization of external costs, and of most results. The NEEDS project also included a case study showing the comparative international uses of total costs for policy and decision making (Bureau, et al., 2006), and other relevant prior work in the international use of external costs and cost-benefit analysis also includes Hirschberg, et al. (2000 and 2003) and Roth, et al. (2009).

2.3 Multi-criteria decision analysis

Instead of aggregating multiple criteria into a single monetary measure, each individual decision-maker could combine his own preferences with the problem data to reach his own conclusions. For NEEDS, this means combining individual preferences for different sustainability criteria with established generation technology characteristics to reach an individual preference ranking of the technologies.

The problem is that the complexity of the analysis and an individual's cognitive limitations can prevent single decision-makers from reaching consistent choices, even if they understand the problem and their own preferences. Most people can balance about seven or so different factors when making a decision, but the number of sustainability criteria generally included far exceeds this number.

Multi-criteria decision analysis offers a wide range of tools to assist the individual decision-maker in combining his own criteria preferences with the decision problem data to reach his own conclusions in a structured and consistent way. It is important to choose the correct MCDA method or tool to suit the problem at hand, depending upon a number of factors that may include the following -

- Are the decision variables continuous or discrete?
- Is the problem to find an optimum strategy that mixes individual options, or to rank mutually exclusive alternatives?
- Is the MCDA method suited to the size of the problem (number of criteria and variables)?

- Are the decision criteria objective/qualitative, subjective/qualitative or both?
- Do criteria preferences include the need for threshold limits or vetoes?
- How are risk, uncertainty and utility issues considered?
- Does the MCDA model correctly handle mathematical or theoretical issues (e.g. maintaining preference rankings when an alternative is dropped)?
- Is the method easy to understand and to use?

Choosing an appropriate MCDA method or tool is necessary, but not sufficient. For the best results, it should also be used as part of a structured MCDA process. For the NEEDS project, this process has included the major steps listed below (the order is general, but some steps proceeded in parallel).

1 Determine stakeholder groups and gather participant names

2 Establish criteria and indicators (with stakeholder input)

3 Select the technological alternatives (with stakeholder input)

4 Quantify the technology- and country-specific indicators

5 Analyze the MCDA methodology requirements

6 Develop and/or select the most suitable MCDA method(s)

7 Implement and test the selected method(s)

8 Elicit stakeholder preferences, and provide individual MCDA results

9 Analyze aggregate stakeholder results, and draw conclusions

In particular, stages 5 and 6 are reported upon separately in the NEEDS deliverables on the requirements analysis (technical report T9.1, Makowski, et al., 2006) and on the multi-criteria methodology (technical report T9.2, Makowski, et al., 2006).

In the end, MCDA should not be a "black box" where decision-maker simply dumps in problem data and his own preferences, turns the crank, and gets out "the answer." Instead the entire process should be an aid to thinking and decision-making, with an iterative approach to learning about the decision problem, the effects of different criteria preferences and the tradeoffs between different solutions. The decision-maker can see the consequences of his preferences, see whether or not the results agree with any preconceived ideas of the desired outcome, and hopefully reconcile any differences to a more consistent understanding.

Prior relevant literature that illustrates the international uses (including Switzerland, Germany and China) of MCDA in exploring sustainability issues in the electric sector include Hirschberg, et al. (2000 and 2004), Haldi, et al. (2003), and Roth, et al. (2009).

3 Methodology

This chapter describes in more detail most of the steps in the overall MCDA process that were outlined in the previous section (except that the analysis and results are presented in chapters 4 and 5). The emphasis here is on describing the MCDA method – from the requirements analysis to new algorithm development, testing, selection and implementation as a web-based survey of sustainability preferences.

3.1 Stakeholders

Stakeholders are key to structuring the MCDA analysis, and particularly in selecting the criteria and alternatives. In the NEEDS context, this means choosing the sustainability criteria and indicators for environmental, economic and social issues. If stakeholders feel that important criteria or technologies have been omitted, it can affect the credibility of results and overall effectiveness of the project. For this reason, the RS2b team created a comprehensive list of stakeholder groups and sub-groups associated with the electric sector planning debate, as shown below in Table 1.

The RS2b team members in the four different NEEDS countries of France, Germany, Italy and Switzerland contributed stakeholder candidate names that were placed on the contact list for the NEEDS surveys related to external costs, sustainability indicators and sustainability preferences. Where possible, the stakeholder groups for these candidates were identified in advance, but individual stakeholders were also invited as part of the sustainability survey to choose either a different stakeholder group or to choose a further stakeholder sub-group, along with other demographic data that was collected. A significant number of the stakeholders also came from outside the four NEEDS countries. The distribution of stakeholders contacted for and responding to Survey 3 by country, stakeholder group and other subgroups is reported in Chapter 4.

Although stakeholders were required to use an email address to login to the survey, the results of these surveys were held strictly confidential, and results were only analyzed and published on an anonymous, aggregated basis.

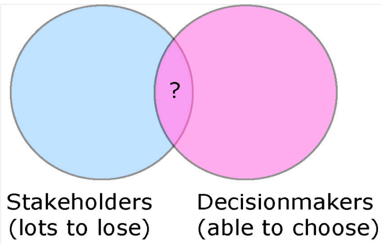
Table 1 - Stakeholder groups and sub-groups for NEEDS RS2b

Stakeholder Groups and Sub-groups
Energy Supplier
Centralized or Decentralized
Manufacturer
Technology Agency
Transmission and Distribution
Sectoral Association
Energy Consumer
Technology Supplier
Energy Consuming Industry
Agriculture
Transport Sector
Services
Households
Technology Agency
Sectoral Association
Non-Governmental Organization (NGO)
International
European
National
Government Energy or Environmental Agency
European
National
Regional/Local
Regulator / Government Authority
European
National
Regional/Local
Industry Group/Association
European
National
Regional/Local
Government/Politician
Left/Green
Center/Liberal
Right/Conservative
Researcher/Academic
Energy: Fossil
Energy: Renewables
Energy: Nuclear
Energy: Demand
Energy: Systems Analysis
Energy: Other
Energy: Non-Energy
Consultant
Small or Medium
Large (> 30 employees)
Other (self-identified)

It is perhaps worthwhile expanding slightly on the difference between stakeholders and decision-makers, as these two terms are frequently used interchangeably. Stakeholders have something to win or lose in the planning debate (“at stake”), while decision-makers can actually make an impact by their choices (as illustrated in Figure 1 below). The two groups often overlap to varying degrees, but they are not strictly identical. For example -

- Some decision-makers have little personally at stake (e.g. regulators),
- Some stakeholders can only make decisions for their own group (e.g. utilities), and
- Some stakeholders have little decision-making power (e.g. customers).

Figure 1 - Stakeholders v. decision-makers



The NEEDS survey participants have generally been called stakeholders within this report, but as a group they naturally include many people who are also decision-makers.

3.2 Criteria and indicators

Definitions – A *criterion* is a basis for decision-making that captures a single issue or area of concern. Each criterion may be divided into sub-criteria that are lower in the criterion hierarchy. At the lowest level of criterion hierarchy, each branch of the hierarchical tree must have an *indicator* that measures the performance of each technology for the criterion in question. Indicators may be objective or subjective, quantitative or qualitative, and a scale that makes either minimum or maximum values preferred. For use in the MCDA methodology, qualitative indicators must be quantified by subjective judgment, and both quantitative and qualitative indicators are generally transformed or scaled based on the full group of alternatives. The hierarchy need not have the same number of levels for every branch.

Requirements - When constructing a structured hierarchy of criteria for a complex problem like NEEDS, there are a number of concerns or requirements that must be addressed (i.e., there are criteria for choosing criteria…). These are summarized in Table 2 below.

Table 2 - Criteria and indicator requirements

Criteria & indicators should…	This study's interpretation
1. Capture essential technology characteristics & enable differentiation.	– The **criteria and indicators** should be **concrete and readily understandable** by stakeholders. – **Binary** indicators should be avoided if possible, to allow gradual distinctions between technologies (this includes value ranges with distant outliers). – **Scenario-dependent assumptions** should be avoided (e.g. future energy mix, or market penetration) to focus analysis on technologies, not scenarios.
2. Assure indicators are representative (if not necessarily complete).	– Each indicator should be representative, and thus **well indicative,** for a given criterion. All indicators together should **capture all of the main decision criteria, but** need not to cover all of a criterion's 'space' ('completeness').

Criteria & indicators should…	**This study's interpretation**
3. Keep number of indicators reasonable and strive for balance between categories.	– The number of indicators for each criterion should be limited, and relatively consistent across criteria.
4. Avoid excessive overlap.	– Indicators should be as independent as possible. Overlapping or double-counting indicators may introduce bias.
5. Aggregate indicators if this involves minimum or no subjectivity.	– Quantification should be transparent, meaning: o data sources be specified, o the link between these data and the actual indicator should be as simple and direct as possible. If indirect, calculations & assumptions should be specified. – The calculation should be consistent for all technologies.
6. Be practical & feasible; indicators generated within RS2b or available from other research streams.	– Data availability within NEEDS warranted. – Work to within the scope of the anticipated and contracted person-months.

<u>Criterion hierarchy</u> – Based on these requirements, the following set of criteria and indicators was constructed (Hirschberg, et al., 2008).

Table 3 - NEEDS hierarchy of criteria and indicators

Criteria / Indicator	Description	Unit
ENVIRONMENT	Environment related criteria. Source: NEEDS Research Streams 1a & 2b, using Life Cycle Analysis (LCA)	
RESOURCES	Resource use (non-renewable)	
Energy	Energy resource use in whole life-cycle	
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 electricity generation technology chain.	MJ/kWh
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.	MJ/kWh
Minerals	Mineral resource use in whole life-cycle	
Metal ore	This criterion quantifies the use of selected scarce metals used to produce 1 kWh of electricity. The use of all single metals is expressed in antimony-equivalents, based on the scarcity of their ores relative to antimony.	kg(Sb-eq.)/kWh
CLIMATE	Potential impacts on the climate	
CO2 emissions	This criterion includes the total for all greenhouse gases expressed in kg of CO2 equivalent.	kg(CO2-eq.)/kWh
ECOSYSTEMS	Potential impacts to ecosystems	
Normal operation	Ecosystem impacts from normal operation	
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.	PDF*m2*a/kWh
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.	PDF*m2*a/kWh
Air pollution	This criterion quantifies the loss of species (flora & fauna) due to acidification and eutrophication caused from production of 1 kWh of electricity. The "potentially damaged fraction" (PDF) of species is multiplied by land area and years.	PDF*m2*a/kWh
Severe accidents	Ecosystem impacts in the event of severe accidents	
Hydrocarbons	This criterion quantifies large accidental spills of hydrocarbons (at least 10000 tonnes) which can potentially damage ecosystems.	t/kWh
Land contamination	This criterion quantifies land contaminated due to accidents releasing radioactive isotopes. The land area contaminated is estimated using Probabilistic Safety Analysis (PSA). Note: only for nuclear electricity generation technology chain.	km2/kWh
WASTE	Potential impacts due to waste	
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 the confinement time required for each repository.	kg/kWh
Radioactive waste	This criterion quantifies the volume of medium and high level radioactive wastes stored in underground repositories due to the production of 1 kWh of electricity. It does not reflect the confinement time required for the repository.	m3/kWh

Table 3 - NEEDS hierarchy of criteria and indicators (cont.)

Criteria / Indicator	Description	Unit
ECONOMY	Economy related criteria Source: NEEDS Research Stream 2b contributors for different technologies.	
CUSTOMERS	Economic effects on customers	
Generation cost	This criterion gives the average generation cost per kilowatt-hour (kWh). It includes the capital cost of the plant, (fuel), and operation and maintenance costs. It is not the end price.	€/MWh
SOCIETY	Economic effects on society	
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 is not included. Measured in terms of person-years/GWh.	Person-years/GWh
Fuel autonomy	Electricity output 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.	Ordinal
UTILITY	Economic effects on utility company	
Financial	Financial impacts on utility	
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 size of the company. It may be necessary to form partnerships with other utilities or raise capital through financial markets.	€
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.	Factor
Construction time	Once a utility has started building a plant it is vulnerable to public opposition, resulting in delays and other problems. This indicator therefore gives the expected plant construction time in years. Planning and approval time is not included.	Years
Operation	Factors related to a utility company's operation of a technology.	
Marginal cost	Generating companies “dispatch” or order their plants into operation according to their variable cost, starting with the lowest cost base-load plants up to the highest cost plants at peak load periods. This variable (or dispatch) cost is the cost to run the plant.	€cents/kWh
Flexibility	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.	Ordinal
Availability	All technologies can have plant outages or partial outages (less 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.	Factor

Table 3 - NEEDS hierarchy of criteria and indicators (cont.)

Criteria / Indicator	Description	Unit
SOCIAL	Social related criteria Source: NEEDS Research Stream 2b survey of social experts. Quantitative risk based on PSI risk database.	
SECURITY	Social Security	
Political continuity	Political continuity	
Secure supply	Market concentration of energy suppliers in each primary energy sector that could lead to economic or political disruption.	Ordinal scale
Waste repository	The possibility that storage facilities will not be available in time to take deliveries of waste materials from whole life cycle.	Ordinal scale
Adaptability	Technical characteristics of each technology that may make it flexible in implementing technical progress and innovations.	Ordinal scale
POL.. LEGITIMACY	Political legitimacy	
Conflict	Refers to conflicts that are based on historical evidence. It is related to the characteristics of energy systems that trigger conflicts.	Ordinal scale
Participation	Certain types of technologies require public, participative decision-making processes, especially for construction or operating permits.	Ordinal scale
RISK	Risk	
Normal risk	Normal operation risk Source: NEEDS Research Stream 2b for life cycle risk data	
Mortality	Years of life lost (YOLL) by the entire population due to normal operation compared to without the technology.	YOLL/kWh
Morbidity	Disability adjusted life years (DALY) suffered by the entire population due to normal operation compared to without the technology.	DALY/kWh
Severe accidents	Risk from severe Accidents Source: NEEDS Research Stream 2b for severe accident data	
Accident mortality	Number of fatalities expected for each kWh of electricity that occurs in severe accidents with 5 or more deaths per accident.	Fatalities/kWh
Maximum fatalities	Based on the reasonably credible maximum number of fatalities for a single accident for an electricity generation technology chain.	Fatal./accident
Perceived risk	Perceived risk	
Normal operation	Citizens' fear of negative health effects due to normal operation of the electricity generation technology.	Ordinal scale
Perceived acc.	Citizens' perception of risk characteristics, personal control over it, scale of potential damage, and their familiarity with the risk.	Ordinal scale
Terrorism	Risk of terrorism	
Terror-potential	Potential for a successful terrorist attack on a technology. Based on its vulnerability, potential damage and public perception of risk.	Ordinal scale
Terror-effects	Potential maximum consequences of a successful terrorist attack. Specifically for low-probability high-consequence accidents.	Exp. fatalities
Proliferation	Potential for misuse of technologies or substances present in the nuclear electricity generation technology chain.	Ordinal scale
RESIDENTIAL ENV.	Quality of the residential environment	
Landscape	Overall functional and aesthetic impact on the landscape of the entire technology and fuel chain. Note: Excludes traffic.	Ordinal scale
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.	Ordinal scale

As this table shows, the NEEDS criterion hierarchy is divided at its top level into the main three conventional areas of sustainability – Environment, Economy and Society. Resources and Climate are below Environment, with Resources further subdivided into Energy and Minerals. At the fourth, lowest level are the specific indicators for which actual values have been determined, either by analysis or by expert judgment. Not all branches have the same number of subdivisions or levels. For example the second level criterion "Climate" in Table 3 leads directly to the indicator of "CO_2 emissions." And in some places the hierarchical tree does not divide at each level (for example, the criterion "Minerals" leads to only one indicator "Metal Ore").

Survey 2 – The criteria and indicator structure developed for NEEDS was submitted for stakeholder feedback by using a web-based survey. This survey and its results are fully described by NEEDS Deliverable 12.3 – RS2b "Implementation, evaluation and reporting on the survey on criteria and indicators" (Burgherr et al., 2006). It concludes that although the stakeholder response rate was modest, it was adequate to conclude that the criteria and indicator structure met with high acceptance.

Overall, the survey confirmed that the proposed set of indicators was comprehensive and accurate for the sustainability assessment of energy technologies. Therefore, only a few indicator descriptions were slightly modified to increase the level of clarity and understanding, and only one indicator – namely "Work Quality" – was eliminated.

3.3 Technology alternatives

The set of 26 advanced generation technologies for the year 2050 that were analyzed in NEEDS are listed below in Table 4. They are fully described in the NEEDS database, economic and environmental reports (NEEDS Deliverables D10.2 and D5.1, Schenler, et al., 2008, and D6.1, Simons, et al., 2008), among others. For the purposes of this report on the sustainability analysis, it is sufficient to show the full list of technologies used as alternatives in the multi-criteria ranking process, and to show the technology name abbreviations that are used in the graphical presentation of results shown in Chapter 5.

Table 4 - NEEDS technology names and abbreviations

PRIMARY ENERGY	TECHNOLOGY	ABBREVIATION
Nuclear	European Pressurized Reactor	EPR
	European Fast Reactor	EFR
Coal,	Pulverized Coal	Hard coal PC
Lignite	Pulverized Coal with post combustion Carbon Capture and Storage	Hard coal PC, post comb. CCS
	Pulverized Coal with oxyfuel combustion and Carbon Capture and Storage	Hard coal PC, oxyfuel CCS
	Pulverized Lignite	Lignite PC
	Pulverized Lignite with post combustion Carbon Capture and Storage	Lignite PC, post comb. CCS
	Pulverized Lignite with oxyfuel combustion and Carbon Capture and Storage	Lignite PC, oxyfuel CCS
	Integrated Gasification Combined Cycle coal	Hard coal IGCC
	Integrated Gasification Combined Cycle coal with Carbon Capture and Storage	Hard coal IGCC, CCS
	Integrated Gasification Combined Cycle lignite	Lignite IGCC
	Integrated Gasification Combined Cycle lignite with Carbon Capture and Storage	Lignite IGCC, CCS
Natural gas,	Gas Turbine Combined Cycle	Nat. gas CC
biogas	Gas Turbine Combined Cycle with Carbon Capture and Storage	Nat. gas CC, post comb. CCS
	Internal Combustion Combined Heat and Power	Nat. gas CHP
	Molten Carbonate Fuel Cells using Natural Gas 0.25 MW	Nat. gas MCFC, small
	Molten Carbonate Fuel Cell using wood derived gas 0.25 MW	MCFC wood gas
	Molten Carbonate Fuel Cells using Natural Gas 2MW	Nat. gas MCFC, big
	Solid Oxide Fuel Cells using Natural Gas 0.3 MW	Nat. gas SOFC
Biomass	Combined Heat and Power using short rotation coppiced poplar	Poplar CHP
	Combined Heat and Power using straw	Straw CHP
Solar	Photovoltaic, ribbon crystalline Silicon - power plant	PV, c-Si, ground
	Photovoltaic, ribbon crystalline Silicon - building integrated	PV, c-Si, rooftop
	Photovoltaic Cadmium Telluride – building integrated	PV, CdTe, rooftop
	Concentrating thermal – power plant	Solar thermal
Wind	Offshore Wind	Offshore wind

It is briefly noted here that not all the technologies were assumed to be present in each of the four NEEDS countries. Italy and Switzerland are assumed to have no lignite resources, landlocked Switzerland has no offshore wind resource, and Germany and Switzerland are assumed to have an inadequate solar resource for solar thermal generation. Other country variations related to resource quality, environmental sensitivity, etc. have been included and described in the relevant NEEDS reports.

