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NEEDS

New Energy Externalities Developments for Sustainability

INTEGRATED PROJECT

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Sub-priority 6.1.3.2.5: Socio-economic tools and concepts for energy strategy.

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1 Introduction

The broad objective of the Research Stream RS2b “Energy Technology Roadmap and Stakeholder Perspectives” within the EU Integrated Project NEEDS (New Energy Externalities Developments for Sustainability) is 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.

Using the widely recognized ‘three pillars’ interpretation of sustainable development, the NEEDS project has defined a broad range of criteria and indicators in order to assess the environmental, social and economical aspects of future, sustainable electricity generating technologies and their associated fuel cycles (see Hirschberg et al., 2008, Deliverable No 3.2).

Within Research Stream RS2b the results for economic indicators have been combined with external costs to produce total costs for the full set of 26 NEEDS technologies, and the results for the full set of environmental, economic and social indicators have been combined with stakeholder preferences to produce individual rankings. These stakeholders include a broad representation of many different viewpoints, including electricity producers, small and large customers, environmentalists, regulators, scientists and individuals. The resulting individual and grouped rankings have then been compared to the total cost rankings.

The total cost approach (including both direct, or internal, and external costs) has been based on the information estimated within other research streams. The Multi-Criteria Decision Analysis (MCDA) approach has involved creating a structured framework to combine the performance of competing technologies (based on criteria performance measured by “indicators” or “metrics”) with new methodologies created for the multi-criteria assessment of discrete alternatives. These indicators may be either quantitative (determined with relative objectivity) or qualitative (assigned a value, but based on more subjective judgment).

Work Package 5 within NEEDS Research Stream RS2b has had the task of combining economic data from other Research Streams and independently developed economic results to produce a range of quantitative and qualitative economic indicators. These indicators have been produced for each of the four countries used in the NEEDS assessment; France, Germany, Italy and Switzerland, using modifications related to country-specific boundary conditions. This work builds upon the results of many other Work Packages in other Research Streams that have been documented in the relevant references that are included in the remainder of this report, which is organized as follows.

Chapter 2 describes the economic indicators, including a brief description of indicator requirements, an overview of the indicators chosen, general methodology, data scenarios and sources, and country-specific adjustments.

Chapter 3 gives a brief listing of the NEEDS technologies and their characteristics necessary to understand the indicator results, as well as links to references for more complete technology documentation.

Chapter 4 contains the main presentation of indicators, any necessary discussion of indicator-specific methodology, graphical representation of the results, and discussion of any patterns based on technology, energy source or country.

Chapter 5 then concludes with an overall discussion of the economic results and their contribution to Research Stream RS2b.

2 Discussion of Economic Indicators

This chapter includes a brief description of indicator requirements, an overview of the economic indicators previously chosen within this Research Stream, a description of the general methodology for the economic analysis, a description of the different technology development scenarios and which one was chosen, a listing of the different data sources and references, and a brief description of the country-specific adjustments.

2.1 Indicator Requirements

The structure and process of designing or selecting a set of sustainability indicators is a relatively complex process, with scientific, functional and pragmatic requirements that may often compete with one another (just as the indicators themselves do). This process of choosing and defining the economic indicators is fully described in a prior report (Bachmann, et al, Deliverable D5.1 - RS2b, "Final report on the establishment of economic indicators"). Table 1 below (slightly abridged from the prior report) describes the goals and their interpretation as applied in RS2b.

Table 1 – Criteria and Indicator Requirements (Hirschberg, 2006)

Criteria & indicators should…	**This study's interpretation**
a. 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.
b. 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').
c. 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.
d. Avoid excessive overlap.	– Indicators should be as independent as possible. Overlapping or double-counting indicators may introduce bias.
e. 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.
f. 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.

2.2 Overview of Economic Indicators

This section presents a summary list of the economic criteria and indicators used in RS2b, their hierarchical structure and units. As mentioned in the previous section on indicator requirements, the previous report in Work Package 5 (Bachmann, et al, ibid) discusses in full the choice, development and definition of the individual criteria and indicators listed below in Table 2. The results for each indicator are discussed below in Chapter 4.

Table 2 - Economic Indicators used in Research Stream RS2b.

CRITERION / INDICATOR	POTENTIAL IMPACT	UNIT
Economy		
Impacts on Customers		
Price of Electricity	Average cost of generation	EUR/MWh
Impacts on Overall Economy		
Employment	Direct Jobs	Person-years/GWh
Autonomy of electricity generation	Medium to long term independence from imports, based on domestic energy storage and/or resources	Ordinal
Impacts on Utility		
Financial Risks		
Capital Investment Exposure	Total capital cost	Euro
Impact of fuel price changes	Sensitivity to fuel price changes	Factor
Risk due to changes in boundary conditions	Construction time	Years
Operation		
”Merit order” for dispatch purposes	Total average variable cost or “dispatch cost”	Euro ¢/kWh
Flexibility of dispatch	Composite indicator	Ordinal
Availability	Equivalent Availability Factor	Factor

The criteria are structured in a four level hierarchy. The top level contains the three dimensions (or “pillars”) of sustainability; in this case it is the economy.

The top level of the economic criteria hierarchy is subdivided into three classes, relating to whether the economic aspect concerns individual customers, the overall economy, or the utility company operating the generator. Utility indicators are further subdivided into the areas of financial risk and operating characteristics. At the lowest level, each criterion has a corresponding indicator that has been quantified either analytically or by expert judgment.

Although the hierarchy contains four levels, some branches of the hierarchical tree only have three levels. For example, the price, employment and autonomy indicators above only go down to the third level. The four-level hierarchy is also used as the basic framework for the environmental and social dimensions of sustainability with some similar exceptions.

2.3 Data Scenarios

Although the focus in NEEDS is on technology analysis, and not on scenario analysis of the future electricity sector, it is generally impossible to forecast future technology price and performance without at least some scenario related assumptions. For this reason and the medium to long time horizon of 2050, the various research teams in RS1a contributing to technology analysis created three scenarios and used them to make cost and performance predictions for each technology. These scenarios were designated as;

1. Pessimistic
2. Realistic/optimistic ("baseline")
3. Very optimistic

The pessimistic and very optimistic scenarios were intended to define and model the expected extremes of technology development, and therefore the upper and lower limits of possible advances. The realistic/optimistic scenario was based on each research team's estimation of what the most likely developments might be, and was therefore used as the basis for the development of the economic indicators (as well as the environmental and social indicators also used in the multi-criteria analysis). However there was no harmonization between the different research teams in RS1a, so the realistic/optimistic scenario for one technology may not necessarily be consistent with the realistic/optimistic assumptions made for another technology (e.g. nuclear or fossil systems v. renewables, or different renewables compared to each other).

2.4 Data Sources

The majority of the economic indicators (5 of 9) were based in large part on the economic technology characteristics contributed by research partners in RS1a. Table 3 below lists the different families of generation technologies and the associated NEEDS partners responsible for providing the data. The partners were asked to specify the following indicator values in a MS Excel spreadsheet template:

- electric capacity (net), net electric efficiency, investment costs (overnight capital costs), fixed operation and maintenance costs, variable operation and maintenance costs, technical lifetime, full load hours per year, expected electricity production per year, description of a typical site (e.g. industrial area, uninhabited area, integrated in an existing building, or distance offshore from coast), and the area covered by the power plant (complete site);
- in the case of cogeneration: thermal capacity (net) and net thermal efficiency;
- fuel chain (if applicable): type of fuel, lower heating value LHV, fuel costs, origin of fuel, consumption per year.