3.4 Technology data

For the NEEDS project, the basic data for the MCDA problem are the sustainability indicator values that characterize the set of NEEDS technologies. These indicator values included data describing technical, economic, environmental, risk, health, safety and social characteristics, and were developed by different NEEDS partners, listed in Table 5 below. Technical analysis included life cycle analysis of the relevant energy chains, and technology indicators were adjusted by country based on resource availability (e.g. solar) and environment (e.g. resources or population downwind that were susceptible to damage).

The technology data were combined into a single technology database that has been fully described in NEEDS Deliverable D10.2 – RS2b with brief technical descriptions, an Appendix using graphics and tables, and two Appendices that give the full set of indicator results as tables and graphs (Schenler, et al., 2008). For full reference material on individual technologies, the reader is also referred to individual technology documentation and reports available online at the NEEDS website.

(http://www.needs-project.org/index.php?option=com_content&task=view&id=42&Itemid=66).

Table 5 - Partners providing NEEDS technology data

Technology Area	Main NEEDS partner responsible	Reference
Nuclear	EDF	Lecointe, et al. (2007)
Advanced fossil systems	PSI and USTUTT.ESA	Bauer, et al. (2008)
Fuel cells	POLITO	Gerboni, et al. (2008), and DOE (2008)
Biomass (CHP)	IFEU	Gärtner (2008), also Tubby, et al. (2002)
Photovoltaic	Ambit	Frankl, et al. (2005)
Concentrating solar thermal power plants	DLR	Viebahn, et al. (2008)
Offshore Wind	ELSAM (now: DONG Energy)	Dong (2008)
Economic indicators	PSI and EIFER	Schenler, et al. (2008)
Environmental indicators	PSI	Simons, et al. (2008)
Risk indicators	PSI	Burgherr, et al. (2008)
Social indicators	USTUTT.ESA	Gallego-Carerra, et al. (2008)

3.5 The MCDA method

Requirements analysis – As mentioned above, multi-criteria decision analysis encompasses a broad range of analytic tools, and it was important to choose a method that was well suited to the NEEDS problem. For this reason, an extensive requirements analysis was made for the technology ranking problem, and a survey was made of multi-criteria methods previously used in related energy planning areas. This work was reported in NEEDS Deliverable D9.1, Requirements analysis for multi-criteria analysis in NEEDS RS2b (Makowski, et al. 2006). The most relevant requirements included the following points.

- Ranking of discrete alternatives (individual technologies, as opposed to optimizing the future generation mix).
- Problem size (36 indicators x 26 technologies x 4 countries).
- Hierarchical criteria structure.
- No need for criteria vetoes, or explicit consideration of risk or uncertainty (apart from possible sensitivity analysis.
- Need for an interactive, online tool to elicit stakeholder preferences.

<u>Development of new methodologies</u> – Based on the NEEDS requirements analysis, it was concluded that existing multi-criteria analysis methods for ranking discrete alternatives had significant deficiencies for the specified NEEDS multi-criteria problem of sustainability assessment. As a result, NEEDS partners at the International Institute for Applied Systems analysis (IIASA) developed and implemented a range of new MCDA methods (or algorithms). This development went far beyond the originally specified scope of the NEEDS analysis, but has led to innovative theoretical developments as well as a very powerful online MCDA tool also suited to future analyses.

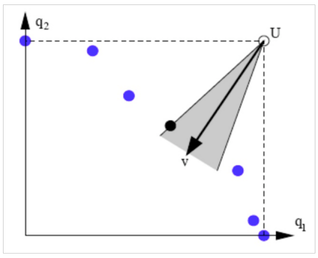
The methods developed (and variations) fall into several main groups, including

- Aspiration/Reservation
- Reference Point (Utopia, Pareto & Nadir)
- Dominating Alternative
- LexMaxReg (improving worst criteria)
- Quantile & Non-linear Aggregation

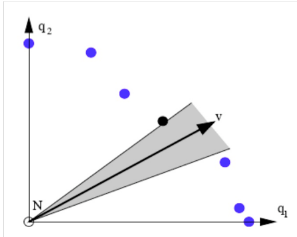
These approaches are described in the report Multi-Criteria Assessment of Discrete Alternatives (Makowski, et al. 2008). The weighted sum approach for MCDA, which is in common use, has well known theoretical deficiencies, but it also has the compensatory advantages of being easy to implement, use and understand. This approach was also implemented for the purpose of comparison.

Figure 2 below schematically illustrates several of these alternative approaches in two dimensions (most can not be very briefly explained). For example, two of the reference point methods start from a point that combines all the best (or worst) technology criteria performance values. From the reference utopia (or nadir) point, the method searches in the direction of a vector that is defined from the stakeholder's preferences. The reference point Pareto method, the criteria are divided into disjoint sets (improve, relax, stabilize and free), and the achievement function is found by adjusting preference weights by these classes. Finally, in the weighted sum approach, the stakeholder's tradeoff preferences define a tangent line whose slope determines which of the Pareto alternatives are selected.

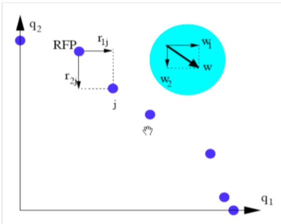
Figure 2 - Schematic diagrams of different MCDA methods



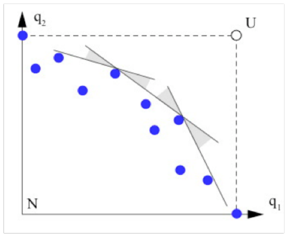
Reference Point – Utopia



Reference Point - Nadir



Reference Point - Pareto



Weighted Sum

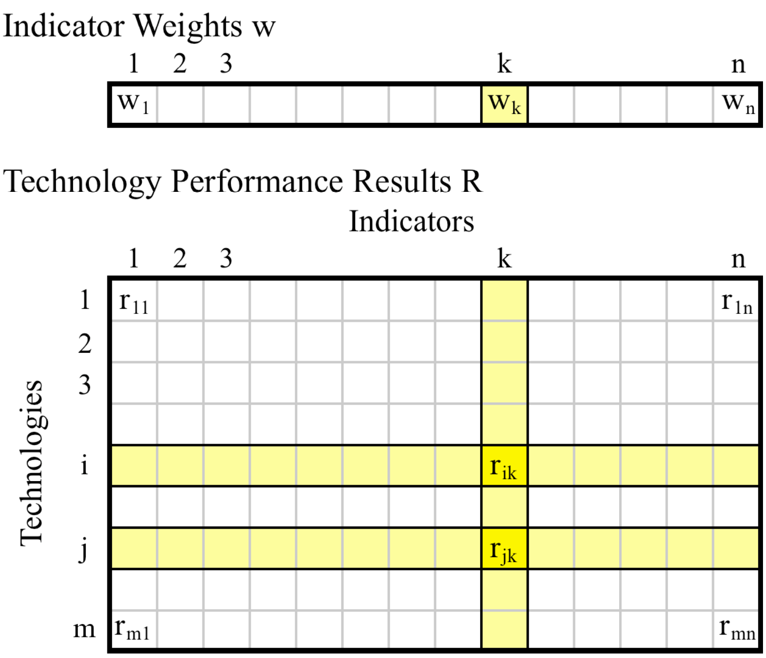
Selection of final methodology – A total of nine different algorithms, plus several additional variations were evaluated, using the weighted sum approach as a reference. The algorithms were blind tested by a team of four PSI NEEDS project members (i.e. the different methods were given numbers and the PSI team did not know which was which) in two successive rounds. For the second round, an additional three modified algorithms were added for a total of 12. The testing was based on how well the methods duplicated expected performance for multiple preference profiles, and the direction and sensitivity of how the methods responded to shifts in preferences. The blind testing process produced two final candidates, although the choice of the winner was not quite unanimous.

Based on this selection process, the winning "M3" method was revealed to be the Dominating-Alternative algorithm.

Description of the Dominating-Alternative (DA) algorithm – This algorithm selects the best alternative out of a set by comparing two alternatives at a time using a dominance index. In the NEEDS sustainability assessment these alternatives are future generation technologies.

The method starts with the array or matrix of technology performance results R. This matrix has m alternatives by n indicators. The stakeholder also supplies a vector of n preferences weights (one for each indicator) as shown below. The performance data adjusted by normalizing them on a scale from 0 to 1 for each indicator, with 0 being the alternative with the worst performance and 1 the alternative with the best performance. The weights for each indicator are obtained by proceeding down the hierarchical criteria tree, multiplying the preferences given by the stakeholder at each successive level. The weights are then adjusted relative to each other so that they will all sum up to 1.

Figure 3 - Nomenclature for indicator weights and performance data



The dominance index d_{ij} for each pair of alternatives sums up the differences between dominance components that are calculated for each indicator. If we compare the alternatives i and j, the dominance components dc_{ijk} and dc_{jik} for the indicator k are calculated based on the product of three factors, i.e.

- the indicator's preference weight (w_k),
- the difference in performance results between the alternatives i and j for indicator k ($r_{ik} - r_{jk}$), and
- a factor β that depends the indicator result for each alternative. That is,

$$dc_{ijk} = w_k * (r_{ik} - r_{jk}) * \beta(r_{ik}), \text{ and}$$

$$dc_{jik} = w_k * (r_{jk} - r_{ik}) * \beta(r_{jk}), \text{ where } \beta(x) = \alpha^{-x} \text{ with } \alpha = 10 \text{ in the present case.}$$

The dominance index that sums up the difference in dominance components is,

$$d_{ij} = \sum_{k=1}^{n}(dc_{ijk} - dc_{jik}) = \sum_{k=1}^{n}[w_k * (r_{ik} - r_{jk}) * (\beta(r_{ik}) + \beta(r_{jk}))]$$

and if $d_{ij} > 0$ then alternative i dominates j, i.e. alternative i is preferred to j.

The exponential factor β is the key to the DA method. This factor β depends on the indicator results for each alternative, and because these results are normalized on the range from 0 to 1, β ranges from $10^{-0} = 1$ to $10^{-1} = 0.1$. This means that weak criteria with bad indicator performance will be emphasized when the overall dominance index is summed up for each pair of alternatives.

Consider an example where $w_k = 0.8$, $r_{ik} = 1$ and $r_{jk} = 0.5$. Then $r_{ik} - r_{jk} = 1 - 0.5 = 0.5$, $\beta(1) = 0.1$ and $\beta(0.5) = 0.32$. So,

$dc_{ijk} = w_k * (r_{ik} - r_{jk}) * \beta(r_{ik}) = 0.8 * (1\text{-}0.5) * 0.1 = 0.04$

$dc_{jik} = w_k * (r_{jk} - r_{ik}) * \beta(r_{jk}) = 0.8 * (1\text{-}0.5) * 0.32 = 0.128$

But if we change to $r_{ik} = 0.5$ and $r_{jk} = 0$, then $r_{ik} – r_{jk} = 0.5 - 0 = 0.5$ (no change), but $\beta(0.5) = 0.32$ and $\beta(0) = 1$, and

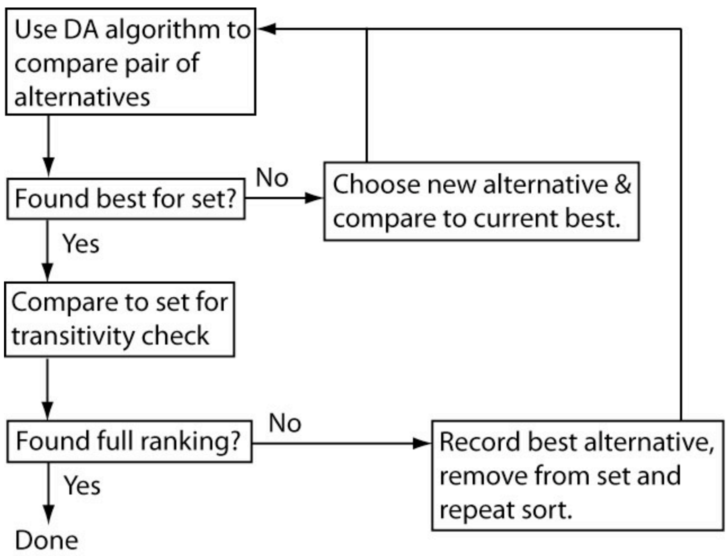
$$dc_{ijk} = w_k * (r_{ik} – r_{jk}) * \beta(r_{ik}) = 0.8 * (0.5-0) * 0.32 = 0.128$$

$$dc_{jik} = w_k * (r_{jk} – r_{ik}) * \beta(r_{jk}) = 0.8 * (0.5-0) * 1.0 = 0.4$$

So when we sum up the dominance index, the contribution from component k will change from 0.04 - 0.128 = -0.124 to 0.128 - 0.4 = -0.272. If β were not present, then only the *difference* in performance for each indicator pair would matter. But with the factor β the *absolute* performance of each indicator also plays a role. This method therefore tends to favor alternatives that lack especially bad results for some indicators, and tends toward alternatives where the performance of their worst indicator is not so bad.

After the better alternative is chosen for the first pair, another alternative is chosen and the process is repeated, until after m-1 comparisons the best of the m alternatives is found. Due to the mathematical nature of the DA algorithm, it is also necessary to check for the transitivity of the ranking. That is, if alternative A is preferred to B, and B is preferred to C, it is still necessary to check that A is preferred to C. Since the best alternative is chosen by successive pairwise comparisons, it has not necessarily been compared to all other alternatives. Checking this requires another m-1 pairwise comparisons for the set of m alternatives. In practice, non-transitivity has not been a problem with the NEEDS data set. To produce a complete ranking, the best alternative is recorded and removed from the set, and the process is repeated to obtain the 2nd best, 3rd best, etc. This process is illustrated in Figure 4 below.

Figure 4 - Flow chart for use of DA algorithm to rank discrete alternatives



3.6 The MCDA survey

In order to obtain sustainability preference information from as many stakeholders as possible, it was decided early in the NEEDS project to use an interactive, web-based MCDA application for Survey 3 (also called the MCDA Survey). The purpose was also to create a MCDA tool that would not just solicit the stakeholder's preferences on sustainability criteria, but also provide back the stakeholder's personal technology ranking results in an interactive way that would provide an iterative learning process for the user. The hope was therefore that the feedback of individualized results would provide an incentive or reward for the stakeholder to participate, since the complexity of the survey posed a learning curve that proved to be a barrier for many participants.

The graphical user interface for this web-based survey was developed in parallel with the different MCDA algorithms. These various algorithms were structured as interchangeable solvers for the graphical user interface, and so the graphical interface was developed and tested at the same time as it was used to anonymize the solvers for the algorithm selection process.

This process of using the NEEDS MCDA survey follows the steps below, and the rest of this section describes how the survey was used in the same order.

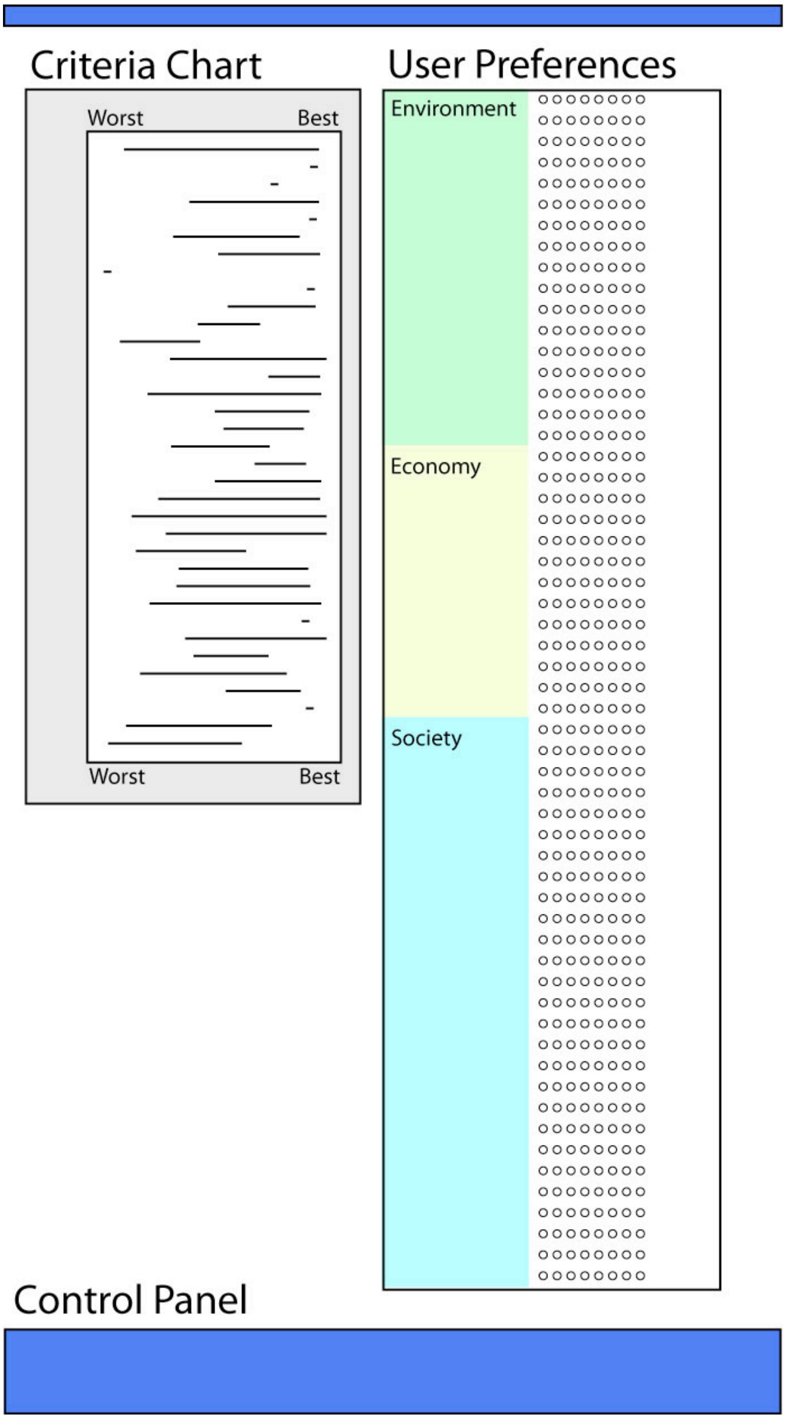
- Access to the survey website
- Entering preferences
- Solving to show technology rankings
- Examining tradeoffs for 'best' technology choice.

The user was then free to repeat the procedure until he was satisfied with both his preference inputs and the resulting technology rankings. Each time a new ranking solution was generated was called an iteration. Each iteration was stored, and could be named and recalled for future changes. All iterations except the last one were kept private to the registered user, and only the last iteration was saved for survey analysis purposes. This process provided immediate feedback and an opportunity for iterative learning for the survey participant, and automatic data collection for the survey operator.

Accessing the survey - The NEEDS Survey 3 of stakeholders' sustainability criteria preferences was divided into two parts. The first part was an online survey of demographic information about each participant that was hosted by the same commercial survey service provider that had also hosted the NEEDS surveys 1 and 2. Participants were then directed to the NEEDS MCDA survey site hosted by IIASA. First time participants were requested to login by providing their email address and preferred language (English or German). A password was then emailed to them for subsequent logins. In this way, participants could log in as often as they wished, and the survey could remember their previous work for future sessions.

The website interface - The overall graphical user interface is presented below schematically in Figure 5. The main screen is made up of three elements.