Table 3 - Partners Providing Technical/Economic Data on NEEDS Technologies

Technology	**Main NEEDS partner responsible**	**Reference**
Nuclear	EDF	Lecointe et al. (2007)
Advanced fossil systems	PSI and USTUTT.ESA	Bauer et al. (2009)
Fuel cells	POLITO	Gerboni et al. (2008)
Photovoltaic	Ambit	Frankl et al. (2005)
Concentrating solar thermal power plants	DLR	Viebahn et al. (2008)
Offshore Wind	ELSAM (now: DONG Energy)	Dong (2008)
Biomass (CHP)	IFEU	Gärtner (2008)

All other economic indicators were estimated by the authors of this document. The individual economic indicators, methods and data sources are described in Section 4 below.

2.5 Country Specific Adjustments

There are a number of reasons why the economic indicator results may vary between the four different countries included in the analysis. These reasons fall into the main three categories described below. Environmental conditions assumed to differ by country can affect the broad range of environmental indicators, but except for the effect of average temperature discussed below they do not generally affect the economic indicators.

- *Resource availability:* Some technologies were eliminated from consideration as future technology options in 2050 based on assumed resource availability in a given country. The largest case of this assumption was for the fuel lignite. It was assumed that there would be no commercially available sources of lignite for Italy and Switzerland. Because lignite has a low energy content by weight, plants are normally located within a relatively short radius of a surface mine (often with transport by conveyor belt). Italy and Switzerland were assumed to have no lignite mines in 2050. Similarly the relatively low quality of the solar resource in Germany and Switzerland is the reason for eliminating the solar thermal technology (parabolic trough collectors), although solar photovoltaic technologies were retained. Offshore wind was also eliminated from landlocked Switzerland. It may be noted here that onshore wind, and hydro were also eliminated from consideration in 2050, since these technologies were not covered in the LCA stream of NEEDS, which only addressed advanced electricity generation options.

  Resource availability is also linked to fuel transportation assumptions for the upstream part of affected technology chains, including the mix of fuel from different locations (e.g. natural gas).

- *Resource quality:* Hours per year of operation were assumed to vary by country for both wind and solar technologies, based on country-specific weather conditions. The resulting changes in annual capacity factor can significantly affect economic results for renewables that are characterized by high capital costs and zero fuel costs.

- *Thermal efficiency:* Weather conditions (i.e. average annual ambient temperatures) were also assumed to affect the generation efficiency of technologies relying on thermal cycles where waste heat must be rejected to the environment. High summer temperatures can lead to derating (reducing) generation capacity, but this factor was handled by assuming that thermal efficiencies were approximately 3% lower in Italy, as compared to France, Germany and Switzerland. This assumption ignores climate variations within countries, but it was judged better to at least acknowledge the major differences between northern and southern Europe. Lower efficiency implies higher fuel consumption and higher results for a range of indicators related to the fuel supply chain. Non-thermal technologies were not affected by this assumption.

The country-specific changes described above are specifically summarized in Table 4 below.

Table 4 – Country-Specific Assumptions for Economic Analysis

Country-specific Assumption	**Country** France	 Germany	 Italy	 Switzerland
Resource availability				
Lignite	√	√		
Solar thermal	√		√	
Offshore wind	√	√	√	
Resource Quality (h/a)				
Offshore wind	4000	4000	3500	-
Solar PV	984	809	1032	922
Thermal Efficiency	-	-	-3%	-

3 Discussions of NEEDS Technologies

3.1 NEEDS Technology List

Twenty six technologies were selected for the NEEDS Integrated Project as possible electricity generating sources in 2050, based on a broad range of primary energy carriers, under the ‘optimistic/realistic’ development scenario. Only technologies for which sufficient research and testing have already been undertaken were selected.

Table 5 below lists these technologies and gives each a relatively brief abbreviation. These abbreviations as used as the technology labels in the graphs of indicator results presented in Chapter 4, and the technologies are also graphed in the same order from left to right.

Table 5 - NEEDS Technology Names and Abbreviations

PRIMARY ENERGY	TECHNOLOGY	ABBREVIATION
Nuclear	European Pressurized Reactor	EPR
	European Fast Reactor	EFR
Fossil	Pulverized Coal	Hard coal PC
	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
	Gas Turbine Combined Cycle	Nat. gas CC
	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
Biomass	Molten Carbonate Fuel Cell using wood derived gas 0.25 MW	MCFC wood gas
Fossil	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

3.2 NEEDS Technology Characteristics

Table 5 below gives a summary of the most economically relevant characteristics for the 26 NEEDS technologies, based on the realistic-optimistic development scenario (see above) for the year 2050.

These 26 technologies are described in the NEEDS RS2b database report, 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, Deliverable D3.10 - RS2b, "Final Report on Combined Indicators Database"). For full reference material on individual technologies, the reader is referred to the NEEDS website -

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

One particular caveat may be mentioned in connection with the technology data, and therefore the economic results in general. As mentioned above, the basic economic assumptions have been taken from the "realistic-optimistic" scenario for 2050, but the scenario description does not have a strict or consistently enforced definition between the various collaborators. In addition, some technology developments are simply considerably more speculative than others. In general of course the newest technologies are the least certain and the hardest to extrapolate out to 2050. So the degrees of "optimism" contained in the data may vary significantly (e.g. between renewables and more conventional fossil technologies).

Table 6 – NEEDS Technology Characteristics

		1	2	3	4	5	6	7	8	9	10	11	12
		Nuclear Plants		**Advanced Fossil**						**Integrated Gasification Combined Cycle**			
		EPR	**EFR**	**PC**	**PC-post CCS**	**PC-oxyfuel CCS**	**PL**	**PL-post CCS**	**PL-oxyfuel CCS**	**IGCC coal**	**IGCC coal CCS**	**IGCC lig**	**IGCC lig CCS**
Characteristics	**Units**	European Pressurized Reactor	Sodium Fast Reactor (Gen IV Fast Breeder Reactor	Pulverized Coal (PC) steam plant	Pulverized Coal (PC) plant with Carbon Capture & Storage (CCS), post combustion	Pulverized Coal (PC) plant with Carbon Capture & Storage (CCS), oxyfuel combustion	Pulverized Lignite (PL) steam plant	Pulverized Lignite (PL) plant with Carbon Capture & Storage (CCS), post combustion	Pulverized Lignite (PL) plant with Carbon Capture & Storage (CCS), oxyfuel combustion	Integrated Gasification Combined Cycle (IGCC)	Integrated Gasification Combined Cycle (IGCC) with Carbon Capture & Storage (CCS)	Integrated Gasification Combined Cycle (IGCC)	Integrated Gasification Combined Cycle (IGCC) with Carbon Capture & Storage (CCS)
Type of fuel		U235, 4.9%	Mixed Oxide	hard coal	hard coal	hard coal	lignite	lignite	lignite	hard coal	hard coal	lignite	lignite
Electric efficiency	%	0.37	0.4	0.54	0.49	0.47	0.54	0.49	0.47	0.545	0.485	0.525	0.465
Electric generation capacity	MW	1590	1450	600	500	500	950	800	800	450	400	450	400
Load factor (expected hours/yr)	hours/year	7916	7889	7600	7600	7600	7760	7760	7760	7500	7500	7500	7500
Annual generation (expected)	kWh/year	1.26E+10	1.14E+10	4.56E+09	3.80E+09	3.80E+09	7.37E+09	6.21E+09	6.21E+09	3.38E+09	3.00E+09	3.38E+09	3.00E+09
Construction time	years	4.8	5.5	3	3	3	3	3	3	3	3	3	3
Capital cost (net present value)	€/kWe	1498	1900	983	1560	1560	989	1560	1560	1209	1505	1209	1209
Total capital cost (net present value)	M€	2383	2756	590	780	780	939	1248	1248	544	602	544	483
Plant life	years	60	40	35	35	35	35	35	35	35	35	35	35
Average cost of electricity	€cents/kWhe	3.01	2.68	2.96	3.94	4.00	3.01	4.08	4.16	6.17	7.26	6.57	6.78