Figure 5 - Graphical user interface for MCDA survey



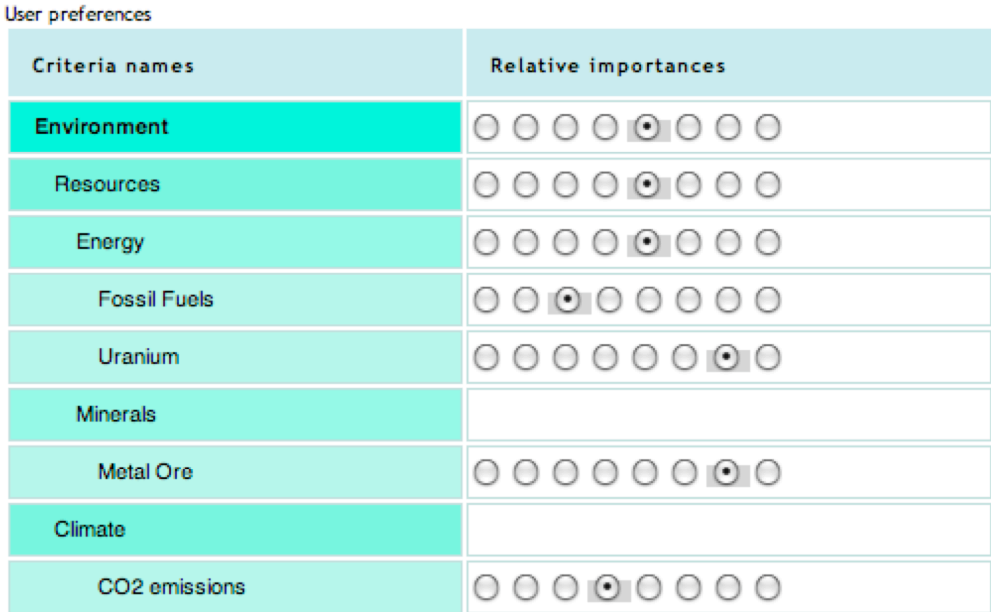
The top left-hand side shows a chart of horizontal bar graphs called the "Criteria Chart." This displays the performances of the technologies for various sustainability indicators. Here it is possible to select and highlight different technologies.

The right-hand side of the main screen displays the preference selection and is called "User Preferences". There is a column of criteria and horizontal lines of buttons. Selecting a button indicates the level of relative importance given to a criterion within the hierarchy.

Across the bottom of the main screen is a blue tool bar (labeled "Control Panel") that contains the various options and commands for the preference analysis. It also contains links for help and further information.

Entering User Preferences - A short section of the chart containing the criteria and preference buttons is shown as an example in Figure 6 below.

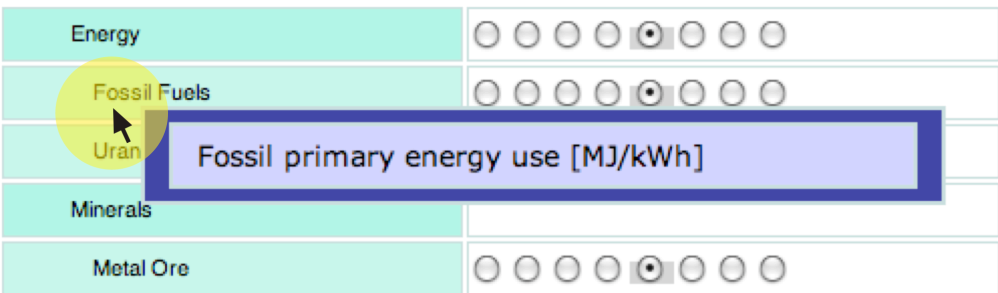
Figure 6 - Example of the criteria and preference buttons in the Preference Chart



The three main indicators of sustainability - **Environment**, **Economy** and **Society** - are the highest level in the criteria hierarchy and are displayed in bold lettering. In Figure 6 it can be seen that the different levels of the hierarchy are also shown by indentation and the intensity of the background color. In this example, "Resources" and "Climate" are the next level in the hierarchy, followed by "Energy" and "Minerals". At the fourth and lowest level are the specific indicators for which actual values have been determined, either by analysis or by expert judgment. However, the full four-level hierarchy system is not always followed. For example the second level criterion "Climate" in Figure 6 leads directly to the fourth level indicator of "CO_2 emissions." And in some places the hierarchical tree does not divide at each level (the criterion "Minerals" leads to only one indicator "Metal Ore"). Because both "Climate" and "Minerals" each have only one indicator they do not require their own preference buttons.

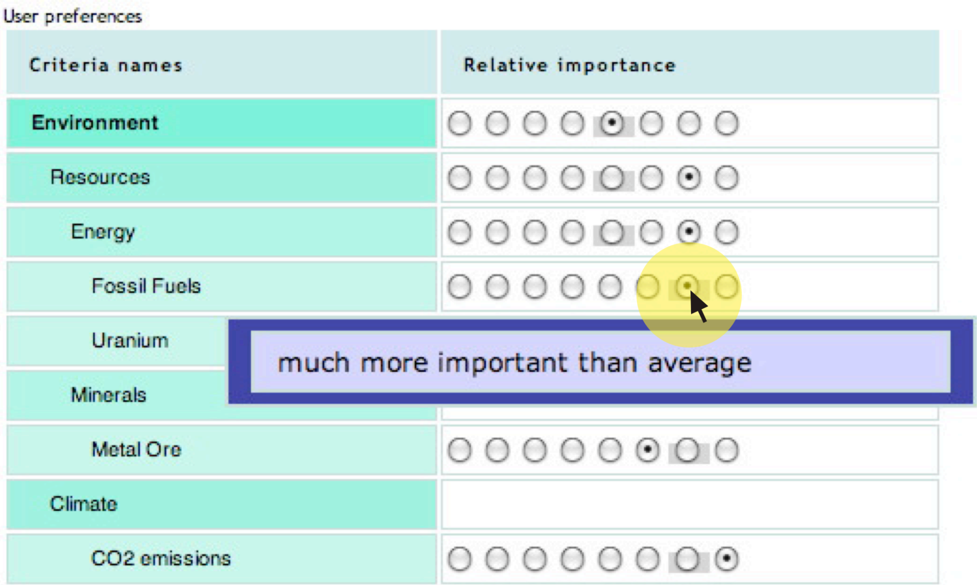
Moving the screen cursor over each criterion revealed a longer and more descriptive name and the indicator units, as shown below in Figure 7.

Figure 7 - "Pop-up" showing longer criterion name.



Preference Selection - The survey participant or user enters his preference for a criterion by clicking on one of the eight buttons on each line. Selecting the leftmost button means that the criterion is entirely ignored (its importance is zero). The remaining seven buttons span the preference range from "vastly less important than average" to "vastly more important than average." Moving the screen cursor over each button shows these levels, as illustrated below in Figure 8. The default setting of the User Preferences block opens with all of the criteria set to "average importance".

Figure 8 - Example of a preference button description for 'Fossil Fuels.'



It is important to understand the multiplicative nature of the preference scale. The seven buttons ranging from "vastly less" to "vastly more" important than average have relative weights of 1/16, 1/4, 1/2, 1, 2, 4, and 16. This means that for the first two steps above or below average, the preference increases or decreases by a factor of two, and for the last step in each direction by a factor of four. At each level below a branching in the hierarchy these preferences are normalized. The overall weight for each indicator is then calculated by multiplying the preferences down the hierarchy.

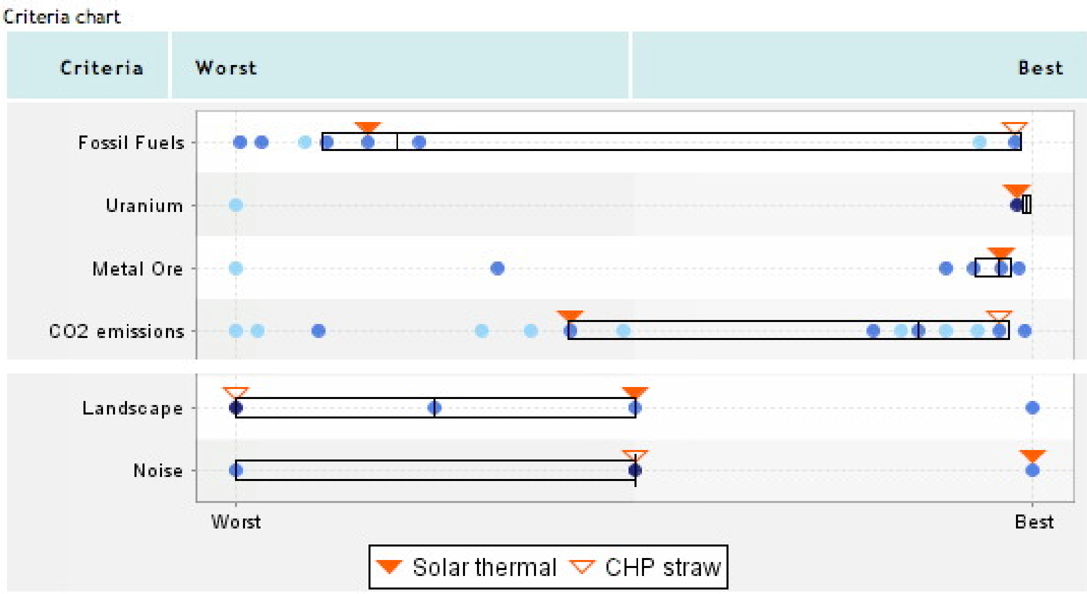
For example, assume that Environment, Economy and Society are equally weighted at the highest level as "average." These preferences (1 each) normalize to values of 1/3 each. Suppose that within Environment that Resources and Climate are "much more than average"(4) and Ecosystems and Waste are "average"(1). Then the preferences on this level normalize to values of 0.4, 0.4, 0.1 and 0.1, respectively. If within Resources, Energy and Minerals are both "much more than average", then the preference values of 4 and 4 normalize to 0.5 and 0.5, and similarly for Fossil Fuels and Uranium (0.5 and 0.5). For this example then the weight for the "Fossil Fuels" indicator is the product of the normalized values calculated for Environment, Resources, Energy and Fossil Fuels, or 0.33 x 0.4 x 0.5 x 0.5 = .0333.

A sense of balance is therefore important in selecting user preferences. Making all the criteria very important has the same effect as leaving them all average or making them all less important. It is best if preferences are given in a balanced way, increasing the importance of some criteria and decreasing others.

The process of multiplying preferences down the hierarchy means that the effect of any one indicator is diluted. This is why the preference scale is multiplicative, not linear, and also why the choice is available to ignore a criterion at any level by setting its weight to zero (using the leftmost button). For example, if the leftmost button for the criterion "Economy" is clicked, then the problem will be solved considering only the remaining environmental and social criteria (obviously you cannot ignore all criteria and get a meaningful answer).

The Criteria Chart - The Criteria Chart block on the left side of the main page shows the performance of each electricity generation technology according to the individual, lowest level indicators. Only this level of the hierarchy is shown in the Criteria Chart because, as mentioned above, it is only for these indicators that actual values have been determined, either by scientific analysis or by expert judgment. Figure 9 below shows the top and bottom parts of the Criteria Chart. The indicators in this chart are in the same vertical order as they are displayed in the Preference Chart.

Figure 9 - A section of the Criteria Chart showing how the criteria values are presented.



It is important to understand that the individual technology performance indicators used in the MCDA algorithm and shown in the graphs above were normalized across the range of results. For example, if an indicator has a range of between 5 (worst) and 10 (best) for all technologies, then the chart was adjusted to a range of 0 to 1. If a higher indicator value means worse performance (e.g. cost or emissions), then the normalized scale was reversed. You will notice that the chart was arranged so that the worst values are always on the left and the best values are always on the right.

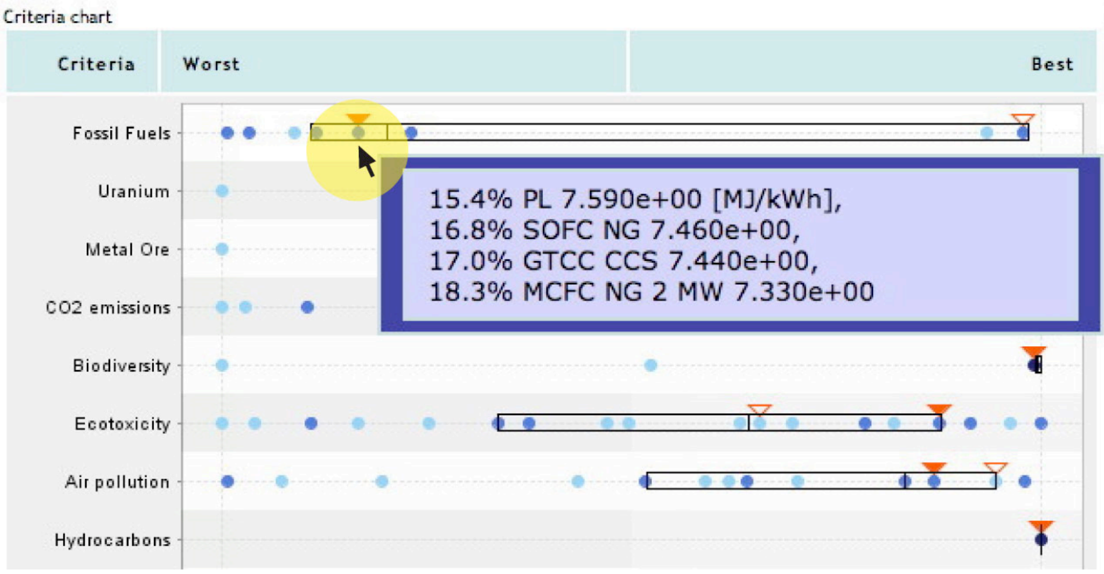
Dots represent technologies on the chart, and are shown in two different intensities of blue as well as black. These colors refer to the number of technologies exhibiting very similar performances and therefore occupying the same position: light blue = 1 technology, dark blue = 2 to 8 technologies and black = more than 8 technologies.

The boxes (optional) highlight the technology distribution by quartiles, with the small vertical line inside each box representing the middle (or median) point. This means that 25% of the technologies lie on the outside of the box to the left, 25% are inside the box to the left of its center line, 25% are inside the box to the right of its center line, and 25% are outside the box to the right. In some cases there may be enough overlapping dots that the upper or lower quartiles may extend all the way to the best or worst ends of the scale.

Individual technologies can be flagged by colored triangles, as indicated by the legend at the bottom of Figure 9 above. The default is to show the one or two best technologies for the last two preference sets solved, but it is also optional to flag selected individual technologies.

Moving the cursor over each dot will display a pop-up window that provides additional information, including the normalized value, the short technology name and the absolute value. The units are shown at the end of the first line, and are of course the same for all technologies. An example of this popup display is shown below in Figure 10.

Figure 10 - Example of a pop-up window describing technologies located under one dot.



In this example, the cursor is positioned over the solid red triangle showing the "best" technology (MCFC NG = molten carbonate fuel cell, using natural gas). The pop-up window shows that this dot represents four technologies in the 25% to 50% quartile (below the median line). The normalized values for these technologies range from 0.154 to 0.183, and since less fossil fuel use is better, the normalized scale has been reversed and the absolute indicator values range from 7.59 to 7.33 MJ/kWh (units of fossil fuel use). In this example MCFC NG 2MW therefore performs marginally better than the other three. The abbreviated technology names can appear rather confusing (which may also help to anonymize them, thus preserving neutrality during the multi-criteria exercise), but their full names can be displayed by selecting the "Ranking table" button in the Control Panel at the bottom of the main screen (see Figure 11 in the following section), which displays both the short and long form of all technology names.

Using the MCDA Application - As mentioned above, the original default setting on the main screen was that all preferences were set to "average importance". From this basis the user could make his own preference selection and then observe changes to the ranking. The following guide was supplied to users to help them arrive at a final ranking result;

MCDA application stepwise user guide.

1. Select a previous set of preferences (or iteration), *if this is not your first session*.
2. Select your preferences, or alter your previous set.
3. Click the pink "Solve" button in the Control Panel (see Figure 11 below). This will save your preferences, before you select any other options.
4. Give a name or add a comment the current preference profile using "Edit the note."

5. Examine the indicator tradeoffs for the currently best technology (as shown by the orange triangle). Which criteria would you like to improve or be willing to compromise? Then click any of the following buttons to see further results:

   - "Ranking chart" – Shows the technologies in ranked order in the form of a bar graph.

   - "Ranking table" – Shows the technology ranking by number and includes the short and long technology names.

   - "Compare by Criteria" - Select a subset of technologies by dragging them from the left column to the right column. Their performances are then shown as a bar chart for the 18 best and 18 worst criteria.

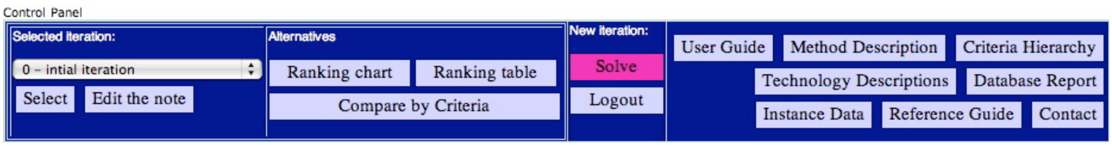
6. In "chart options" (above the Control Panel) technologies can be selected for highlighting by a colored triangle in the Criteria Chart.

7. Repeat until you are satisfied. You can enter any number of new preference profiles, or recall a previous profile and modify it. Simply scroll through the iteration list, and then click "Select" to load the saved profile. You can also take a break by hitting the "Logout" button to exit the website, and then return later to continue your analysis.

   The final preference profile that you save using "Solve" should be your favorite, as it is the only one we will collect for the survey. Therefore you may have to recall an earlier profile and re-solve it so that it becomes your last one.

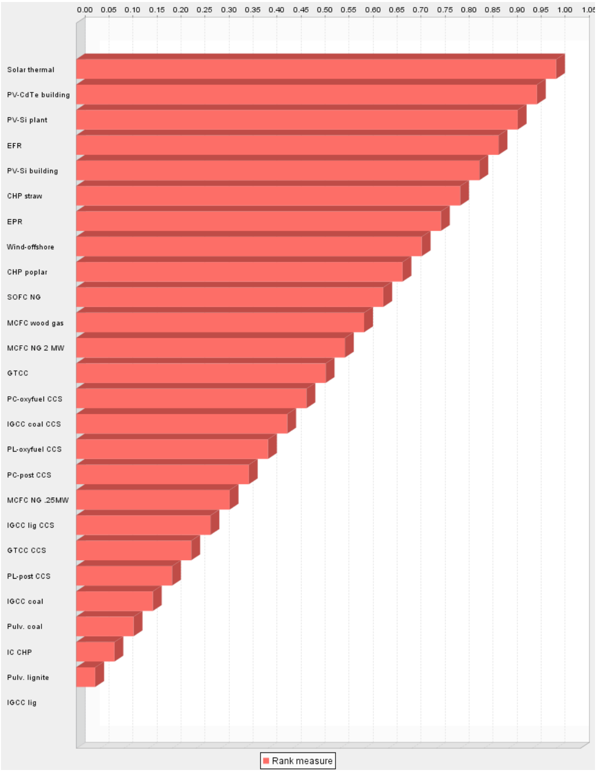
<u>The Control Panel</u> - The final main area of the MCDA survey's graphic user interface is the Control Panel located at the bottom of the page. There are multiple control buttons located within the dark blue panel, as shown in Figure 11 below.

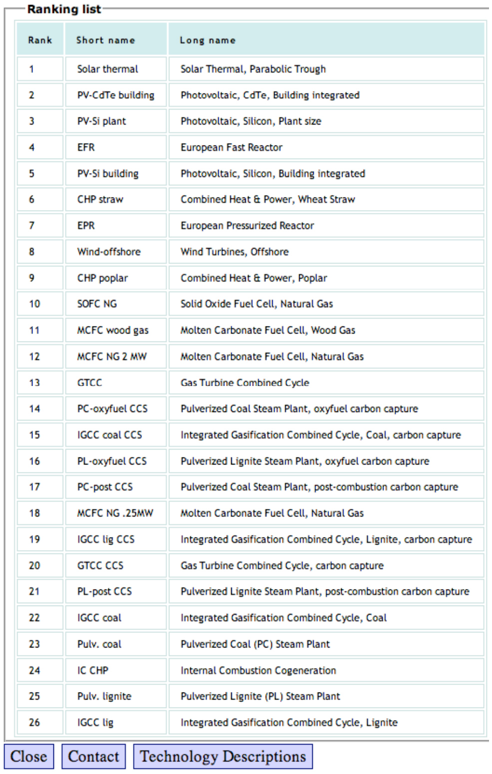
Figure 11 - The Control Panel tool bar.