		13	14	15	16	17	18	19	20	21	22	23	24	25	26
					Fuel Cells				**Biomass CHP**		**Solar**				**Wind**
		GTCC	**GTCC CCS**	**IC CHP**	**MCFC NG**	**MCFC wood gas**	**MCFC NG**	**SOFC NG**	**CHP poplar**	**CHP straw**	**PV-Si plant**	**PV-Si building**	**PV-CdTe building**	**Solar thermal**	**Wind-offshore**
Characteristics	**Units**	Combined Cycle	Combined Cycle with Carbon Capture & Storage (CCS), post combustion	IC engine cogeneration	Molten Carbonate Fuel Cells, natural gas	Molten Carbonate Fuel Cells, wood gas	Molten Carbonate Fuel Cells, natural gas	Solid Oxide Fuel Cells (tubular, natural gas	Steam turbine cogeneration, short rotation forestry poplar	Steam turbine cogeneration, agricultural waste wheat straw	PV, Mono-crystalline Si, Plant Size	PV, Mono-crystalline Si, Building Integrated	CdTe, Building Integrated	Concentrating solar thermal power plant	Wind
Type of fuel		natural gas	natural gas	natural gas	natural gas	wood gas	natural gas	natural gas	SRF poplar	waste straw	sun	sun	sun	sun	wind
Electric efficiency	%	0.65	0.61	0.44	0.5	0.5	0.55	0.58	0.3	0.3	0	0	0	0.185	0
Electric generation capacity	MW	1000	1000	0.2	0.25	0.25	2	0.3	9	9	46.6375	0.4197375	0.839475	400	24
Load factor (expected hours/yr)	hours/year	7200	7200	5000	5000	5000	5000	5000	8000	8000	984	984	984	4518	4000
Annual generation (expected)	kWh/year	7.20E+09	7.20E+09	1.00E+06	1.25E+06	1.25E+06	1.00E+07	1.50E+06	7.20E+07	7.20E+07	4.59E+07	4.13E+05	8.26E+05	1.81E+09	9.60E+07
Construction time	years	3	3	1	0.83	0.83	0.83	0.83	2	2	2	0.5	0.5	3	2
Capital cost (net present value)	€/kWe	440	615	879	1544	1544	1235	1030	2280	2280	848	927	927	3044	1130
Total capital cost (net present value)	M€	440	615	0	0	0	2	0	21	21	40	0	1	1217	27
Plant life	years	25	25	20	5	5	5	5	15	15	40	40	35	40	30
Average cost of electricity	€cents/kWhe	5.99	8.69	11.10	8.74	8.44	7.29	6.73	7.29	6.51	6.30	6.92	7.15	6.31	7.27

4 Economic Indicators and Results

Chapter 4 presents and discusses the results of the economic analysis for each of the nine economic indicators. This discussion includes;

- The purpose of the indicator and what it measures,
- How it was developed and calculated (methodology),
- What are the results, including any patterns by technology, resource or country

Some of this discussion necessarily recapitulates at least some of the material previously presented in the NEEDS RS2b Work Package 5 deliverable D5.1 (Bachmann, et al, Deliverable D5.1 - RS2b, "Final report on the establishment of economic indicators"). The reader is referred to this report for a full discussion of indicator development and definition. However, the current discussion includes enough of this material in context to make this report an understandable and stand-alone report.

When reading the graphs below it is helpful to remember two comments.

- When looking at the graphs below, recall that some columns are missing because the technology is absent from some countries (see Table 4 above).
- It was necessary to abbreviate the technology name labels for each group of 4 columns in the graphs below due to limited space. These abbreviations were made as understandable as possible, given the size constraints, but remember to see Table 2 above for the abbreviation key if any are too cryptic.

4.1 Average Generation Cost (EUR/MWh)

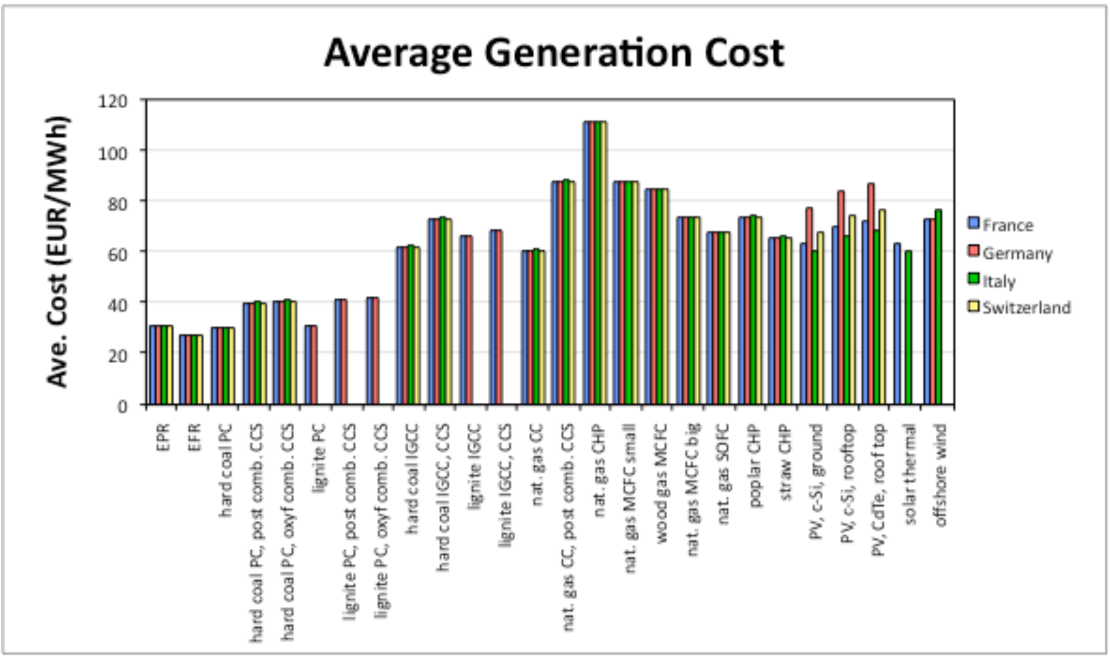
The average generation cost is the basic measure of the internal cost of electricity. To calculate it, the capital cost of the plant is taken (or calculated from the cost per kilowatt times the plant capacity), and then levelized over the lifetime of the plant using an interest rate of 6%. This gives the fixed annual capital cost over the life of the plant (in constant Euros). For the NEEDS project, a slight variation was necessary. The capital costs for each technology were given as "overnight costs," i.e. expenditures for all years over the construction period were simply added together. This ignores the time value of money, that is, the interest that must be spent during construction. This can be significant for expensive plants with long construction period such as coal, or especially nuclear plants. To correct for this effect, the overnight costs were allocated across the construction period using a construction trajectory profile. The annual costs were then discounted forward to the start of operation, and levelized across the plant life as normal. On top of the annual capital costs are added annual fixed and variable operation and maintenance costs (FOM and VOM), and fuel costs (where appropriate). Total annual costs are divided by annual generation, based on plant capacity and assumed capacity factor (hours/year). From this calculation, it can be noted that the capacity factor (hours/year of operation) is a key assumption, particularly for plants with large capital costs and low or zero fuel costs, like nuclear plants and renewables like wind and solar (the main difference is that nuclear capacity factors are subject to improvement and now high, while most renewable capacity factors are low and limited by resource availability at the chosen site).