The "Ranking chart" or "Ranking table" buttons in the Control Panel at the bottom of the main screen (see Figure 11 above) display the bar chart and table screens that are shown below in Figure 12. At the right of the Control Panel there are links to various documents for help and reference, including the User Guide. There is also a "Contact" button that could be used to report problems or ask questions.

Figure 12 - The Ranking Graph and Ranking Table screens.





Ranking list

Rank	Short name	Long name
1	Solar thermal	Solar Thermal, Parabolic Trough
2	PV-CdTe building	Photovoltaic, CdTe, Building integrated
3	PV-Si plant	Photovoltaic, Silicon, Plant size
4	EFR	European Fast Reactor
5	PV-Si building	Photovoltaic, Silicon, Building integrated
6	CHP straw	Combined Heat & Power, Wheat Straw
7	EPR	European Pressurized Reactor
8	Wind-offshore	Wind Turbines, Offshore
9	CHP poplar	Combined Heat & Power, Poplar
10	SOFC NG	Solid Oxide Fuel Cell, Natural Gas
11	MCFC wood gas	Molten Carbonate Fuel Cell, Wood Gas
12	MCFC NG 2 MW	Molten Carbonate Fuel Cell, Natural Gas
13	GTCC	Gas Turbine Combined Cycle
14	PC-oxyfuel CCS	Pulverized Coal Steam Plant, oxyfuel carbon capture
15	IGCC coal CCS	Integrated Gasification Combined Cycle, Coal, carbon capture
16	PL-oxyfuel CCS	Pulverized Lignite Steam Plant, oxyfuel carbon capture
17	PC-post CCS	Pulverized Coal Steam Plant, post-combustion carbon capture
18	MCFC NG .25MW	Molten Carbonate Fuel Cell, Natural Gas
19	IGCC lig CCS	Integrated Gasification Combined Cycle, Lignite, carbon capture
20	GTCC CCS	Gas Turbine Combined Cycle, carbon capture
21	PL-post CCS	Pulverized Lignite Steam Plant, post-combustion carbon capture
22	IGCC coal	Integrated Gasification Combined Cycle, Coal
23	Pulv. coal	Pulverized Coal (PC) Steam Plant
24	IC CHP	Internal Combustion Cogeneration
25	Pulv. lignite	Pulverized Lignite (PL) Steam Plant
26	IGCC lig	Integrated Gasification Combined Cycle, Lignite

Close | Contact | Technology Descriptions

<u>Approaches to Analysis</u> - There are many different ways of using the MCDA application and it was designed to enable users to experiment and to expand their understanding of the interactions and tradeoffs between the 36 sustainability indicators.

Creating an initial set of preferences (or preference profile) could be done in several ways. Two sample strategies include;

- Bottom-up Strategy: Some people prefer to select their preferences starting with the lowest level indicators first. What is learned from balancing the indicators against each other may then help you to choose your preferences at higher criteria levels.
- Top-down Strategy: Other people prefer to begin with the highest level criteria (environment, economy and society) and work their way down the criteria hierarchy, based on their overall perspective of the various aspects of sustainability. Lower level preferences must still be balanced relative to others on the same level of the hierarchy branch.

Once an initial preference profile has been composed, and the MCDA algorithm has produced the resulting technology ranking, the stakeholder could then adjust his preferences. Again, two sample strategies for such adjustments include;

- Technology Profile: Experiment with different preference profiles to learn which preferences promote different groups of technologies, e.g. renewables, nuclear or fossil. Technology choices should be based on indicator preferences, and not vice versa, so this is best viewed as a learning tool on how preferences and technologies are linked together.
- Indicator Tradeoffs: Survey the indicator performance for the current “best” technology to see where you think it performs the worst (and best). Then increase your preference weight on the worst indicators, or decrease the weight on indicators where the performance is better than you think necessary. Resolve to see if the “best” technology changes, and if so whether the tradeoff between indicators has improved. This second method is recommended on theoretical grounds,

because it focuses on indicator performance and is neutral on the identity of the top technology alternative.

The NEEDS team operating the MCDA survey received a broad range of feedback from survey participants. Many survey users were impressed by the power of the MCDA tool and enthusiastic about the possibilities for learning about technology tradeoffs and generating their own rankings. Other participants found the survey process very challenging, from the login process to the graphic interface and sustainability implications. The survey team did finally conclude that although survey 3 covering sustainability criteria preferences was a natural progression from surveys 1 on the external cost approach and survey 2 on the criteria and indicator selection and structure, the term survey did not really convey either the challenge or power of the tool that had been developed. Another term (like "sustainability exercise" or "technology mapping of sustainability performance") might have better prepared the participants to expect that a larger time and learning commitment would be required and rewarded.

4 Analysis

This chapter briefly describes the analytic process followed in the NEEDS analysis of the sustainability criteria survey, including the survey response patterns, software tools and analytic procedure.

4.1 Survey response

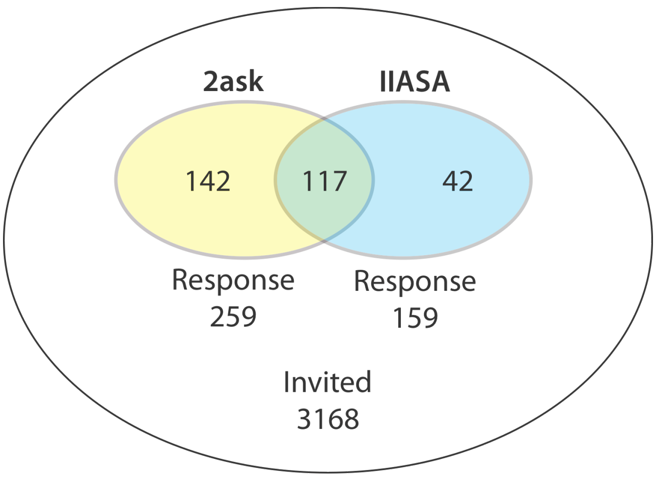
As mentioned above, the survey was conducted in two parts – the first part to collect demographic data was hosted on a commercial survey website (www.2ask.net), and the second part to collect the participants sustainability preferences and provide them ranking results using the custom MCDA algorithm and interface was hosted by IIASA. The first step of the analysis was therefore to cross-match the results of these two separate surveys and to combine the data for the participants.

The overall response rate and the overlap between the surveys are shown below in Figure 13. Out of a total of 3168 emailed survey invitations, 259 people (8.2%) responded to the 2ask survey of demographics and 159 people (5.0%) responded to the IIASA-hosted survey of preferences. The overlap contained a total of 117 people (3.7%) who responded to both surveys. The relative difficulty and time commitment of the two surveys is indicated not only by their overall response rates, but also by the fact that 74% of the IIASA respondents also completed the 2ask survey, but only 45% of those responding to the 2ask survey also completed the IIASA survey.

After the two surveys were cross-matched, there remained a number of holes in the demographic data. That is, for those who completed the survey of preferences there were cases where data was either partially missing (from the 117 who answered both surveys) or wholly missing (from the 42 who answered only the preferences survey).

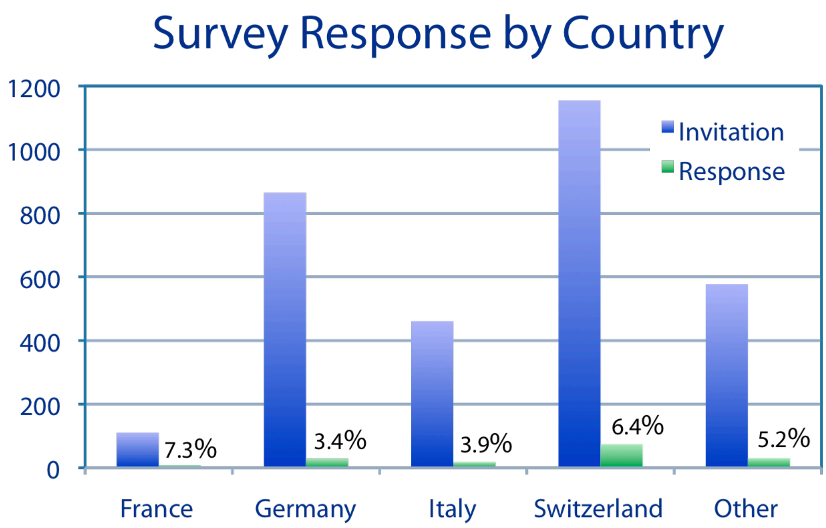
The overall analysis of stakeholder preference patterns was based on the full 159 participants who completed the online survey at the IIASA website, but when analysis was done on subsets based on demographic indicators some individuals were excluded. This accounts for the fact that stakeholder statistics do not always add up to the same total number of participants.

Figure 13 - Overall NEEDS stakeholder survey response



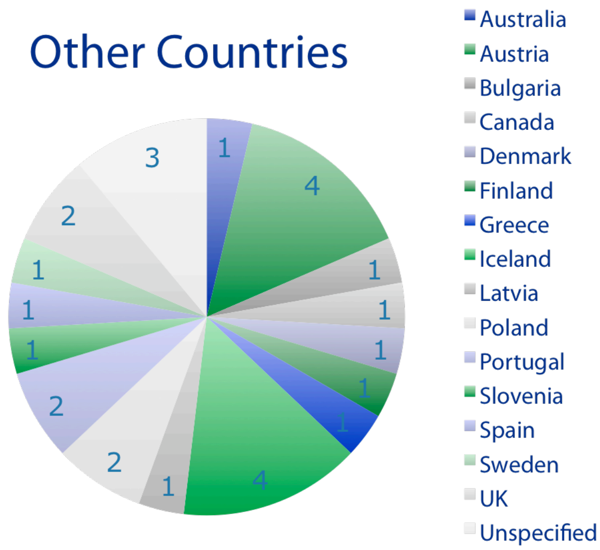
The NEEDS partners from the four different NEEDS countries submitted different numbers of names. The distribution of participants invited and responding are shown below in Figure 14. As can be seen, the Swiss and German NEEDS partners invited the largest number of participants (1154 and 864, respectively), but the overall response rate was led by the French (7.3%).

Figure 14 - NEEDS stakeholder survey response by country



The distribution between the other countries was broadly spread, with the top responses from Austria (4) and Iceland (4).

Figure 15 - NEEDS stakeholder survey response from other countries



The NEEDS partners identified prospective participants as belonging to the stakeholder groups chosen, and stakeholders were also allowed on the 2ask survey to confirm or change this identification by selecting one of the pre-existing groups shown or by filling in a self-chosen group name. Based on the pre-identification of participants, it was possible to directly identify 2333 of the names by stakeholder group (74%), and some further analysis of email addresses allowed an additional 586 stakeholders to be identified by group for a total of 2919 (or 92%). The total response by stakeholder group is shown below in Figure 16. (Note that a total of 120 respondents who gave their preferences could be identified by group, 3 more than the 117 who filled out both surveys.)

Figure 16 - NEEDS stakeholder survey response by stakeholder group

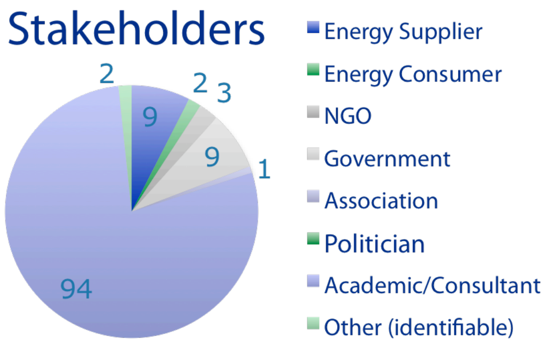
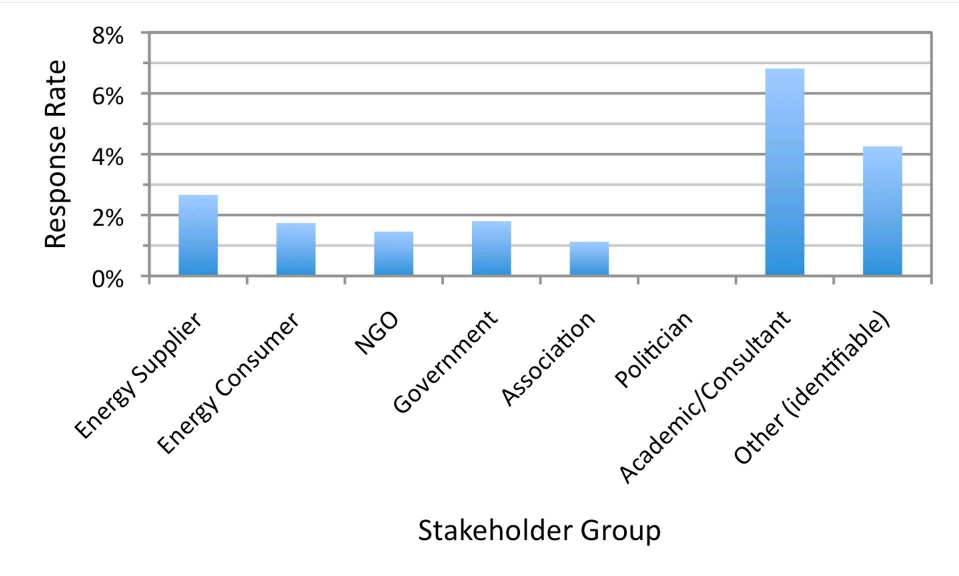


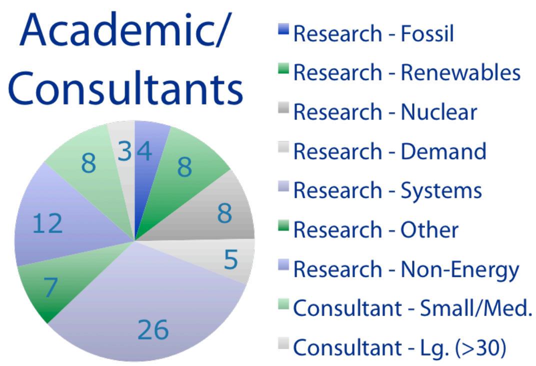
Figure 16 shows that the academic/consultant stakeholder group provided the majority of responses. This was partially due to the fact that the academic/consultant stakeholder group made up the largest share (about 40%) of the participants initially invited to participate in the survey. The academic/consultant stakeholder group's participation rate was also higher, as shown below in Figure 17.

Figure 17 – NEEDS survey response rate by stakeholder group



This dominance by the academic/consultant group made it of particular interest to see the breakdown within this group, which is shown in Figure 18 below.

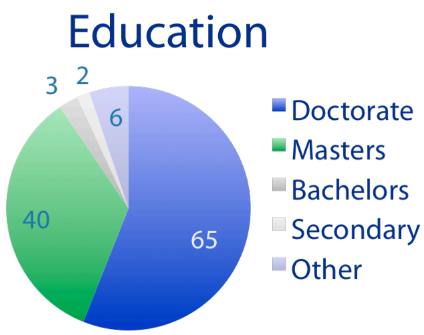
Figure 18 - NEEDS stakeholder survey breakdown for academics



Although only 81 of the 94 academic/consultant stakeholders identified themselves by a sub-group, it is possible to see that the response was dominated by energy systems researchers (26), followed by non-energy researchers (12) and small and large consultants were represented by 8 and 3 responses, respectively.

This overall dominance by the academic/consultant group also had a strong impact on the distribution of academic qualifications of those responding to the survey, as shown below in Figure 19.

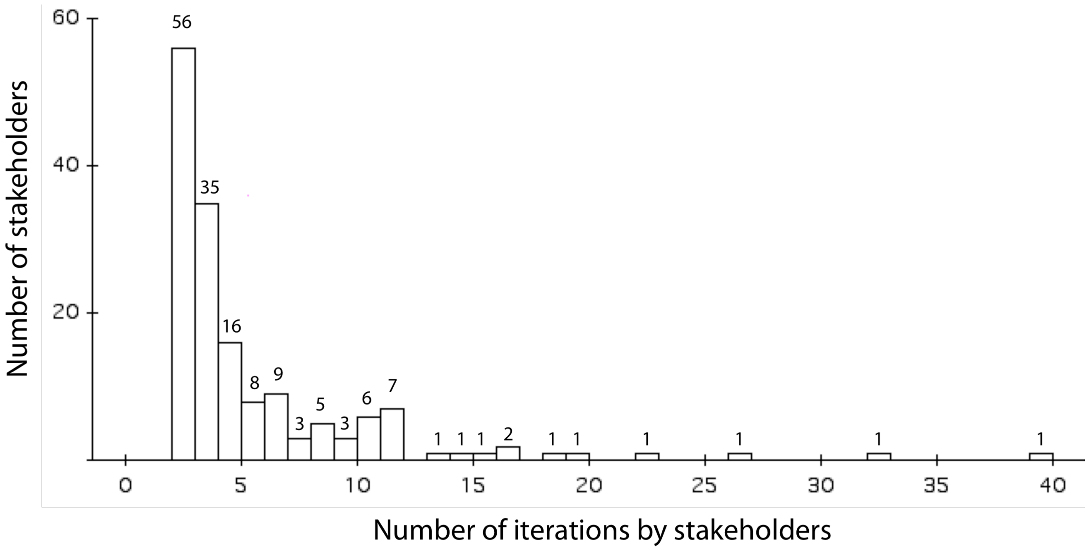
Figure 19 - NEEDS stakeholder survey response by education



This figure shows that of those stakeholders completing the preferences survey, a total of 65 (56%) had doctorates, followed by 40 with Masters degrees (34.5%), and 11 with lower degrees (9.5%).

Finally, it was also interesting to see how many time the survey participants adjusted their preferences (i.e. the number of iterations they made in completing the survey). This statistic is shown below in Figure 20. It should be noted that the distribution of survey iterations begins with 2, because the initial, default preference profile (all criteria of "average importance") was counted as the first iteration. It can be seen that the majority of participants made 11 or fewer iterations (93%). The largest number of iterations were performed by the survey team members who did extensive testing before finally giving their own final preferences for the survey.

Figure 20 – Distribution of survey iterations by NEEDS stakeholders



Overall, completing the combined demographic and preference surveys represented a significant commitment of time and effort by the participants. This was reflected in the overall response rate of 5% for the preference survey (participants with missing demographic data were accepted for the overall preference analysis). This compares to the response rate of 9.7% for Survey 2 on the choice and acceptability of the sustainability criteria and indicators, where 660 people began and 275 completed the survey from an invitation list of 2835 (the invitation list for Survey 3 was largely based on Survey 2). In spite of this, much personal feedback was received by the survey operators expressing very positive appreciation of the power of the MCDA application developed and the overall learning experience by those participants who persevered.

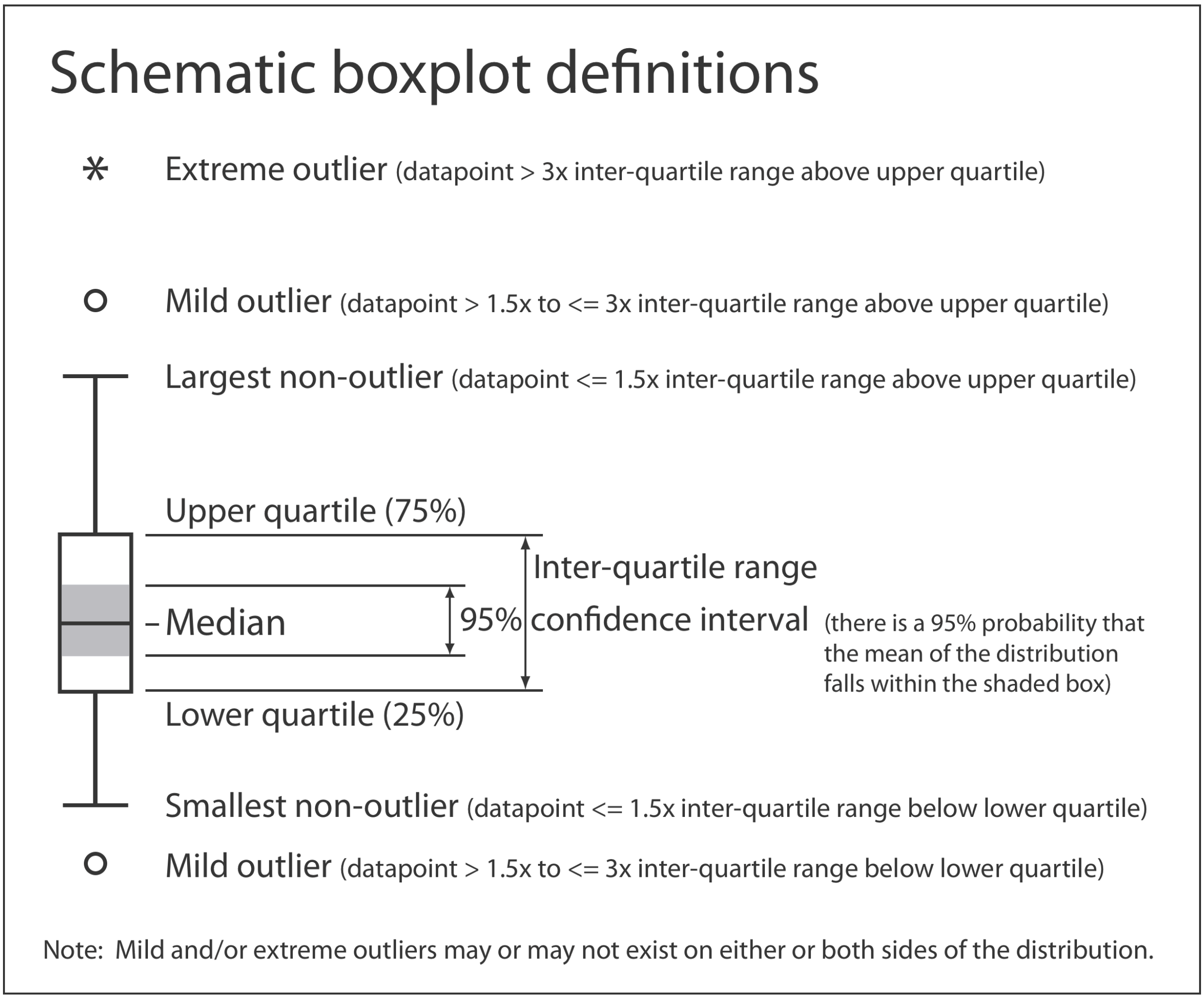
The survey team believes that if such a survey were to be repeated, it would be preferable to combine both the demographic and preferences sections into a single survey, even if the demographic section interface was cosmetically less professional or attractive, and also that using another term than survey (e.g. exercise or application) in the invitations might give a more reasonable expectation of the commitment required.

4.2 Analytic tools

After the data from the demographic and preference segments of the survey were reconciled, the combined data were analyzed using the DataDesk software package (www.datadesk.com) for graphical data exploration (or data mining) and the SAS statistical software package (www.sa.com) for clustering analysis. The DataDesk software allows graphs and summary statistics to be easily examined for different stakeholder subsets, and facilitates exploration of patterns or trends in the results.

The most useful graphical representation of the data for stakeholder criteria preference inputs, criteria weights and technology rankings was found to be a series of boxplots. To explain this type of graph, a generic boxplot is shown below in Figure 21. The median is the value in the data set with half the values above it, and the other half below it. The central box shows the limits of the two quartiles (quarters of the data set) above and below the median. The gray band showing the 95% confidence interval is not always included in the definition of a boxplot, but it is optionally displayed in DataDesk. If the data set analyzed is assumed to be a sample taken from a larger population, then the mean (or average) for the whole population has a 95% probability of falling within the gray band shown. The "whiskers" of the boxplots show the range of values that are within 1.5 times the interquartile range above or below the upper and lower quartiles. Outlier values are shown individually, with different symbols for mild and extreme outliers (further than 1.5 and 3 times the interquartile range beyond the upper and lower quartiles, respectively). Thus, the boxplot graphically shows the center and range or distribution of values for a single variable.

Figure 21 - Guide to interpreting box plot graphs



An initial boxplot analysis of the stakeholder groups based on country, language, self-identified stakeholder interest group, education, age, etc. did not reveal any strong differentiation in their preference inputs, weights or technology rankings (i.e. their sustainability preferences were not strongly linked to any demographic group).

4.3 Cluster analysis

Based on the lack of identifiable preference patterns within the self identified groups, it was then natural to ask whether the survey participants formed any natural groups based on their preferences, and, if so, how these groups might correspond to any of the original stakeholder groups to which the survey participants belong.

In order to explore this question, a cluster analysis was performed on the survey data to see if the participants would naturally divide into different groups, based solely on their preference responses, weights or technology rankings. After initial experimental clustering exercises were performed on the preliminary survey data set, the analysis for the final data set was focused on stakeholder weights. As explained above, the survey collected user preferences by recording the position of buttons clicked for each criterion, using a non-linear scale from “vastly less” important than average to “vastly more” important than average (equivalent to values of 1/16 to 16). These values were then transformed to criterion weights based on their relative values at each level of each branch of the criterion hierarchy tree, and normalizing so that all weights added up to zero on each level. Because of this transformation from preference inputs to preference weights, it was felt that the weights were better for clustering (for example, two different sets of preference inputs - one evenly low and one evenly high – could give the same weighting profile), and because in the end the MCDA algorithm operates from the weights. It was also felt that grouping survey participants by their preference weights was preferable to grouping them by their resulting technology rankings, because the real question is to see whether similar preference groups exist and whether their results can be observed in the ranking results.

This clustering analysis was performed using the statistical software package SAS, and in particular its clustering algorithm called FASTCLUS. The FASTCLUS algorithm takes a set of points in an n-dimensional space, and sorts them into groups or clusters that minimize the Euclidean distance between the points in each cluster and the center of that cluster.

This procedure combines an effective method for finding the initial clusters with a standard iterative algorithm for minimizing the sum of the Euclidean (root mean square) distances from the cluster means. The result is an efficient procedure for disjoint clustering of large data sets. A set of points called *cluster seeds* is selected as a first guess of the means of the clusters. Each observation is assigned to the nearest seed to form temporary clusters. The seeds are then replaced by the means of the temporary clusters, and the process is repeated until no further changes occur in the clusters. If there are missing values, PROC FASTCLUS computes an adjusted distance by using the non-missing values. Observations that are very close to each other are usually assigned to the same cluster, while observations that are far apart are in different clusters. The algorithm can be outlined as follows.

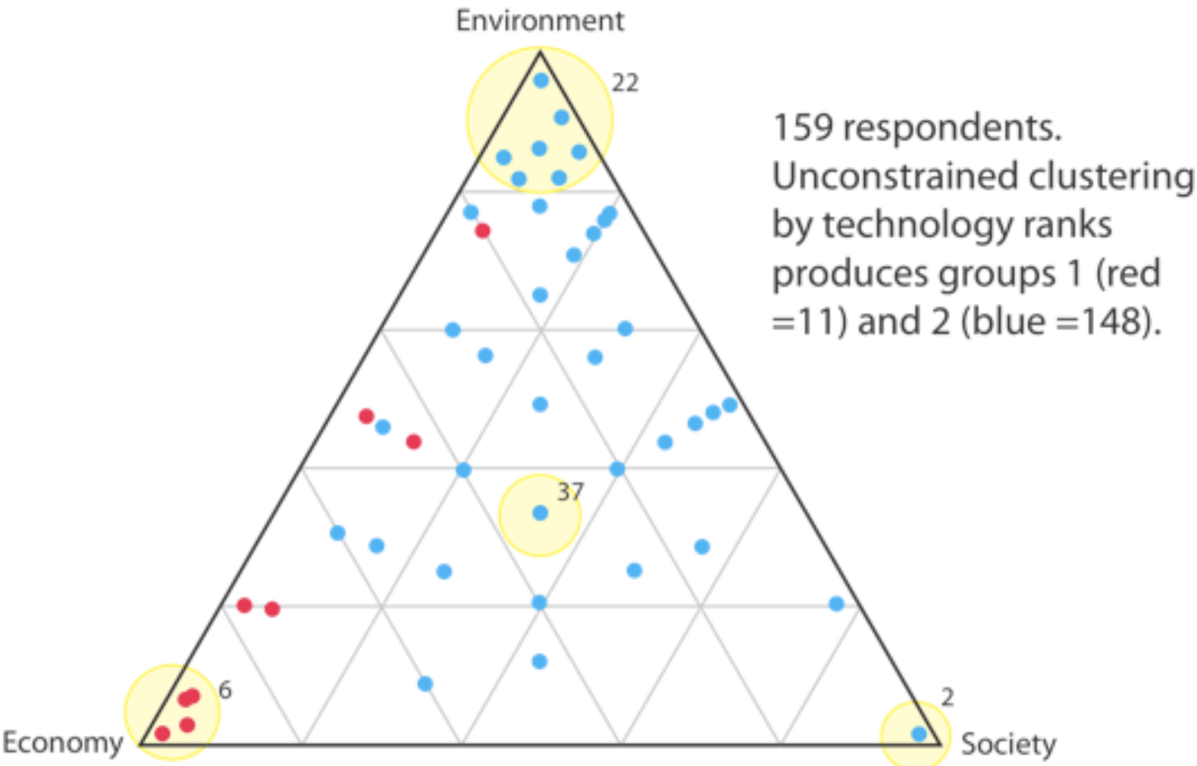
- Cluster seeds are generated by using the
  - first complete data point (with no missing values), plus
  - each new point separated from all prior seeds by more than a minimum radius, up to a maximum number (an optional constraint).
- Each new point that is not a new seed is assigned to the nearest cluster (by Euclidean distance).
- Each new point that is not a new seed can swap with an already existing seed if
  - It is farther from the closest seed than the minimum radius, or
  - It is farther from all other seeds than its nearest neighbor seed is.
- Each seed is replaced by the cluster mean (this procedure may be incremental).

The procedure is repeated until it converges (or until a maximum number of iterations is reached).

This FASTCLUS algorithm was applied to the stakeholders’ preference weights for the sustainability criteria. Surprisingly, even though this clustering process was not constrained it resulted in naturally separating the survey participants into just two separate clusters. This can be seen in Figure 22 below, which shows how the survey participants are distributed based on the weight they give to the three highest levels of the sustainability criterion hierarchy. The overall for the environmental, economic and social categories of criteria naturally sum up to one. Therefore if the weights for all participants are plotted in three dimensions the results all fall on a plane within the triangle bounded by (1,0,0), (0,1,0) and (0,0,1), and this equilateral triangle can be rotated as it is shown in Figure 22 below. The unconstrained clustering procedure produced a majority group with 148 members shown in blue, and a minority group of 11 members shown in red. Many points overlap, so fewer than 159 points are actually visible. The minority red subset includes all the people who highly valued economic criteria overall, as well as some of the points on the triangle side between the extreme economy and environment corner points. The two subsets overlap on this side, because the clustering procedure considers all the criteria, not just the top three criteria levels shown on this graph.

In addition to the two cluster subsets indicated by the blue and red points, Figure 22 also shows four yellow circles that indicate stakeholders with preference profiles that are either balanced or extreme. The 37 participants who weighted environment, economy and society equally all overlap in the single point at the center of the triangle, while the yellow circles at the extreme corners for environment, economy and society each include 22, 6 and 2 participants, respectively.

Figure 22 - Distribution of stakeholder weights for top sustainability criteria

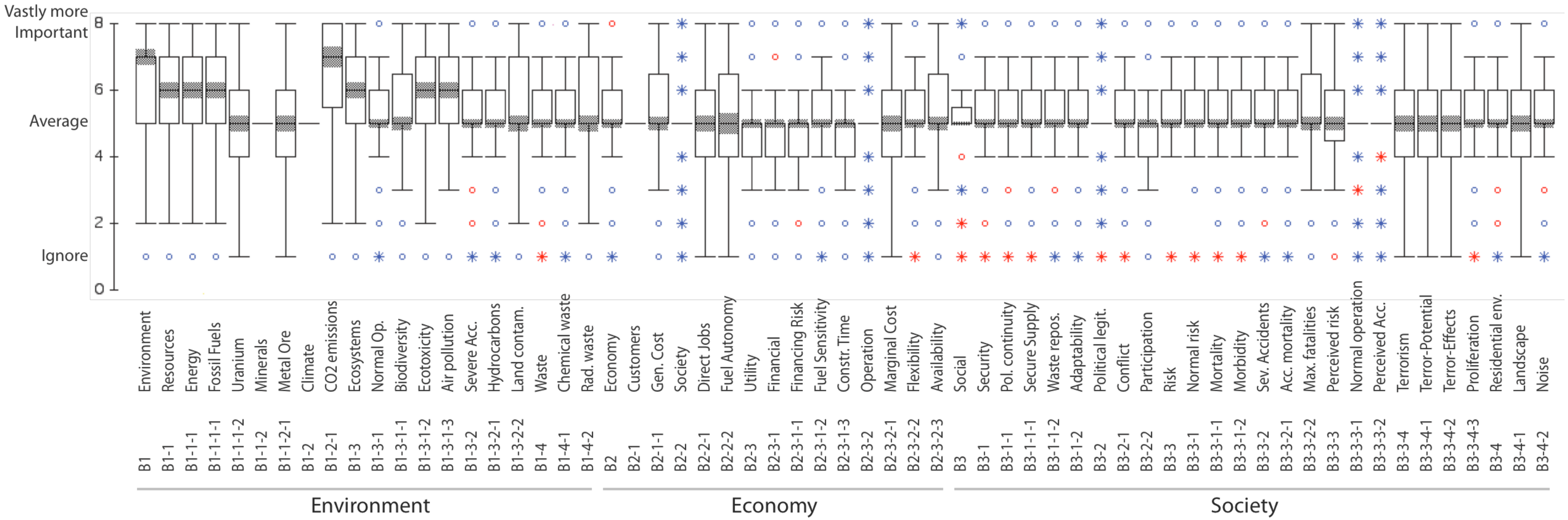


5 Results

This chapter presents and discusses the results of the sustainability analysis. The distribution of preference inputs and weights for each of the sustainability criteria is given first, followed by the distribution of the technology rankings for the full survey and different subsets. The technology ranking results for the Dominating Alternative MCDA algorithm are then compared to the Weighted Sum MCDA algorithm used as the reference standard. Finally, the results of the total cost calculations by technology are presented for each country for comparison with the MCDA technology rankings.

Figure 23 below shows the preference inputs entered by the stakeholders using the MCDA software application for the survey of sustainability criteria preferences. The vertical scale shows the position of the button clicked for each criterion. There were only 8 buttons (the 0 on the scale is due to the graphing by the data mining software), using the scale of 1 = "Ignore", 2 = "Vastly less important than average", 3 = "Much less important than average", 4 = "Less important than average", 5 = "Average", 6 = "More important than average", 7 = "Much more important than average" and 8 = "Vastly more important than average", with the relative numerical values of 0, 1/16, ¼, ½, 1, 2, 4, and 16, respectively. The horizontal axis shows the criteria hierarchy by number and name from the top three levels down to the indicators at the lowest levels (the criteria hierarchy numbers start with a "B" because the graph shows the button positions).

Figure 23 - Distribution of stakeholder inputs



The close ("o") and distant ("*") outlier values are colored red (majority cluster) and blue (minority cluster) in this and the following boxplots. Please see Chapter 4 for the definition of the outlier points and the cluster groups.

Note that people were more likely overall to rate criteria as average or above, rather than below average. The environment (overall) and CO2 emissions (in particular) were rated as most important. The criteria that stakeholders overall left as "average" included resource use (uranium and minerals), direct jobs, marginal cost and terrorism. Only some of the economic indicators were rated overall as less important than average. There are five cases where the variance is so small that the full boxplot does not show at all, and only its central bar appears (B2-2 Society, B2-3-2 Operation, B3-2 Political Legitimacy, B3-3-1Normal Operation (risk of normal operation) and B3-3-2 Perceived Accidents (perceived risk of accidents)). In addition the Mineral, Climate and Customer criteria (B1-1-2, B2-1and B2-1, respectively) only show a central bar at the button value 5 ("Average"). This is because each of these criteria has only a single indicator each below it on the criteria tree (B1-1-2-1 Metal Ore, B2-1-1- CO2 emissions and B2-1-1 Gen. Cost, respectively), and so these critieria did not have any buttons for input (see Figure 6). During the process of converting the button position inputs to weights, each of these lower level indicator values (which were stakeholder inputs) were promoted to replace the higher level criteria values of 5 (which was an arbitrary placeholder value, and not a stakeholder input).

This process of converting the values of the criteria preference inputs (button values) into criteria weights was further explained above in Chapter 3, and the distribution of the stakeholder weights that were obtained are shown below in Figure 24.