The average generation cost is valuable as a proxy for the cost to the customer, but the full cost includes grid costs and utility overhead costs (general and administrative). Taxes, profit, and cross subsidies are also included in the consumer's price. Nevertheless, the average cost of generation is of fundamental interest to stakeholders.

Looking at Figure 1 below, we can see that the low end of the range of average costs is dominated by the nuclear technologies, followed by the coal and lignite plants. For the coal, lignite and gas plants, it is worth noting the increase in average costs caused by the addition of carbon capture and storage systems, with the associated loss of plant efficiency. Continuing across the graph, the highest average cost belongs to the small, distributed cogeneration units. The internal combustion and fuel cell cogeneration units receive a credit for the fuel value of the heat they co-produce, but this does not overcome the dis-economies of scale due to their small size. The larger fuel cells and centralized biomass cogeneration plants are again lower in cost due primarily to their lower size. What is most remarkable about this graph is the fact that renewables, and in particular solar photovoltaics are so cheap. This requires a strong learning curve to be climbed by the year 2050, and may lie on the optimistic end of the optimistic/realistic scenario.

Regarding country differences, it may be noted that the effects of lower thermal efficiency for combustion plants in Italy is barely noticeable, but the effect of different capacity factors (hours/year) for wind and solar in the four different countries is clearly visible and significant.

Figure 1 – Average Generation Cost



4.2 Direct Labor (Person-years/GWh)

This indicator is defined as the amount of direct labor required for each technology chain, averaged over the total generation for the planned life of the plant. It is measured by the average amount of labor in person-years per GWh. Direct labor includes the labor required to build, operate and decommission the plant, and to extract or harvest, process and deliver the fuel. Direct labor does not include the indirect labor content of components or materials supplied to the plant or fuel cycle. This measure also does not include any indicator of whether the jobs are part or full time, the pay or quality of the jobs, or job-related risk (for which the reader is referred to the social indicators). Whether it is more desirable to minimize or maximize the labor content of an energy technology may depend upon the stakeholder's point of view. For the purpose of the multi-criteria decision analysis (which requires a scale direction for each indicator), it was assumed that more jobs were better.

Methodology – Labor calculations were made for each technology for fuel extraction, fuel transport, plant construction and plant operation (generation). Because of the relatively long time horizon, a number of general assumptions were made that tended to level country differences, as listed below. It should be noted that labor calculations are of course subject to the same uncertainties as other economic calculations, including learning curves, international trends and other factors. The labor results are therefore best viewed in relative terms rather for than absolute precision.

General assumptions -

1. It was assumed that amount of labor to build and operate a technology is fixed based on the technical specification in 2050. Maturing technologies follow a learning curve of decreasing cost and labor until reaching their 2050 specification.
2. It was assumed that it will take the same amount of labor to build and operate a technology in all of the four NEEDS countries. This is based on an assumption of similar capital to labor cost ratios in these countries.

Technology specific data and sources – In addition to these general assumptions, specific assumptions were made for the following technology groups.

1. Nuclear – General nuclear assumptions include;
    - It was assumed that France, Germany, Switzerland & Italy have so little native uranium that in 2050 this will be imported from the international market, and hence all have the same labor contents for production.
    - The EPR and EFR fuel cycles were based on prior work at PSI, using averaged mining and processing data (Cameco), and centrifuge enrichment for the EPR (Urenco). Reprocessing labor was included, but fabrication labor and waste disposal labor were considered negligible.
    - Fuel transport labor was considered negligible due to the very high energy content of the fuels.
    - Construction labor for the EPR (in man-yr/MWe) was assumed to be the same as for Gen III and III+ units.
    - The EFR labor requirements were assumed to be proportional to their cost, i.e. the man-yr/€ spent is assumed to be constant for both EPR and EFR.
    - An EFR life of 40 years was assumed to be conservative. A life 40 v. 60 years makes a relatively small difference in discounted costs with 6% interest, but the average labor content was not amortized. This contributes to the higher labor content for the EFR.
    - O&M is not necessarily directly proportional to MWe. Based on the NEI average for new plants and the DOE average for 2 Gen III+ units at one site, a plant workforce of 550 was chosen.

    Construction and operation labor data sources (DOE, Nuclear Energy Institute, Clean and Safe Energy Coalition) were also checked online against labor estimates in the online popular press for 10 planned new nuclear plants in the U.S.

2. Coal/lignite – Assumptions included;
    - France, Italy & Switzerland have no coal production, so labor content was based on a blend of imports. Most coal historically imported to Germany has come from S. Africa, Poland and the US, so these are the most likely sources for the future. Shipping costs mean that coal would likely come from the "Atlantic market" by ship, or by rail from Eastern Europe.
    - Germany has significant coal reserves (producing 84% of domestic demand in 2006), but domestic production has been declining due to non-competitive costs. It seems likely that German labor will remain expensive, and that mining will continue to decrease, or that the remaining mines will be automated to a labor content that is at most equal to the global standard.
    - Mining productivity for all four countries was therefore assumed to be equal by 2050, including domestic production and imports.

- Mining productivity will continue to improve at a rate roughly equivalent to available past data (US and Australia). The countervailing factor here could be a loss in productivity due to lower quality reserves, but in the past productivity gains have increased quickly enough to overcome this trend.
- Ship, train, conveyor labor were considered negligible based on sample calculations of direct labor (not infrastructure), based on crew sizes, trip lengths and times and payloads. For this reason, country differences based on the weighted average distances from coal resources were also ignored.
- Construction – The basic assumption was that all the coal plants have the same labor per Euro of capital cost, with any economies of scale already reflected in the average capital cost (€/kW). Units with CCS include 400 km of pipeline and CO_2 wells in this capital cost.

Data sources included a survey of US and Australian productivity trends, total employment and production figures for Atlantic trade producers like S. Africa, and cross reference to REPP 2001 (Singh, et al.).

3. Natural gas – Assumptions included;
   - It was assumed that France, Germany, Switzerland & Italy have so little natural gas that in 2050 this will be imported from the international market, and all have the same labor contents for production.
   - The gas production labor was based on sectoral employment, rather than direct labor to drill and produce at the well. This was because oil and gas are co-produced, so sectoral labor was split based on their relative shares.
   - Weighted average transport distances in Europe from producers to the four countries considered were approximately the same as transport distances in the US where there were much better sectoral employment numbers for the gas transport network, so this was used as the basis for transport labor.
   - The construction and operation labor content for the CCGT was assumed to be the same per Euro of capital cost as for a coal steam plant, based on similarities in site, components, occupational or trade mix, etc. Again, the CCGT CCS technology included the cost and labor for the CO_2 pipeline and sequestration.
   - Small engine cogeneration construction labor was based on engine plant productivity using an online survey of new plant construction stories in the press. This labor was doubled to account for auxiliary components and doubled again for installation in a new building. Operation labor was based on estimated annual maintenance.
   - Fuel cell construction labor content was probably the least certain of all technologies considered due to very little actual production experience to date, and large uncertainty about the learning curve (which is much less optimistic than for PV). This is further complicated by uncertainty about FC lifetimes, where premature failures can drive up the average construction labor contribution.