Figure 24 - Distribution of stakeholder weights

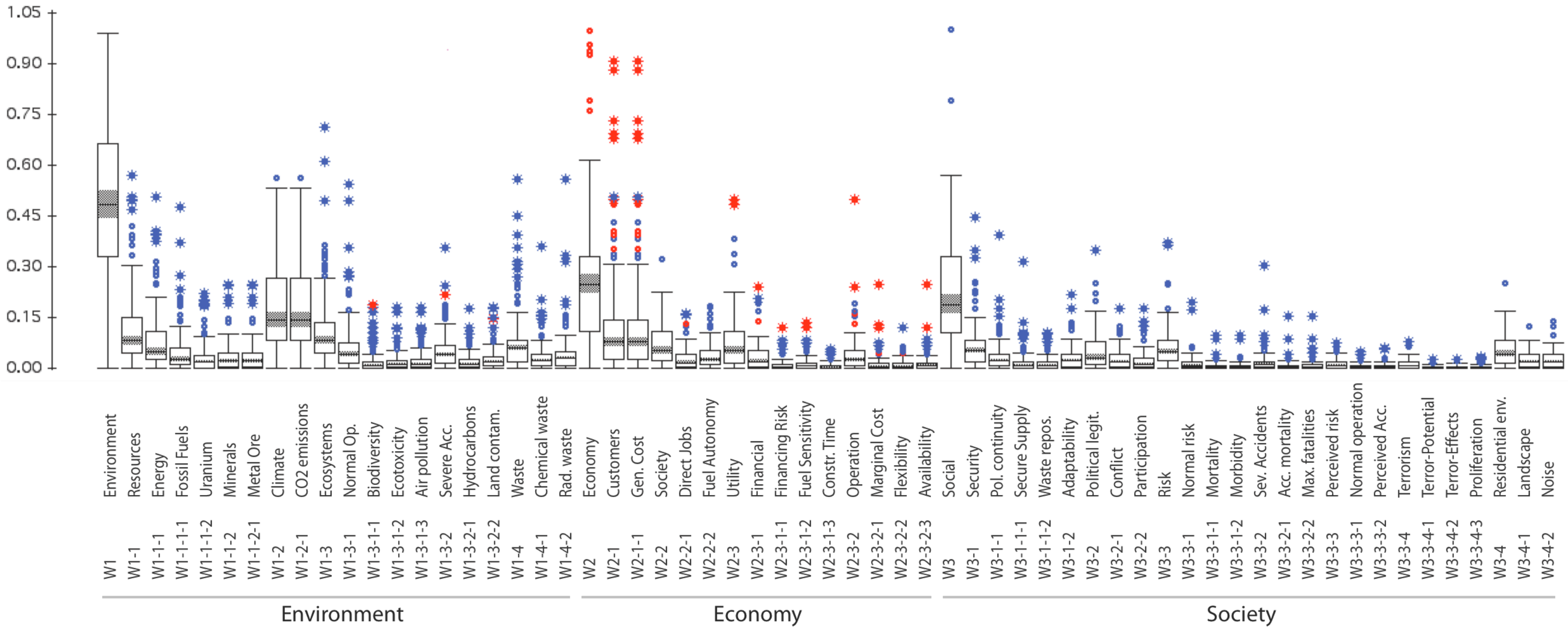
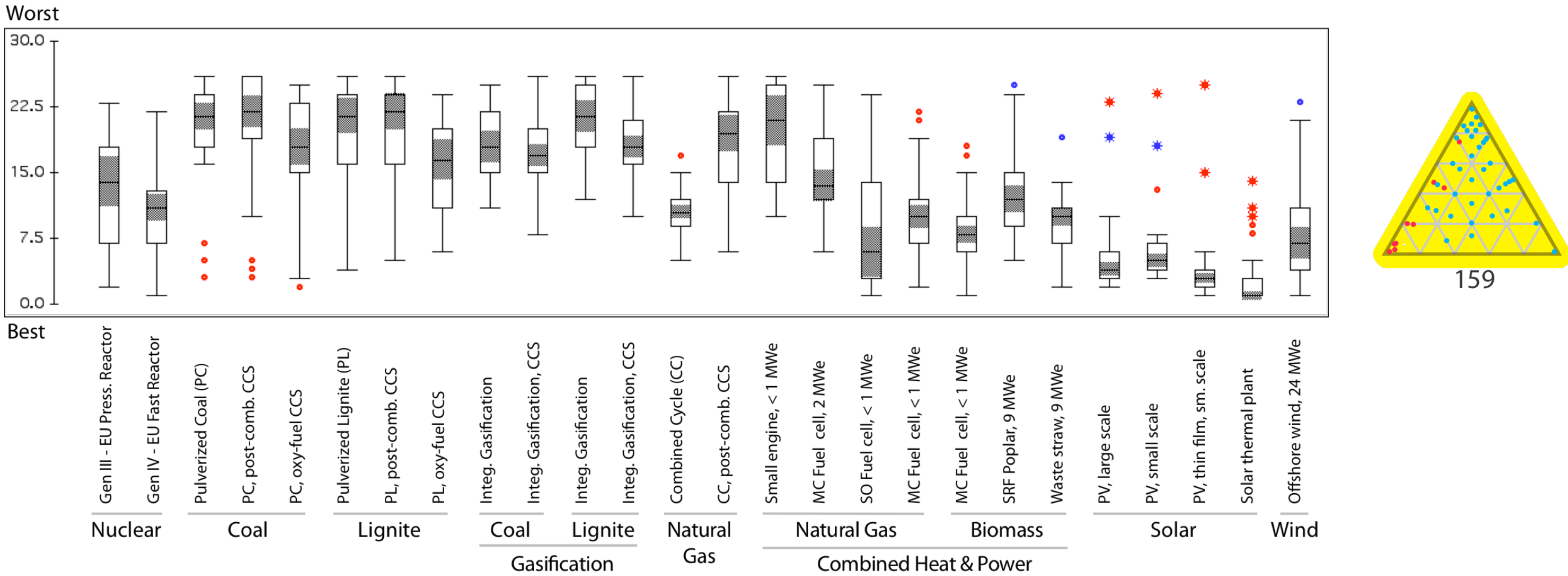


Figure 24 shows that the relatively much more even distribution of criteria input values was transformed into a broader distribution of weights, where the lowest branches of the hierarchy tree have quite small individual weight values. The values at each level sum to one, and add together up the tree, so it is easy to see that the overall average weight is highest for the environment (median value about 0.48), followed by the economy and society (median values about 0.25 and 0.18, respectively). Note that the minority cluster group of stakeholders shown by the red points has much higher weights on the economy overall and on generation cost in particular.

Figure 24 also illustrates quite clearly the fact that with even a moderately large set of criteria the impact of any one factor is easily diluted and it becomes very difficult for any one criterion to dominate the analysis. (This could be different if the MCDA method chosen allowed for a single technology to be vetoed if one or more criteria exceed some threshold, but that is not the case with either the Dominating Alternative or Weighted Sum methods.)

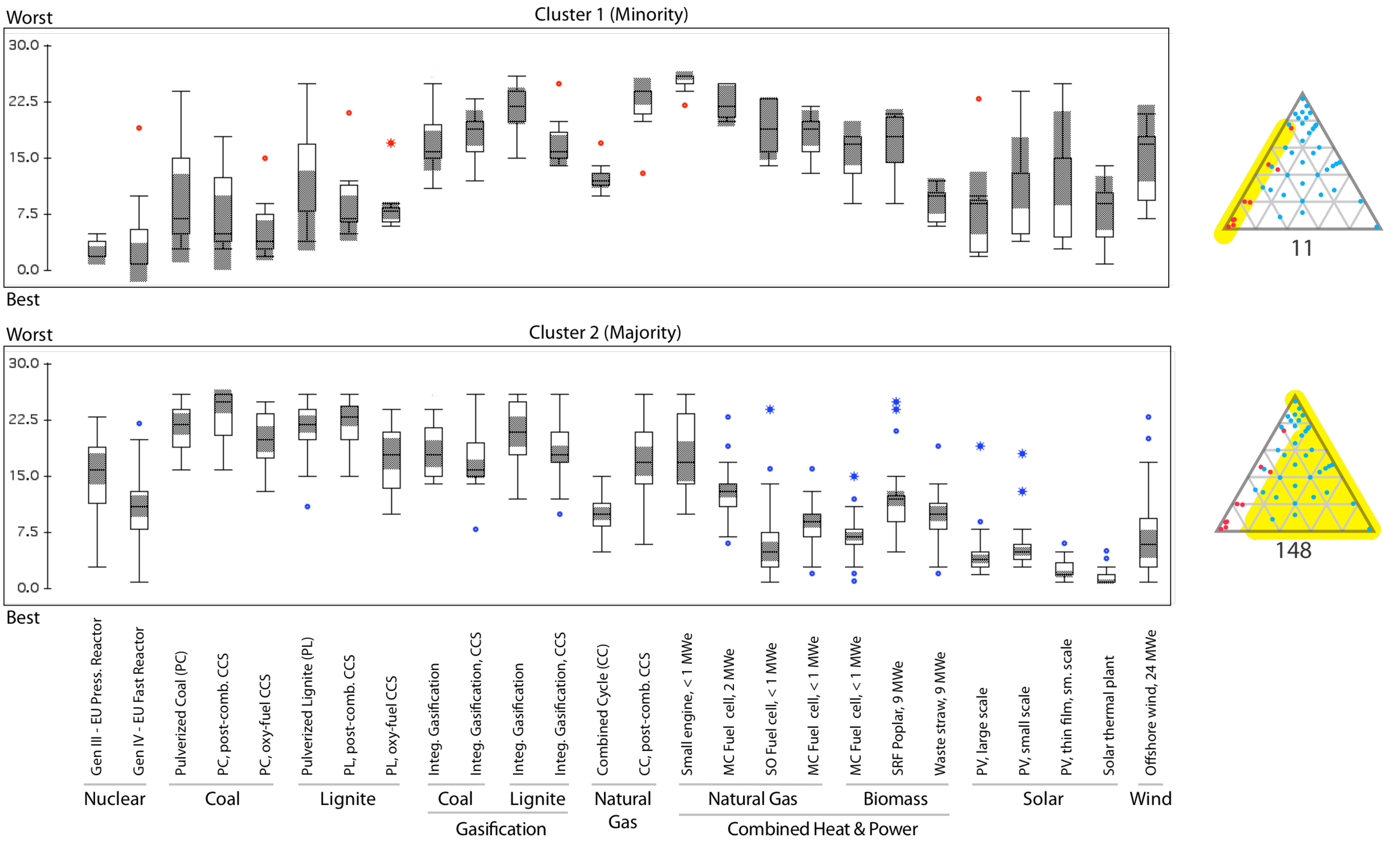
Combining each individual stakeholder's indicator weights with each technology's indicator values produces technology rankings for each stakeholder. The distribution of these individual rankings for the full set of stakeholders is shown below in Figure 25 by a boxplot for each technology. It should be emphasized that since the best technology in each ranking was number 1, the technologies that are most preferred overall are those that have the lowest and smallest distributions. For example, the solar PV technologies, and in particular the solar thermal technology, are consistently preferred by a majority of stakeholder with only a few outliers.

Figure 25 - Overall technology rankings



This set of overall ranking distributions was then separated into the majority and minority clusters by weight, as explained in Chapter 4 and shown in Figure 26 below.

Figure 26 - Technology rankings by stakeholder cluster

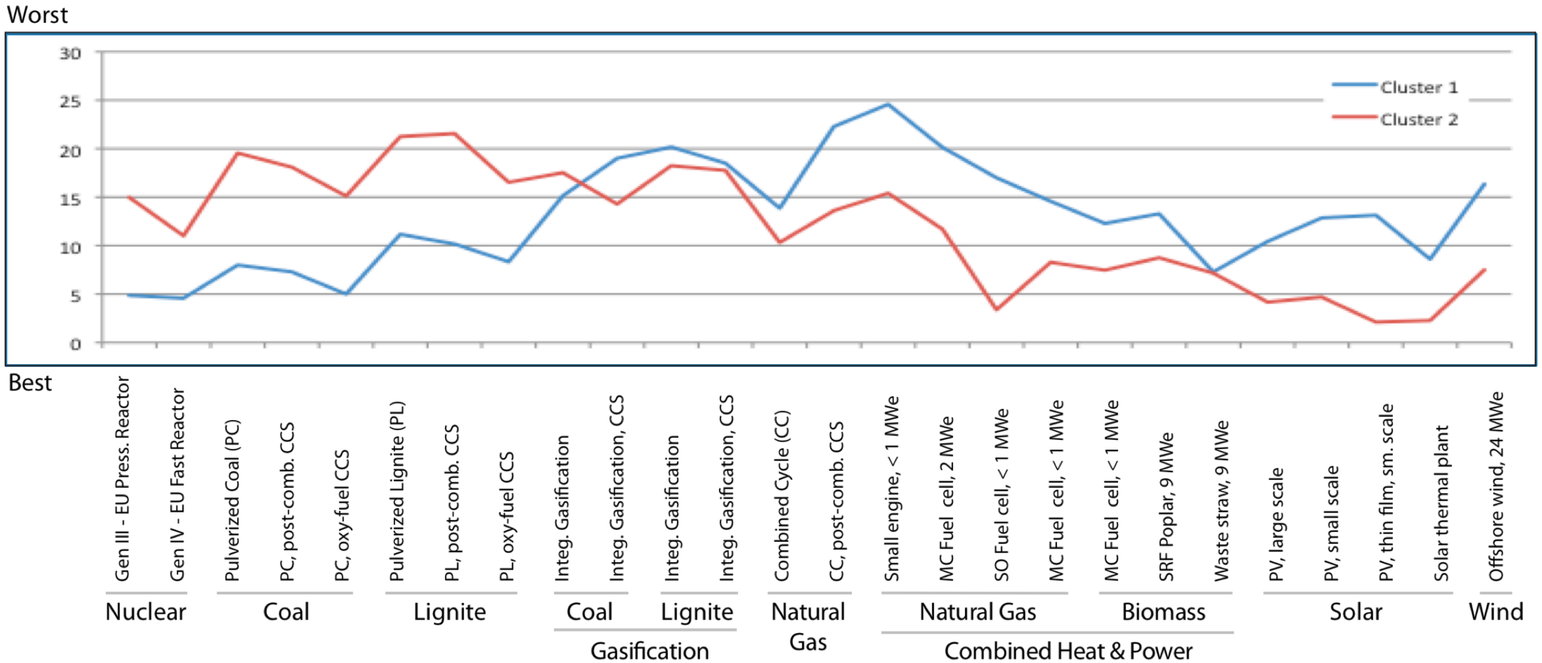


These two graphs show the significantly different ranking distributions for the majority and minority cluster groups. The top level weight distribution differences between these two groups are shown above in the triangular graph in Figure 22, and in schematic form to the right of the boxplot graphs. The numbers under the schematic triangle graphs indicate the fact that the minority cluster group 1 had 11 stakeholders, and the majority cluster group 2 had 148 stakeholders. We can see that that for cluster 1 the nuclear and fossil technologies rank much better (lower) and also show more variability than they do for cluster 2. Likewise, in general, those stakeholders in cluster 1 rank the renewable technologies lower and with more variability (only the small engine cogeneration is very consistently poor).

These patterns of relative technology performance and the differences between clusters 1 and 2 were consistent between the four different NEEDS countries when the data mining software was used to display the boxplots for each country as a subset. Naturally there is somewhat greater variability for poorly performing technologies than for the best performing technology, because not all the technologies were available in each country. That is, the best technology for each stakeholder is ranked number one in all countries, but the worst technology for each stakeholder would be ranked 26 in France, 25 in Germany, 21 in Italy and 19 in Switzerland. When the individual ranking results are aggregated, this give a larger variability for the technologies that rank worse overall.

To make the differences between the cluster ranking performance clear in a different and somewhat simpler way, Figure 27 below shows the average of the technology ranks for each technology for the two cluster groups. Again we see that cluster 1 that weights cost more heavily favors nuclear and coal/lignite technologies, while cluster 2 favors the gas, biomass, solar and wind technologies (the coal and lignite gasification technologies at the crossover and the waste straw biomass are about equal).

Figure 27 - Average technology ranks by stakeholder cluster



The results shown above were for two cluster groups that separated naturally, based on the stakeholder criteria weights (the clustering was unconstrained). It is also interesting to see how the technology ranking distributions look for other groups with different criteria weight distributions. Figure 28 below shows the technology ranking boxplots for four groups with one relatively even and three extreme criteria weight distributions (based on the top criterion level weights for environment, economy and society. These subsets of stakeholders were described in Section 4.3 and shown in the triangle graph Figure 22. The location and number of members in each stakeholder subset are also shown by the schematic triangle graphs shown to the right in Figure 28 below.

Figure 28a - Technology rankings for different mixes of sustainability criteria weights

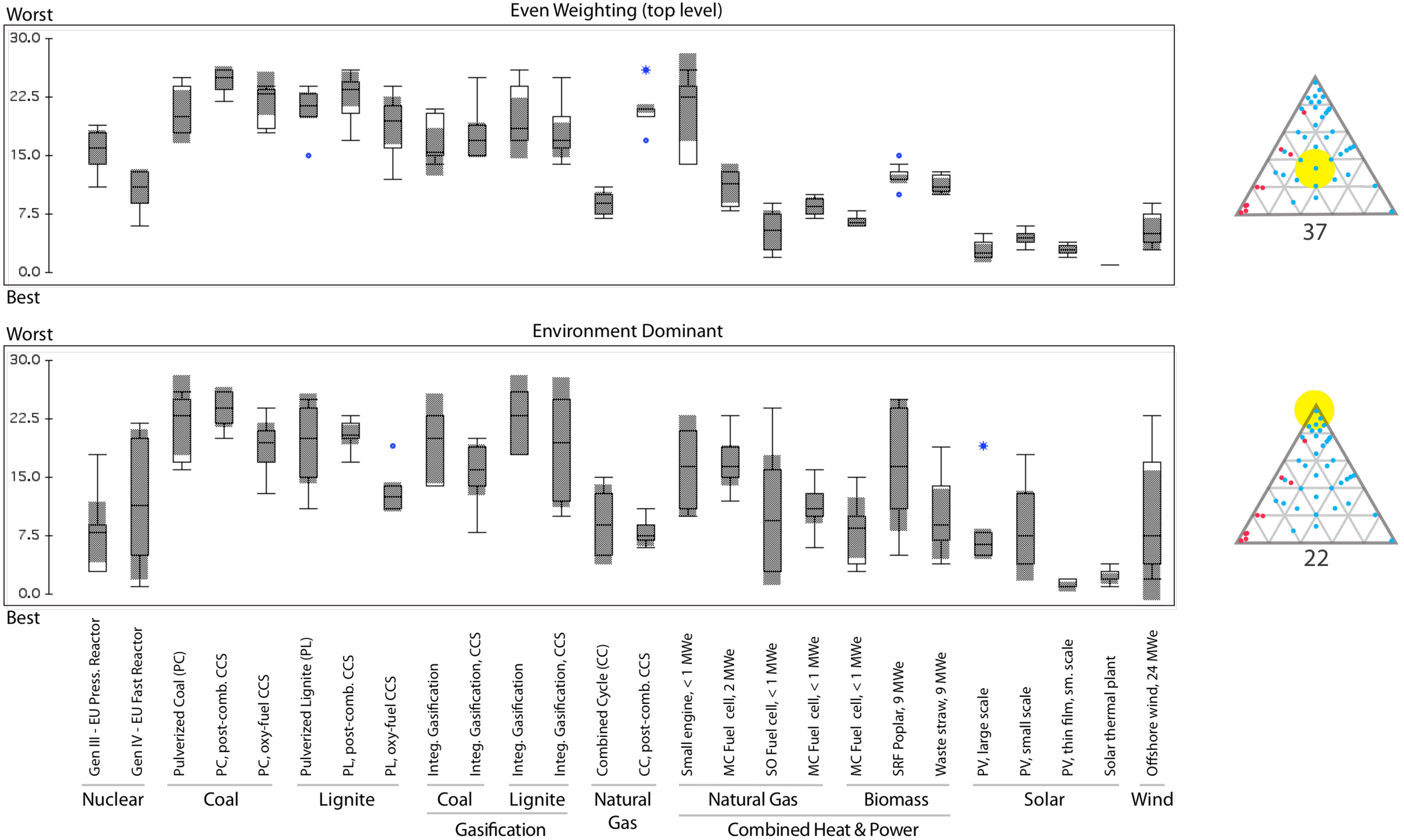
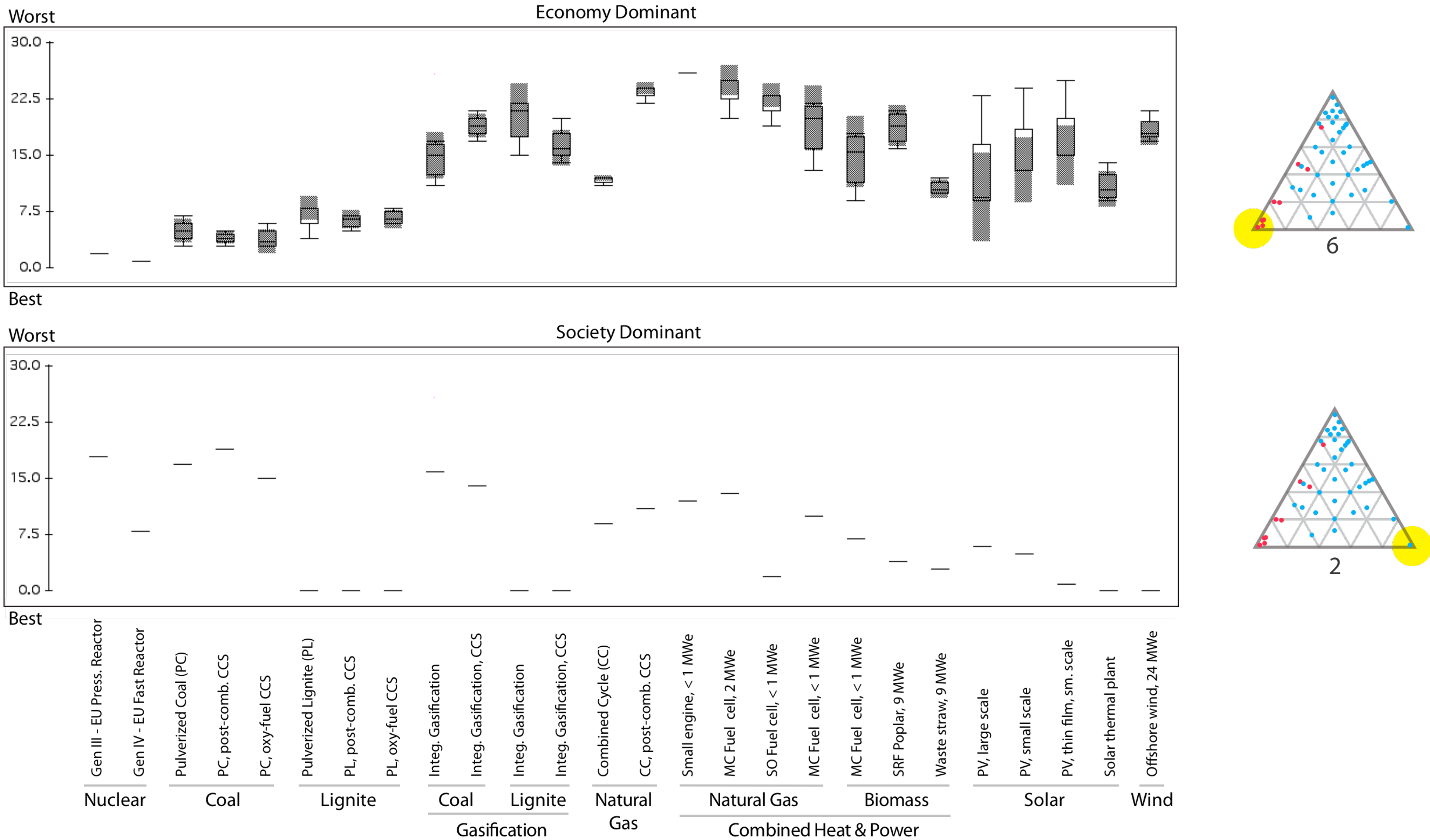