4. Biomass - Assumptions included;
   - The labor content of biomass fuel was based on the REPP 2001 (Singh, et al.) report, except that for waste wheat straw the labor estimate for switchgrass was adjusted by subtracting the labor to grow the crop, since this labor was allocated to the wheat production.
   - The labor to build and operate the biomass power plants was regarded to be the same per Euro of construction cost as for coal plants.
   - The wood gas fuel cell was assumed to require the same labor to build and operate as a natural gas fuel cell.

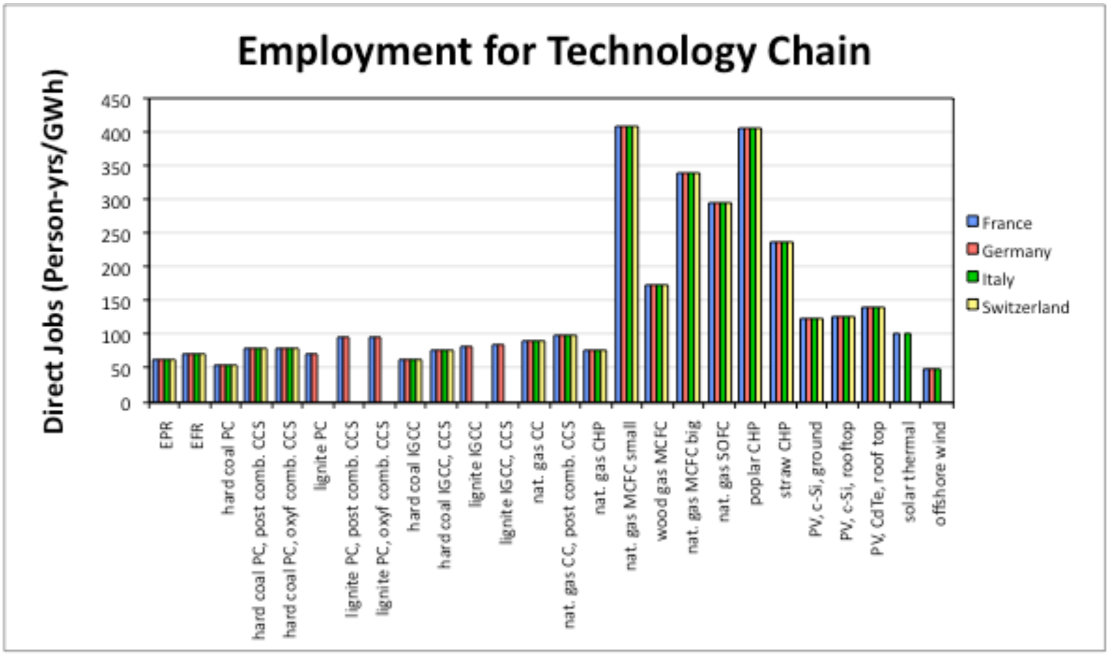
5. Solar/wind - Assumptions included;

   - Solar and wind fuel extraction and transport labor are of course zero.
   - Solar PV construction labor was based on REPP 2001 (Singh, et al.) but then adjusted downwards based on the technology learning curve assumed by the NEEDS partners supplying the capital costs. Labor was assumed to be proportional to cost for both PV types (c-Si and CdTe).
   - Solar thermal construction labor was based on conversation with a firm designing and building such plants (www.newenergypartners.com), but then adjusted upward based on perceived proportionality with other technologies.
   - Off shore wind construction labor content was also based on REPP 2001, but then adjusted from onshore to offshore siting based on prior work at PSI. Again, the labor content was assumed to decrease proportionally with the capital cost learning curve.

   Solar and wind data were also compared against other sources, including NREL (Tegen et al.), and UC Berkeley (Kammen, et al).

Results - The more conventional, non-renewable technologies (i.e. nuclear and fossil) require relatively little direct labor in their technology chains, reflecting the higher energy density of their primary energy resources, which affects both the fuel chain and plant size. The distributed generation and biomass labor content is higher, but also shows mixed results. The small engine cogeneration labor content is small, reflecting both the relatively higher energy density of natural gas and the very high labor productivity of engine manufacturing (most of the labor goes into onsite installation). On the other hand, the labor content for the distributed fuel cell cogeneration was quite high, reflecting the high cost and uncertainty related to the learning curve for this technology. Biomass labor is high, reflecting a lower energy density and labor intensity in harvest and transport, although this does depend on the biomass crop (straw, poplar or wood waste). Solar labor content is surprisingly low, reflecting the very positive learning curve assumed (labor was assumed to go down with costs). Solar PV labor content is higher than for the solar thermal technology due to smaller unit sizes. Offshore wind's labor content is low, reflecting manufacturing and emplacement labor for large turbines and countering the trend for other renewables.

Figure 2 – Direct Labor



There were no significant differences between countries, although the differences in transportation distances for fuels imported to the four NEEDS countries were considered. This shows that the average distances were relatively close and that the fuel transport labor was not dominant in the energy chain.

4.3 Independence from Foreign Energy Sources (Ordinal)

This indicator is intended to measure the relative safety from interruption of, or dependence on, foreign energy resources. Two elements were considered in determining this indicator: 1) whether the primary energy resource was foreign (imported) or domestic; and 2) whether the primary energy resource was exhaustible (fossil or nuclear) or renewable. This indicator was not explicitly calculated, but rather based on the rule incorporated in Table 7 shown below, using expert judgment to scale the relative value of the abundance and type of domestic fossil and nuclear resources.

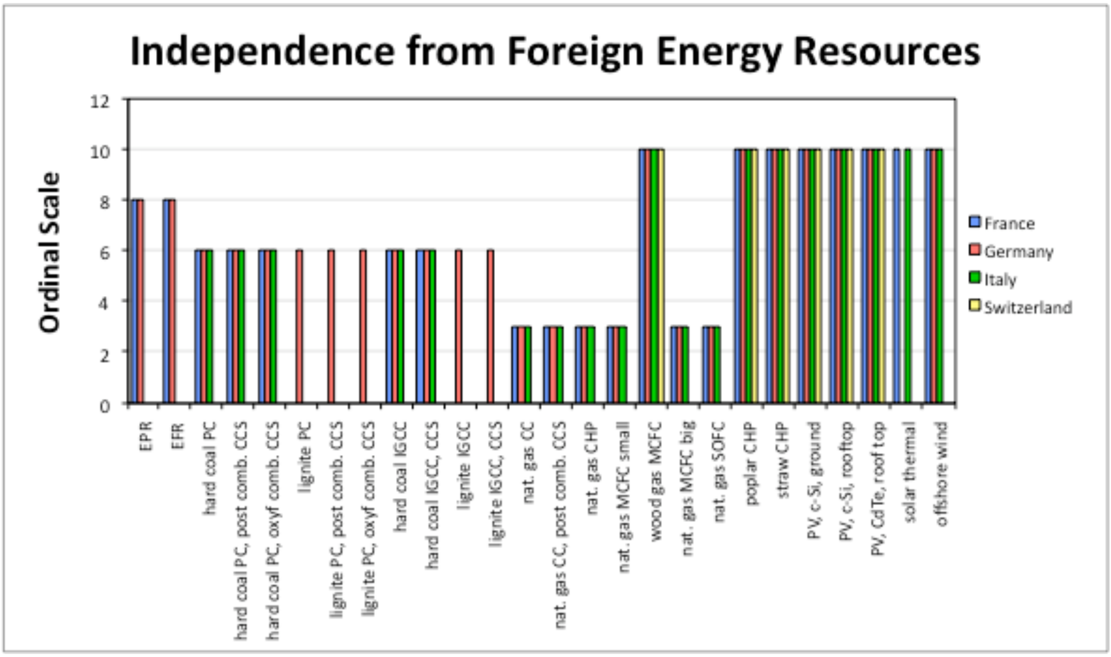
Table 7 –Independence from Foreign Energy Sources

Group name	Value	Description
Imported energy carrier	0	Technologies that rely on fuels or energy resources that must be imported.
Domestic oil	2	For oil-fired technologies in countries where domestic oil resources are available.
Domestic gas	3	For gas-fired technologies in countries where domestic gas resources are available.
Domestic coal	6	For coal-fired technologies in countries where domestic coal resources are available.
Domestic uranium	8	For nuclear technologies in countries where domestic uranium resources are available (includes extraction from seawater).
Domestic renewable energy resource	10	For technologies which rely on renewable energy fluxes present in a given country (e.g. hydro, solar, wind, wave and geothermal).

The graph for this indicator simply reflects the primary energy resource used by each technology and the rule in Table 7 above. Renewable (solar, wind and biomass) resources perform best in terms of energy source import independency, followed by nuclear, coal and gas units. No oil-fired technologies were present in the set of 26 NEEDS technologies considered for 2050. The results were strongly dependent on country, based on the presence of known domestic resources. Uranium extraction from seawater was assumed to be a possibility in 2050 for this indicator, so only landlocked Switzerland is missing uranium as a domestic resource. Germany and France were both assumed to have lignite as a domestic resource, although Germany could presumably support a greater market penetration of this resource. Switzerland lacks significant known coal, lignite and natural gas resources. All renewable energies are available in all countries, except the solar resource in Germany and Switzerland was assumed to be insufficient for solar thermal plants, and Switzerland has no offshore wind resource.

A number of alternative indicator formulations were originally proposed for this indicator involving the ability to stockpile resources or the lifetime of various energy reserves but these were ultimately rejected. This was in part based on the uncertainty of scenarios predicted for the year 2050, and the question of whether known or assumed future reserves and consumption rates should be chosen. The real problem however with these approaches was that the lifetime of renewable resources is effectively infinite (good of course, in itself). But this results in an effectively binary indicator that is one for renewables and zero for all other resources, ignoring the significant differences in the nearer term between nuclear and the various fossil resources.

Figure 3 – Medium to Long Term Independence from Foreign Energy Sources



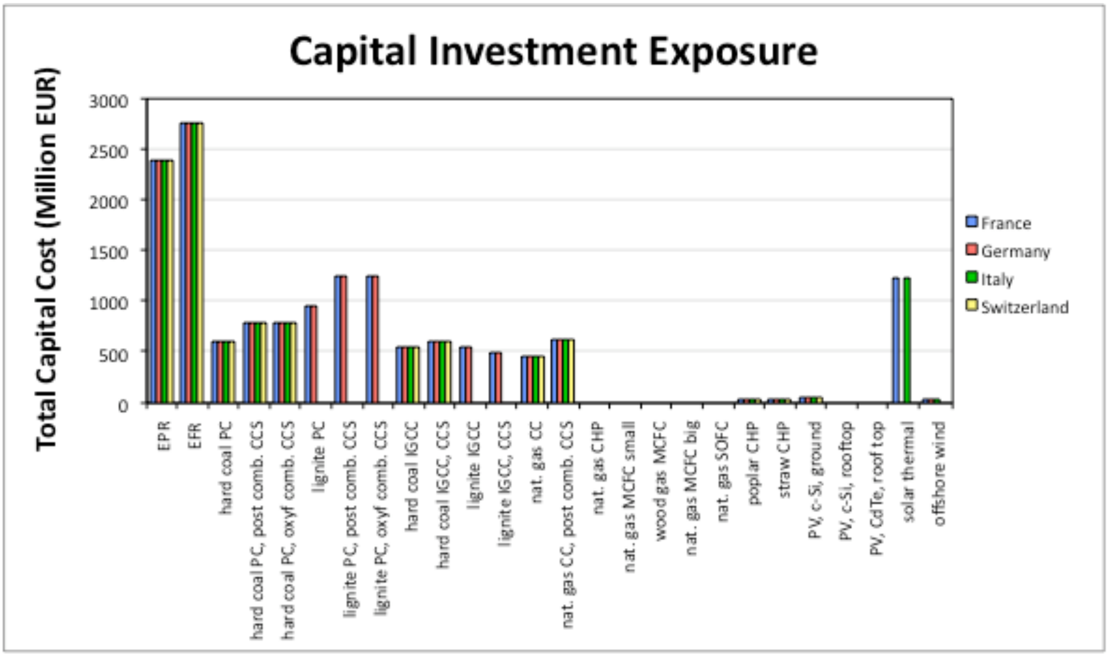
4.4 Total Capital Cost (Euro)

Two measures of the different aspects of risk related to building large and expensive power plants were included in the range of economic indicators, total cost and construction time. The total capital cost indicator is intended to measure the financing risk involved when a utility company commits to building an expensive generation plant. This risk can be very significant if the plant is large relative to the total size of the company, and often leads to shared ownership (e.g. of nuclear units) to spread the risk across several owners. The capital cost was supplied by the technology teams identified in Table 3 above, and did not require further analysis, except for the adjustment from overnight costs to present value costs described in Section 4.1 above in the discussion of average generation cost.

Notice that this indicator measures the total capital cost for a single unit, and not the average cost per kilowatt of capacity. This means plants with low unit sizes score well by this measure, even if they are very expensive on a capacity (per kilowatt) basis. This is appropriate because individually small units do not pose much financial risk to a company, and if conditions change then the risk of building a fleet of small units (e.g. wind turbines) can be limited by halting construction of the remaining units.

The biggest financing risk is related to building the nuclear technologies, with the EFR costing more than the EPR. This is relatively obvious, because total cost equals size (kW) times specific cost (EUR/kW), and the nuclear technologies are both large in size and relatively expensive per kilowatt. Of particular note are the cost premiums associated with carbon capture and storage for the coal, lignite and gas technologies, and the high total cost for the solar thermal plant compared to the solar PV units. The advantage of PV over solar thermal is because the individual solar trough collectors are connected to a large centralized generation unit with thermal storage, leading to a high total cost for the entire installation. No cost differences were assumed for construction in the four different countries in 2050, so there are not country differences in this indicator.