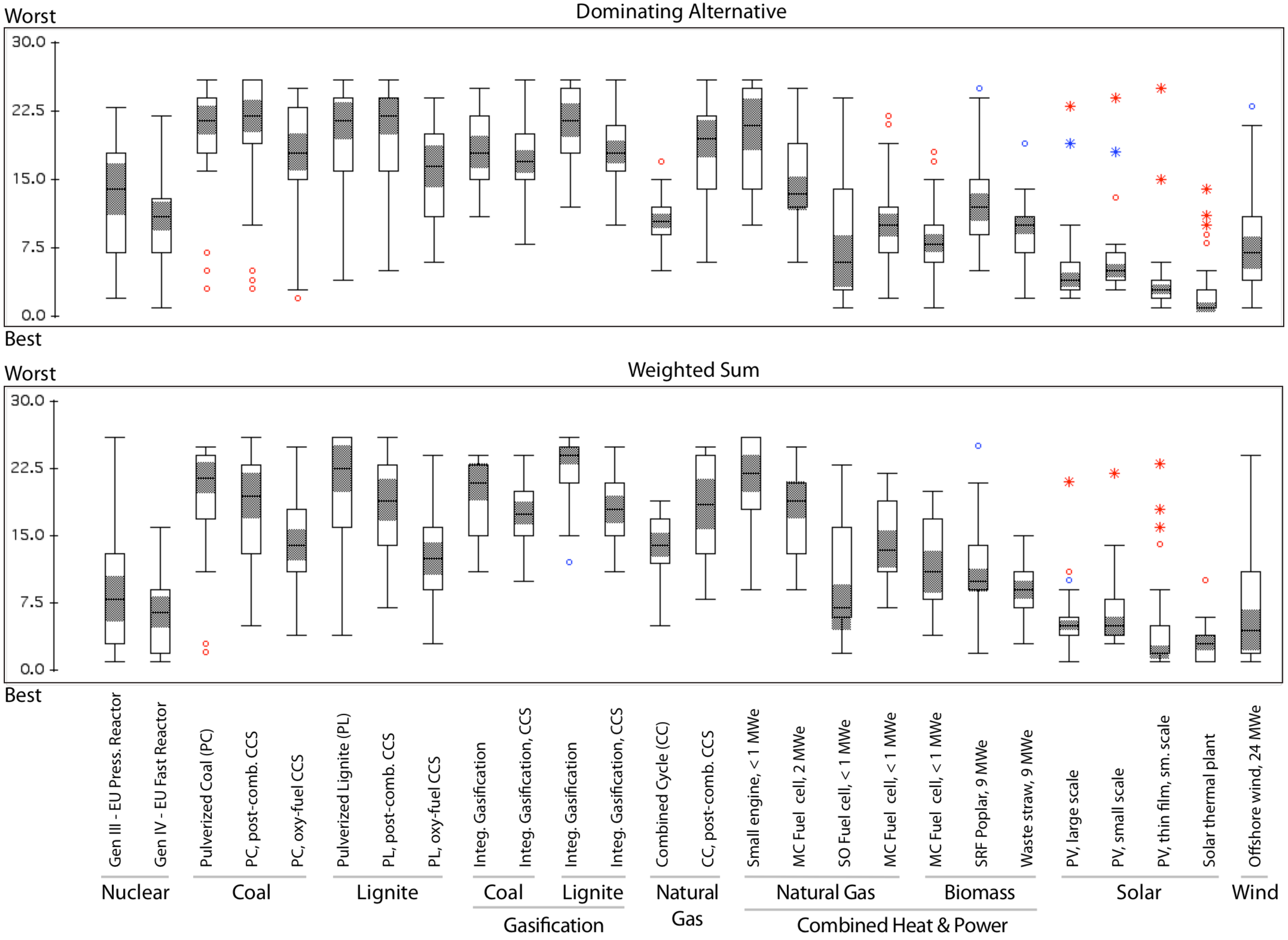
Figure 28b - Technology rankings for different mixes of sustainability criteria weights (cont.)



The even weighting profile is similar to the cluster 2 profile previously shown, but with a lower variability. This makes sense, since the evenly weighted subset is more uniform (with less emphasis on the environment), and they are both large subsets that mostly overlap. The extreme environmental subset has a ranking with more variance in the rankings. Nuclear power rankings (and in particular the EFR rankings) are more variable for the environmental subset than for any of the other subsets. This shows that it is not just important that the emphasis on the environment is high, but also what the balance is between the different environmental components, because nuclear power does well in some categories and not in others (e.g. CO_2 v. nuclear waste). The economic subset is of course quite similar to the results for cluster 1 above, but even more extreme, since at least some members of cluster 1 were partway along the environment/economy axis. The number of stakeholders that took an extreme weight on social issues (to the exclusion of the environment and economy) was so small (2), that there were not enough data points to create a boxplot. By coincidence, these two stakeholders both gave even preference values for all the lower social criteria, so their weights were the same and the differences in their rankings were solely due to the technologies missing in some countries.

As explained above in Chapter 3, the Dominating Alternative algorithm for the MCDA ranking of discrete alternatives was developed and chosen from a number of alternatives for use in the NEEDS sustainability analysis. The Weighted Sum method had been previously used by some of the NEEDS partners, and has known advantages (easy to use, explain and understand) and known disadvantages (mathematical shortcomings). The weighted sum method was used as a reference during the (initially) blind selection process, and it is therefore interesting to compare the ranking distributions for these two different methods. Figure 29 below shows the boxplots for the technology ranking distributions using the DA and WS algorithms.

Figure 29 - Comparison of MCDA ranking methodologies



The overall similarities in the ranking distributions produced by these two algorithms are strong, but there are some differences. The nuclear technologies do much better under the weighted sum method. Also, the coal and lignite technologies using carbon capture and storage (CCS) did relatively better under the weighted sum approach. Solar technologies do well in the relative rankings under both approaches, but their performance is more robust (having less variance) under the Dominating Alternative approach. The offshore wind technology does better under the weighted sum approach, but is less robust (the wider boxplot shows more variance).

One of the major purposes of the NEEDS sustainability analysis is of course to compare the MCDA sustainability rankings that have been examined so far with the single criterion, total cost results for the NEEDS technologies. The total technology costs for France, Germany, Italy and Switzerland are shown below in Figures 30 through 33. The legend shows the different cost components, including the low and high estimates of greenhouse gas related costs. Lower costs are of course better. Because these results are separated by country, rather than by cluster group or other criteria weight group, some technologies are missing from those countries where they were judged to be inappropriate.

Figure 30 - Total technology costs for France

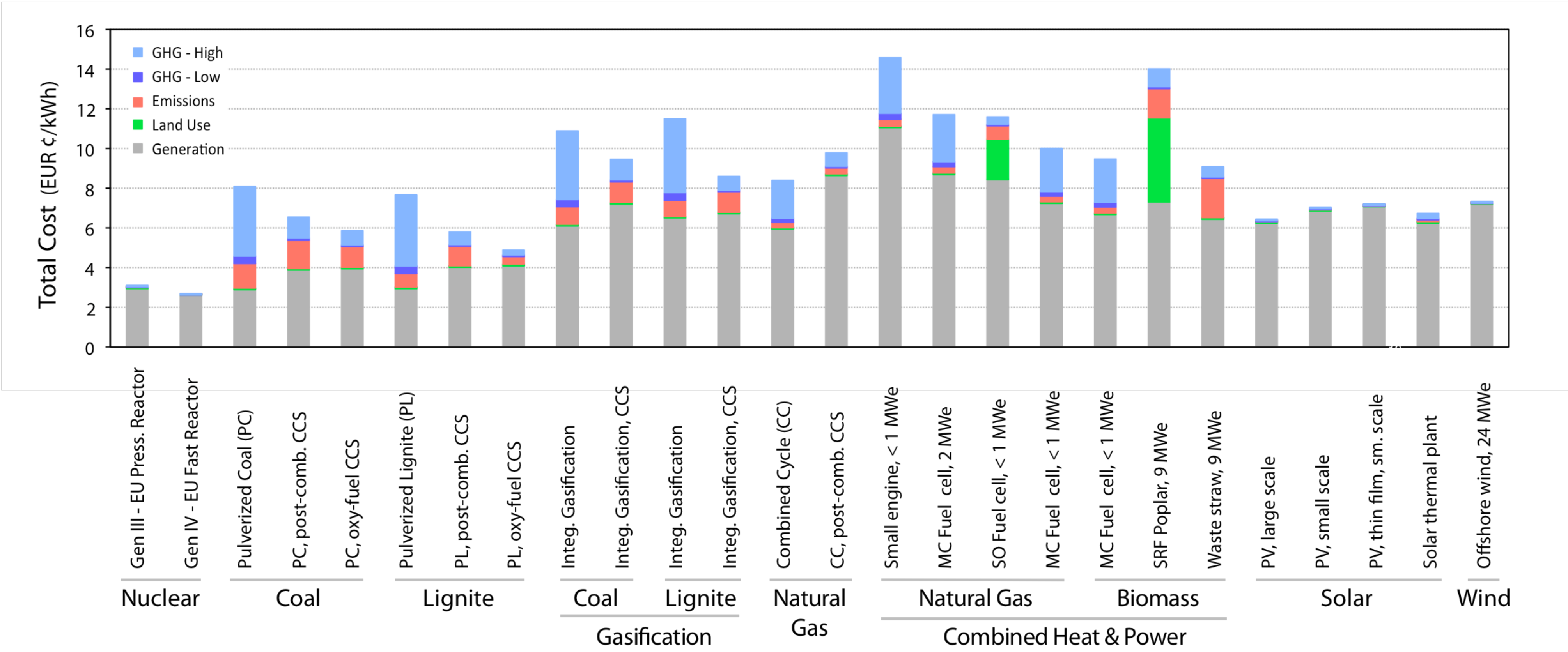


Figure 31 - Total technology costs for Germany

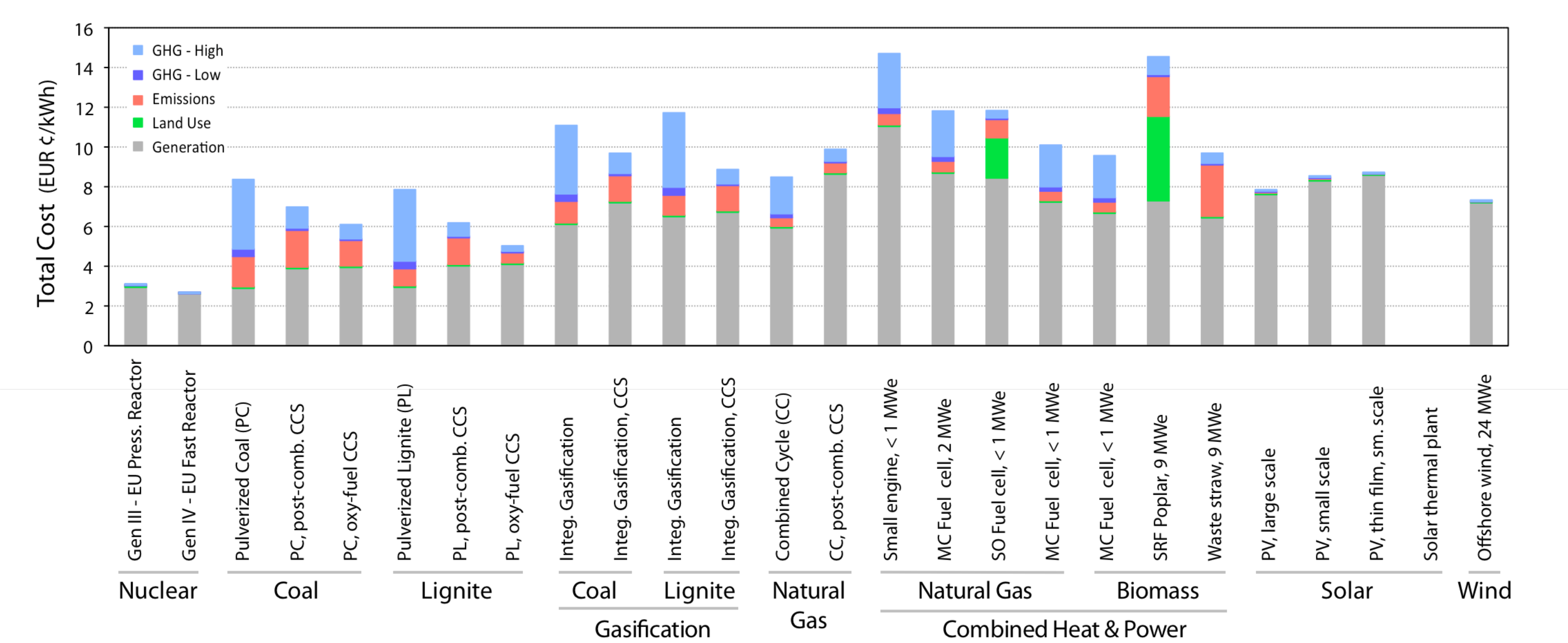


Figure 32 - Total technology costs for Italy

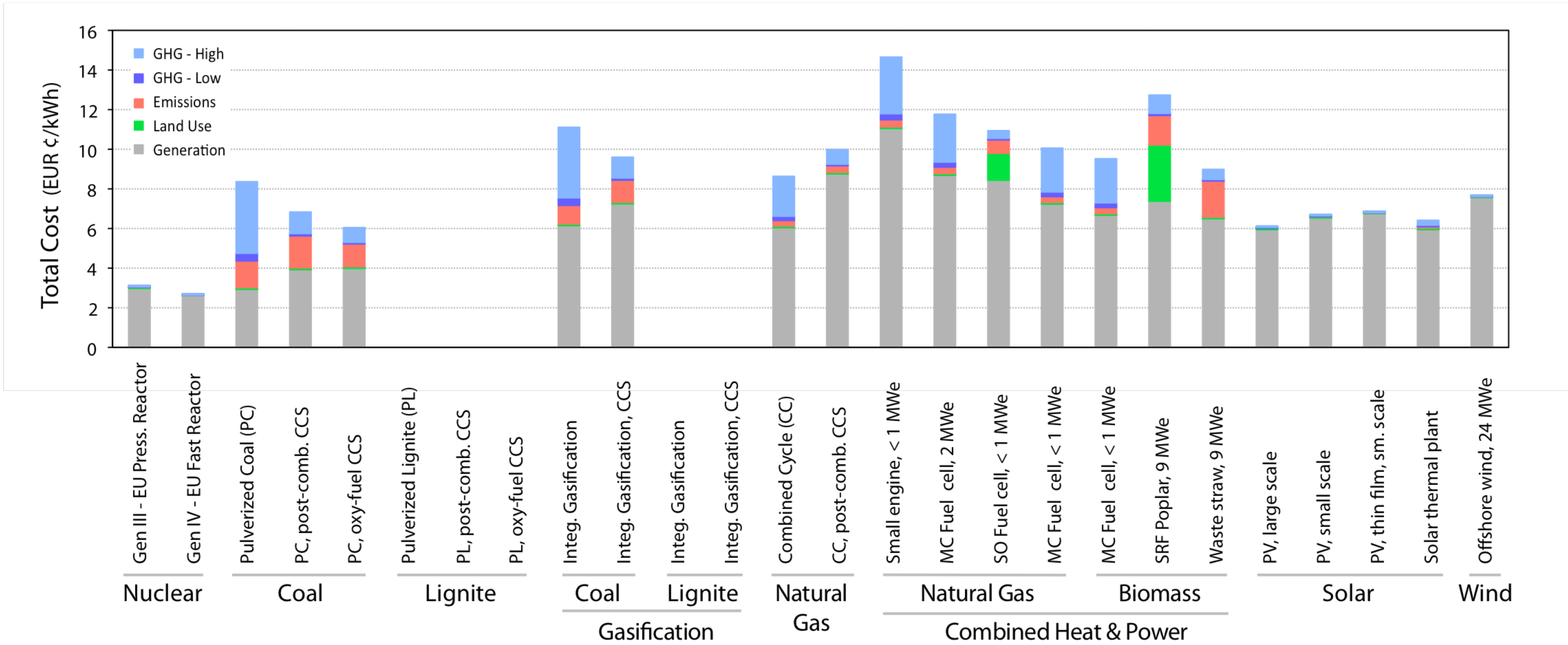
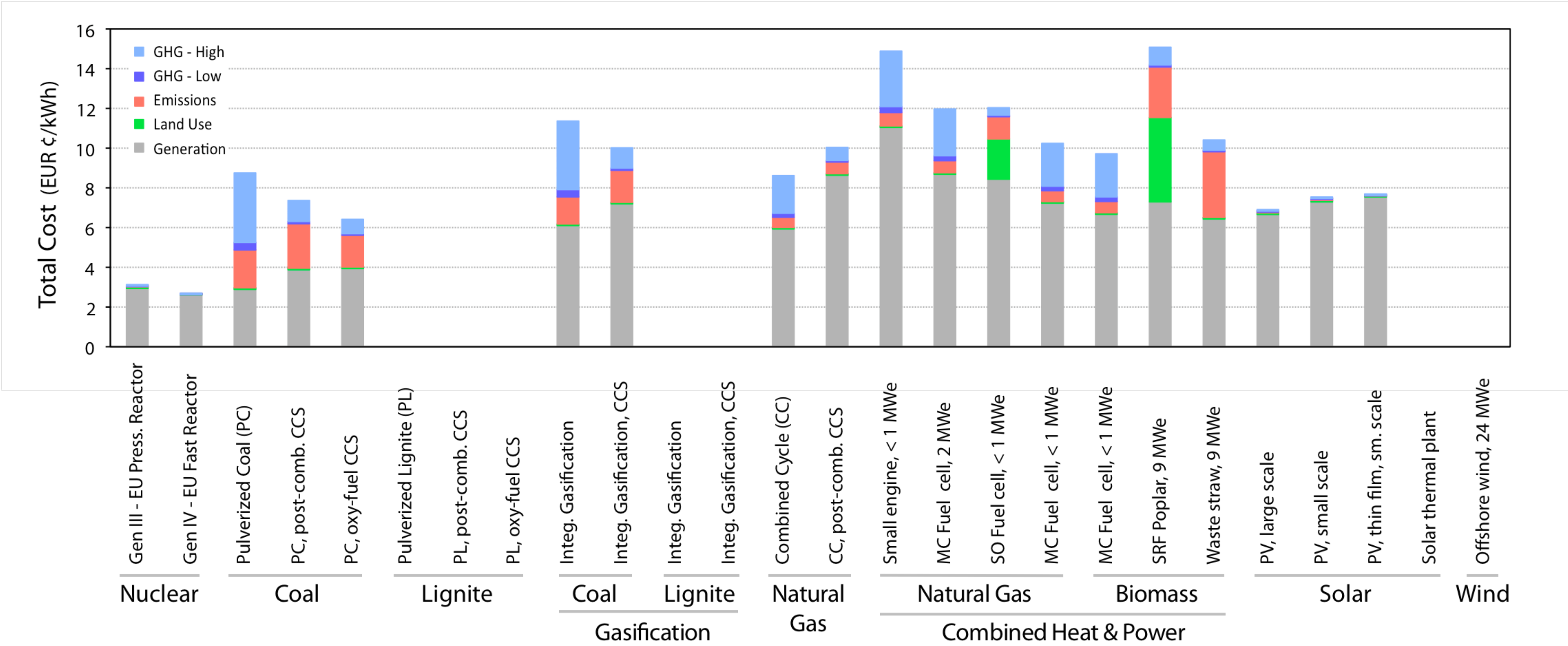


Figure 33 - Total technology costs for Switzerland



It can be somewhat difficult to look at the four graphs above, and compare how the technologies rank by total cost either within or across countries. For this reason the data behind these graphs are shown below in Tables 6 and 7, based on whether a lower or higher value was used for monetizing the cost of greenhouse gases. The total cost and technology ranks are shown for each country, and the tables are ranked by the costs for France (because it has all 26 technologies). It is can be seen that the order of the rankings differ somewhat between the countries, with the best (lowest cost) technologies tracking more closely than the worse (higher cost) technologies.