Figure 4 – Total Capital Cost



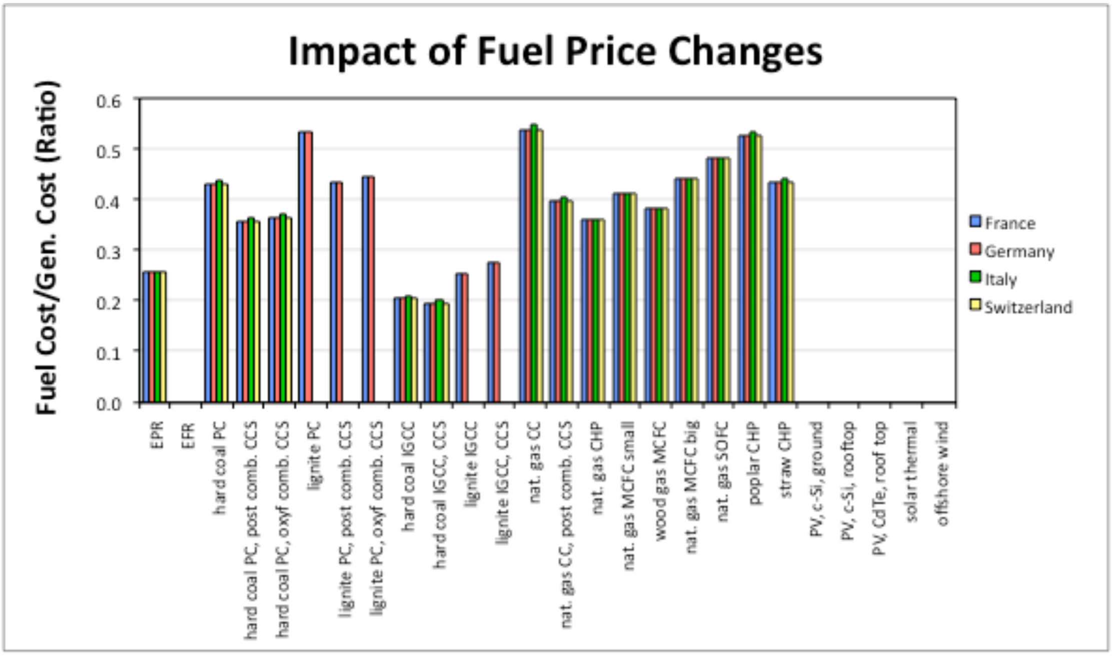
4.5 Impact of Fuel Price Changes (Factor)

This indicator measures the effect of fuel price changes on the cost of generation, and it was calculated using the ratio between the average cost of fuel per kWh and the average cost of generation per kWh. As the cost of fuel is of course part of the average cost of generation, the data for this ratio were already available from previous calculations (Section 4.1 above). This ratio was used rather than attempting to quantify the actual uncertainty or risk of fuel price volatility in 2050, which would have been more scenario dependent. This indicator therefore measures the *sensitivity* of the generation cost to the cost of fuel, rather than the *likelihood* that the fuel price may change.

The average cost of the fuel per kWh was based on the fuel delivered to the plant. An exception to this rule was made for the EFR, because the breeder reactor uses fuel reprocessed from spent nuclear fuel, and the value of this waste spent fuel was assumed to be zero. Renewables are split between solar and wind, which have a fuel cost that is zero, and biomass where cultivation and transport costs are relatively high.

The technologies least affected by fuel price changes are therefore the solar and wind technologies and the EFR. The IGCC plant with and without CCS is at or below the results for the EPR, which reflects both the high capital cost of the IGCC, and the relatively high fuel price assumed for the EPR. The pulverized coal and lignite plants also show the same effect of high capital costs reducing the fuel price sensitivity ratio, with lower values as expensive capital costs carbon capture and storage were added into the average cost. Natural gas and biomass plants have the highest fuel price sensitivity ratio. Country differences in the thermal efficiency of combustion affect the fuel cost more than the average cost in this ratio, and are small but visible.

Figure 5 – Ratio of Fuel Cost to Generation Cost



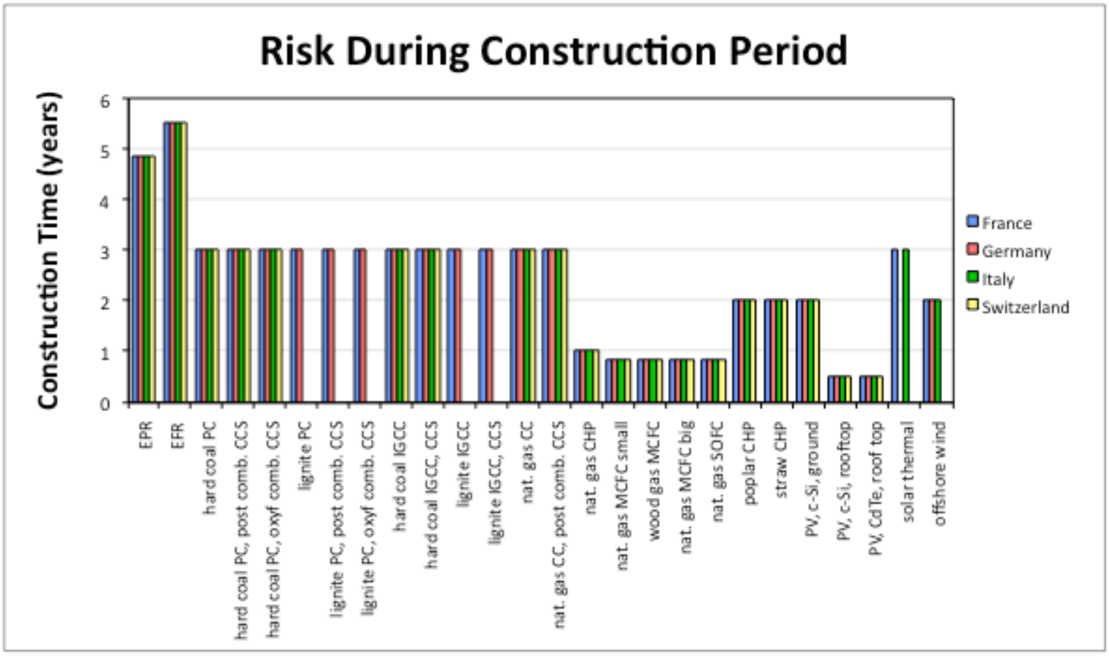
4.6 Construction Time (Years)

The measure of construction time is the second economic indicator linked to the investment risk of constructing large, lengthy generation projects. This indicator is specifically linked to the risk that conditions bearing on the decision to build might change during the construction period. This has historically been particularly true in the case of nuclear construction projects where political opposition, referenda, or safety or environmental regulations, etc. could lead to either cancellation of construction or costly design changes. The total capital cost indicator (how much is at risk) is linked to the construction period indicator (how long is it at risk). These factors often co-exist and exacerbate company risk exposure.

Nuclear plants, followed by large coal and lignite plants, have the longest construction time. The nuclear plant construction times (less than 5 year s for the EPR and about 5 ½ year for the EFR) are relatively low compared to historical experience where political opposition delayed construction and drove costs up. These construction times are based on pre-approved designs built on aggressive schedules to keep costs down. Current experience with the first EPR project in Finland has exhibited delays, but series construction experience by 2050 should reduce current uncertainty in this regard.

Note that shorter construction times are reasonably linked to small unit sizes for the distributed cogeneration and renewable projects. The longer construction time for the solar thermal technology is linked to the large overall unit size (as opposed to individual solar dish Stirling units), and the longer construction time for offshore wind is linked to the time required to fabricate and place the units offshore, including submarine cables and onshore power substations.