The tables also show the MCDA rankings, using the average for the complete stakeholder set, including all four countries (the boxplot distributions for this set are shown in Figure 25). Because these ranks are averaged across all stakeholders, their spread is not so extreme (the range is between 2.8 for one photovoltaic technology to 20.5 for integrated gasification combined cycle using lignite).

Table 6 – Total costs and ranks using low GHG valuation, compared to average MCDA ranks

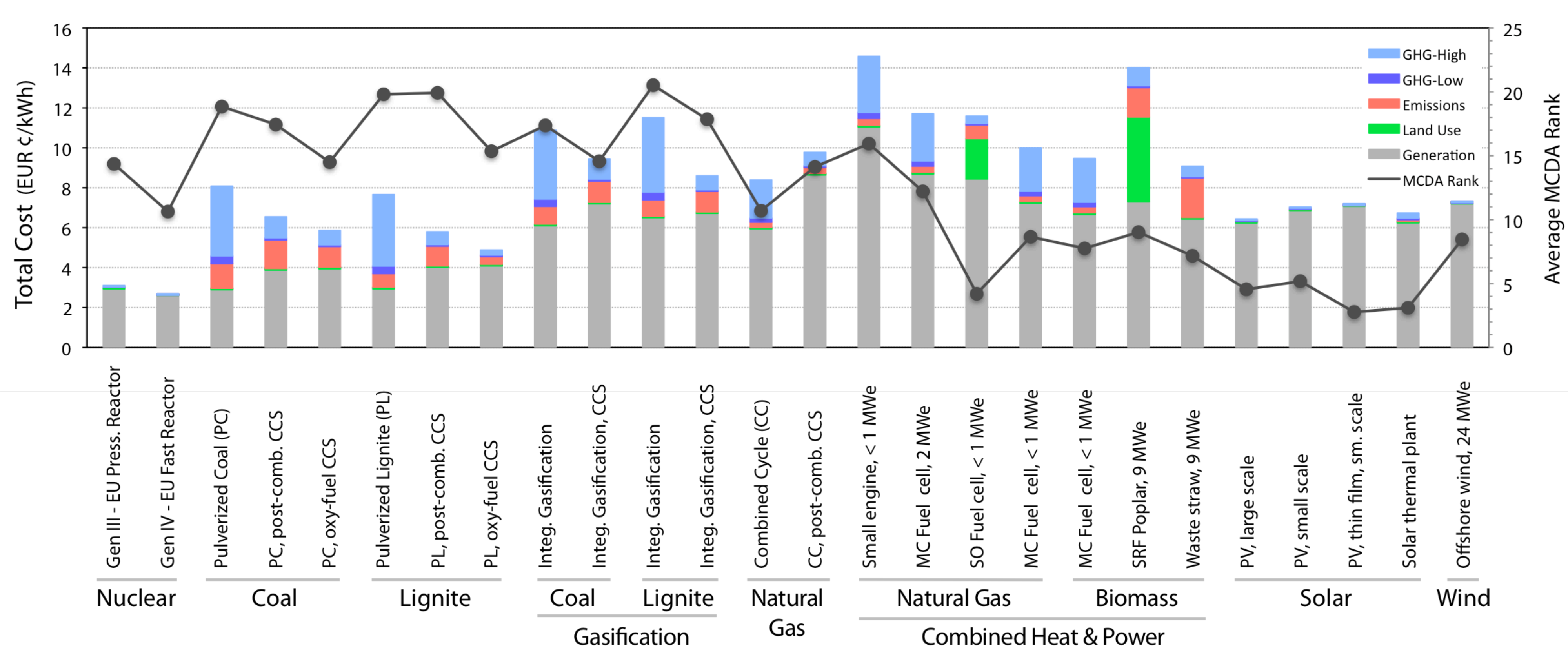
NEEDS Technology #	Name	France		Germany		Italy		Switzerland		MCDA Average
2	EFR	2.69	1	2.69	1	2.70	1	2.70	1	10.6
1	EPR	3.08	2	3.10	2	3.12	2	3.11	2	14.4
6	PL	4.08	3	4.26	3					19.8
3	PC	4.58	4	4.87	5	4.75	3	5.25	3	18.9
8	PL Oxyf. CCS	4.63	5	4.75	4					15.4
5	PC, Oxyf. CCS	5.13	6	5.38	6	5.30	4	5.69	4	14.5
7	PL Post CCS	5.15	7	5.51	7					19.9
4	PC, Post CCS	5.48	8	5.92	8	5.74	5	6.31	5	17.4
22	PV Plant	6.39	9	7.80	13	6.09	6	6.86	7	4.5
25	Solar thermal	6.47	10			6.17	7			3.1
13	NG CC	6.48	11	6.64	9	6.62	8	6.72	6	10.7
23	PV Building	7.00	12	8.49	17	6.68	9	7.49	8	5.2
24	PV CdTe	7.19	13	8.72	19	6.86	10	7.68	10	2.8
19	SOFC	7.28	14	7.45	11	7.29	11	7.54	9	7.8
26	Offshore wind	7.31	15	7.32	10	7.68	13			8.5
9	Coal IGCC	7.43	16	7.64	12	7.55	12	7.91	11	17.4
11	Lig IGCC	7.78	17	7.98	14					20.5
18	MCFC	7.83	18	8.00	15	7.84	14	8.08	12	8.7
12	Lig IGCC CCS	7.90	19	8.15	16					17.9
10	Coal IGCC CCS	8.43	20	8.67	18	8.55	16	8.99	13	14.6
21	Straw	8.57	21	9.18	20	8.47	15	9.90	16	7.2
14	NG Post CCS	9.10	22	9.29	21	9.24	17	9.38	14	14.1
16	MCFC	9.33	23	9.53	22	9.35	18	9.62	15	12.2
17	MCFC	11.22	24	11.46	23	10.55	19	11.66	17	4.2
15	CHP	11.77	25	11.98	24	11.79	20	12.09	18	15.9
20	Poplar	13.12	26	13.65	25	11.81	21	14.19	19	9.0
		EUR ¢/kWh	Rank	EUR ¢/kWh	Rank	EUR ¢/kWh	Rank	EUR ¢/kWh	Rank	Rank

Table 7 – Total costs and ranks using high GHG valuation, compared to average MCDA ranks

NEEDS Technology #	Name	France		Germany		Italy		Switzerland		MCDA Average
2	EFR	2.70	1	2.70	1	2.71	1	2.70	1	10.6
1	EPR	3.10	2	3.12	2	3.14	2	3.13	2	14.4
8	PL Oxyf. CCS	4.85	3	5.00	3					15.4
7	PL Post CCS	5.73	4	6.11	5					19.9
5	PC, Oxyf. CCS	5.78	5	6.02	4	5.97	3	6.34	3	14.5
4	PC, Post CCS	6.43	6	6.87	6	6.72	7	7.25	5	17.4
22	PV Plant	6.43	7	7.85	9	6.13	4	6.90	4	4.5
25	Solar thermal	6.70	8			6.39	5			3.1
23	PV Building	7.04	9	8.54	12	6.72	6	7.54	6	5.2
24	PV CdTe	7.20	10	8.73	13	6.88	8	7.69	7	2.8
6	PL	7.28	11	7.47	8					19.8
26	Offshore wind	7.32	12	7.33	7	7.69	9			8.5
3	PC	7.71	13	7.99	10	7.98	10	8.38	8	18.9
13	NG CC	8.19	14	8.29	11	8.42	11	8.42	9	10.7
12	Lig IGCC CCS	8.52	15	8.79	14					17.9
21	Straw	9.02	16	9.63	17	8.93	12	10.35	14	7.2
19	SOFC	9.24	17	9.34	15	9.29	13	9.49	10	7.8
10	Coal IGCC CCS	9.34	18	9.58	16	9.49	14	9.90	11	14.6
14	NG Post CCS	9.71	19	9.82	18	9.91	16	9.97	12	14.1
18	MCFC	9.77	20	9.88	19	9.83	15	10.01	13	8.7
9	Coal IGCC	10.52	21	10.72	20	10.73	17	11.00	15	17.4
11	Lig IGCC	11.11	22	11.32	21					20.5
16	MCFC	11.46	23	11.57	22	11.51	19	11.72	16	12.2
17	MCFC	11.55	24	11.79	23	10.90	18	11.99	17	4.2
20	Poplar	13.91	25	14.44	25	12.63	20	14.98	19	9.0
15	CHP	14.28	26	14.41	24	14.35	21	14.59	18	15.9
		EUR ¢/kWh	Rank	EUR ¢/kWh	Rank	EUR ¢/kWh	Rank	EUR ¢/kWh	Rank	Rank

To show the comparison between the total cost and MCDA rankings more visually, the total cost results for France and the average MCDA rank for all four countries were combined in Figure 34 below.

Figure 34 - Total costs v. average MCDA ranking



The most basic result shown in this figure is that the total cost and MCDA rankings are clearly different. Naturally, the total costs include the direct economic costs, plus the monetized value of indirect environmental costs. The MCDA results include some further, non-monetized economic and environmental indicators, but the main difference is in the social criteria that are ignored by the total cost calculation. The social criteria are overall weighted below the environmental and economic criteria (see Figure 24 above), but it is clear that their inclusion is important enough to make a significant difference between the total cost and MCDA rankings.

6 Summary and Conclusions

Goal

The ultimate goal of this Research Stream was to broaden the basis for decision support beyond the assessment of external costs and to extend the integration of the central analytical results generated by other Research Streams. This task included mapping how the sustainability performance of different technological options varies based on stakeholder preference profiles, and also analyzing whether stakeholders could be grouped by their sustainability criteria preference profiles, and whether these profiles corresponded to any pre-identified demographic groups (stakeholder group, nationality, etc.).

Accomplishments

To achieve these goals, a comprehensive framework for evaluating the sustainability of electricity supply technologies (including the associated fuel cycles) has been developed, implemented and applied with active participation by stakeholders in various stages of the process. The elements of this process described in this report have included the following steps:

- Establishment of sustainability criteria and indicators (with stakeholder input)
- Quantification of the technology- and country-specific indicators
- Establishing the indicator database for a broad range of future technologies in four countries
- Analysis of MCDA requirements
- Development of MCDA methods meeting the requirements
- Testing and adapting the methods
- Selection of the most suitable MCDA method
- Development of a web-based user interface for conducting the stakeholders preference survey and interactively providing MCDA rankings
- Conducting the web-based survey of stakeholder preferences, providing individual MCDA results to participants
- Analysis of the results of MCDA including comparison with total costs

Over 3000 stakeholders were invited to participate in the MCDA survey. Of these, 259 provided demographic data (via the 2ask survey site) and 159 completed the MCDA survey. The most survey responses were from Swiss participants, followed by Germany, other countries, Italy and France. The relative number of participants was based upon both the initial distribution of the survey invitations and in the national participant response rates. The MCDA survey response was relatively low and somewhat below anticipated. This was judged to be due to the fact that the MCDA exercise was far more demanding than a traditional survey, requiring a significant commitment of time and effort. Nevertheless, it was felt that the number of responses was adequate for drawing both some general and concrete conclusions.

General Conclusions

Given the results of the MCDA process outlined above and described in this report, it is possible to reach a number of general conclusions about using MCDA for the sustainability analysis of generation technologies in the NEEDS project, including the following:

- Stakeholder showed wide acceptance of the proposed criteria and indicator set for MCDA.

- Analysis of stakeholder preferences did not show significant grouping by pre-identified stakeholder group, by nationality, or other demographic data.
- Stakeholders preference profiles naturally formed two separate groups, based on unconstrained cluster analysis, and these groups' preferences produced significantly different technology rankings.

Ranking of Technologies by Total Cost v. MCDA

Two approaches were used by RS2b for the evaluation and ranking of the technological options. The first approach was based on total cost calculations (i.e. summing direct costs plus external costs). Total costs were estimated based on the information available from other research streams (RS1a and RS1b), with some country-specific adjustments made as necessary by RS2b. The second approach was to use Multi-Criteria Decision Analysis (MCDA), combining in a structured manner knowledge of specific attributes of the various technologies with stakeholder preferences.

The total cost approach has the advantage of being conceptually simple, and produces technology rankings that are unambiguous. Its merits for cost-benefit assessment are undisputable. However, stakeholders do not always agree on the choice of methods used to monetize the externalities and the values obtained, so final rankings are often controversial. The main problem is that not all criteria relevant to sustainability are easily monetized. In particular, social criteria are scarcely included in the total cost approach.

MCDA also has advantages and disadvantages. It provides a learning process that can familiarize stakeholders with the relative strengths and weaknesses of competing technologies (i.e. there are tradeoffs, but "no free lunch"). MCDA can guide informed debate and decision making in a way that is structured and fact-based. MCDA also addresses many criteria simultaneously (or in parallel), rather than sequentially, including social and other factors that are difficult to monetize.

On the minus side, MCDA is a complex and time-demanding process that requires the participation of many stakeholders, who need to agree on the criteria set and hierarchy, and on the associated indicators. Social indicators are explicitly included, but their quantification is not always robust.

Ranking Technologies - Specific Conclusions

The following patterns were identified for these two methods of aggregating sustainability criteria.

Total Costs –

- Within the external cost estimation framework applied in NEEDS, nuclear energy exhibits the lowest total costs.
- Renewables (whose production costs are assumed to strongly decline - drastically in the case of solar technologies), have a rather wide range of total costs, with biomass technologies (especially poplar) on the high side and solar and wind on the low.
- The ranking of fossil technologies relative to (remarkably improved) solar and wind technologies strongly depends on the value used for the GHG damage cost.
- Direct combustion coal and lignite technologies have lower total costs than coal and lignite gasification and natural gas.
- Within the coal and lignite technologies, the total cost rankings are sensitive to the GHG damage cost. That is, the low GHG damage value favors coal and lignite plants without CCS, while the higher GHG damage value favors plants with CCS.
- Adding CCS to the gas combined cycle unit increases total costs across the range of GHG costs.

MCDA Results

- The MCDA approach favors renewables, in particular the solar technologies that benefit from the large cost reductions that are assumed.
- Including a wide set of social criteria leads to an overall lower ranking of nuclear, with the GEN IV fast breeder performing better than GEN III EPR.
- Coal technologies perform worst in MCDA while centralized gas options rank in the midfield, along with nuclear.
- CCS-performance is mixed, i.e. fossil technologies with CCS may rank better or worse than the corresponding technologies without CCS, depending on which specific CCS option is used.
- Renewable technologies, and in particular solar, rankings are more robust (i.e. they are less sensitive to stakeholders' criterion weights that the fossil or nuclear options).
- Emphasis on the environment penalizes fossil options relative to other technologies (similar to the balanced weight subset); emphasis on economy penalizes renewable options; emphasis on social penalizes nuclear.
- The ranking of fossil units with CCS is generally higher and less variable (sensitive to differences between stakeholders) than units without CCS, particularly in the case where environmental criteria are emphasized.
- Emphasis on economy disfavors or penalizes combined heat and power (CHP), coal gasification and renewables (in that order).
- Emphasis on social criteria penalizes the nuclear EPR over the EFR, and also disfavors the coal and lignite fossil technologies
- Few stakeholders actually weighted social factors high relative to economy and environment, but the addition of social indicators (plus non-monetized economic and environmental indicators) is sufficient that MCDA technology rankings vary significantly from total cost rankings.
- For MCDA, the overall average rankings are highest for renewables (solar, wind and biomass), followed by natural gas (combined cycle and CHP, solid oxide fuel cells are especially good) and nuclear technologies, and finally the coal and lignite technologies are overall worst.

<u>Overall Conclusions</u>

This study concludes that an individual's preference profile for the range of sustainability criteria has a decisive influence on his personal MCDA ranking of the technologies considered. This influence is particularly pronounced for technologies that have a highly differentiated profile, i.e. strong performance on some indicators and weak performance on others. We can also conclude that the use of cluster analysis to group stakeholders by their preference weights shows that these groups also have distinct differences in the distributions of their technology rankings, and that rankings are similarly sensitive to technology's with a differentiated mix of criteria performance.

Such technologies may be controversial; nuclear energy is the most pronounced example having these features. Thus, given equal weighting of environmental, economic and social dimensions and emphasis on the protection of climate and ecosystems, minimization of objective risks and affordability for customers, the nuclear options are top ranked. On the other side, focusing on radioactive wastes, land contamination due to hypothetical accidents, risk aversion and perception issues, terrorist threat and conflict potential, the ranking changes to the strong disadvantage of nuclear energy. This emphasizes the need of further technological developments towards mitigating the negative impacts of these issues.

The ranking of fossil technologies highly depends on the emphasis put on the environmental performance, which in relative terms remains to be a weakness, more pronounced for coal than for gas.

Renewables show mostly a stable very good performance, based on highly improved economics. Still emphasis on the economics along with flexibility and availability of stochastic renewables, and health effects of biomass technologies, leads to some shifts towards lower ranking.

This research stream has demonstrated that indicator-based sustainability assessment is feasible for current and future technologies, and has the potential to guide the debate on the future energy supply in a structured manner and support informed decisions.

There are several improvements and extensions of the present NEEDS that would be both feasible and desirable. An immediate extension would be to conduct one or more workshops to gather stakeholder preferences, in addition to the web-based survey results presented in this report. A moderated workshop would allow the stakeholders to be guided through the interactive MCDA process in a focused way, and also aid in spreading the results of the NEEDS project. In addition, there could be further improvements made in the consistency of indicators and more robust quantifications of some "soft" social indicators. The scope of the analysis could also be extended to other electric system options, including scenario analysis of different generation technology mixes, demand technologies and management (e.g. heating systems, or load leveling), and policies for system operation. The geographic scope of the evaluation could be extended beyond the current four European countries. Finally, the same overall NEEDS approach could also be applied to current and future mobility options.

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