Figure 6 – Construction Time

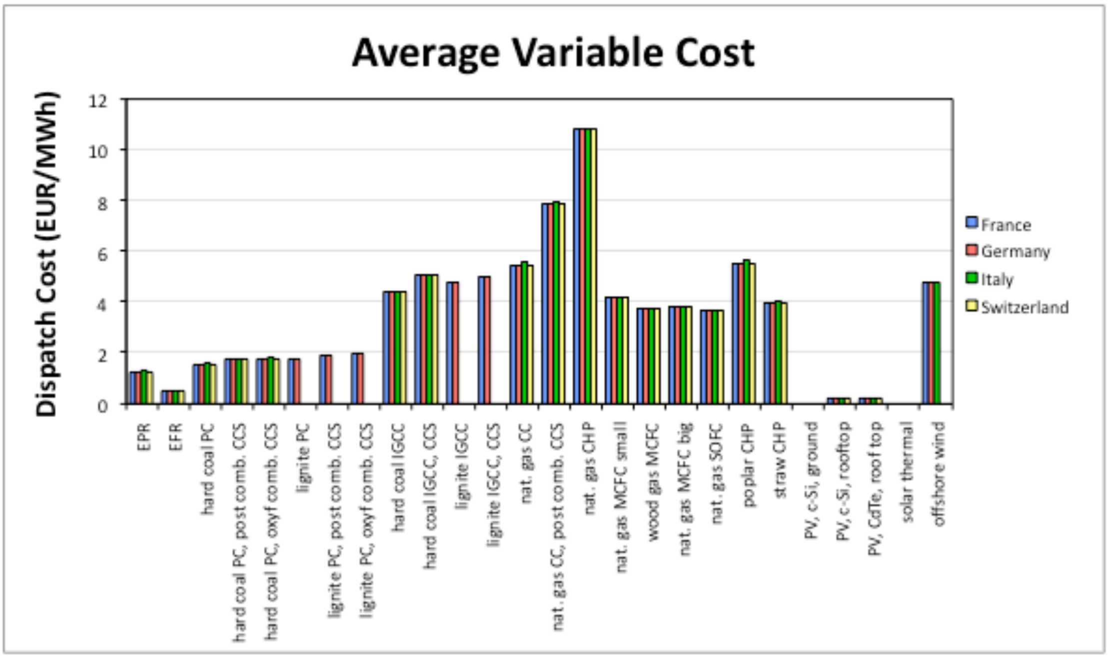


4.7 Average Variable Cost (EUR ¢/kWh)

The average variable cost of generation is the marginal cost of generating a kWh of electricity from a plant. This variable cost is composed of variable operation and maintenance costs (the wear-and-tear cost of operation) plus the fuel cost per kilowatt-hour. This cost is important, because it is the marginal cost of generation (or "dispatch cost") that determines the order in which plants are put into operation ("dispatched"). The last plant dispatched also determines the marginal generation cost for the entire system, which has important effects on overall system operation including the determination of peak or time-of-day tariffs, or the prices for shedding dispatchable loads or charging electric vehicles. For these reasons the average cost of generation for individual technologies may be of interest to a wide range of stakeholders. The components of variable cost do not need to be separately calculated, because they are already part of the calculation of the average cost of generation discussed in Section 4.1.

The best performing techniques in terms of dispatch costs are solar technologies where the fuel costs are zero, and nuclear plants where fuel costs are low. Notice that the variable cost of generation for the solar technologies is only variable O&M, and often the split between fixed and variable O&M can be difficult to determine. Also note the significant cost difference between the nuclear EPF and EFR technologies, reflecting the difference in fuel cycles between the burner and breeder reactors. Although the low variable cost of these technologies would promote their dispatch, in reality their flexibility is reduced by the fact that the nuclear units are base load plants that basically run whenever they are available (i.e. they are always already dispatched), and the solar resource is not controllable. These technologies are followed in the dispatch order by the pulverized coal and lignite plants, the IGCC technology, and finally the natural gas, biogas and biomass technologies. Variable cost for the offshore wind technology is relatively high, reflecting the expected high cost of offshore maintenance. The effects of lower thermal efficiency for combustion plants in Italy are more visible for variable cost than for average cost (where the effect is diluted by the levelized capital costs), but the effect is still quite small and barely noticeable.

Figure 7 – Average Variable Cost of Generation

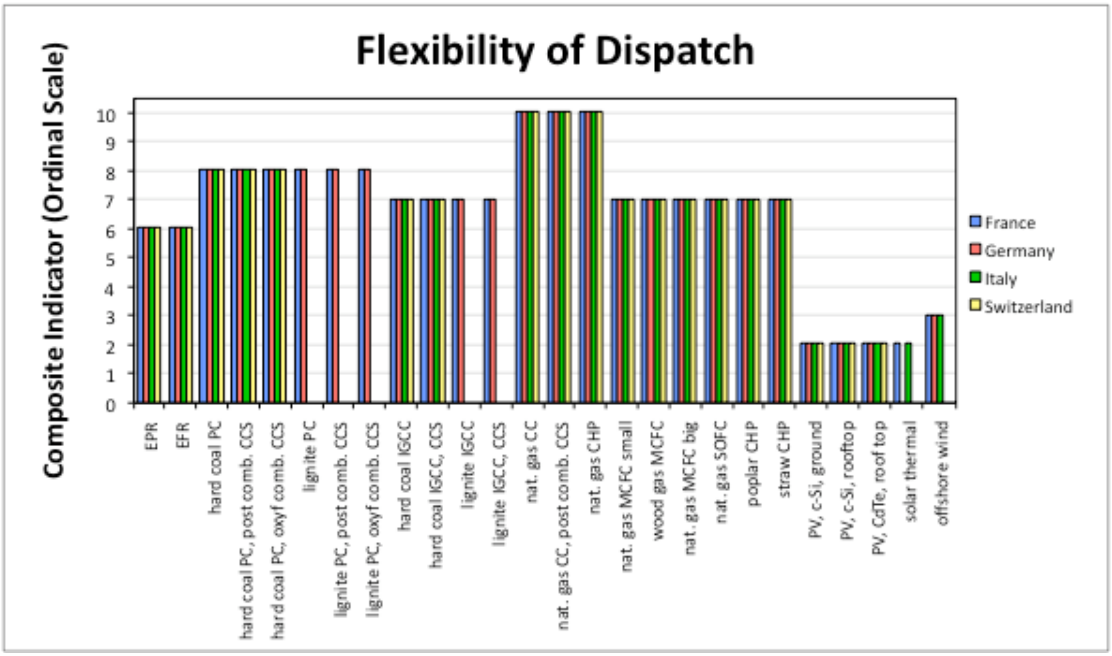


4.8 Flexibility of Dispatch (Ordinal)

Flexibility of dispatch is an indicator that is based on two factors that concern power system operators – how predictable is future generation from plants they do not control, and how far in advance must they decide to operate (dispatch) plants they can control. Both predictability and dispatchability are non-linear in nature. For example, if a refueling outage or long range weather prediction is known far in advance then changing this by an hour or two will have little effect. But if a system operator is deciding what plants to dispatch to meet the load predicted for the next hour, then at least one hour of predictability or control is required. Note that the desired direction of the time scale is reversed for these two factors – for predictability longer advance notice is better, and for dispatchability a shorter necessary control time is better. Due to the complexity of balancing all these factors, this indicator was based on expert judgment rather than calculated. For the purposes of system control, dispatchable plants are preferred to non-dispatchable resources. For this reason, the dispatchable plants were given values between 6 and 10, with the shortest control times being the highest, and non-dispatchable technologies were given values between 1 and 5 with the longest prediction times being highest.

The results for this indicator show that the large natural gas combined cycle plants and small natural gas fueled internal combustion engine cogeneration units have the fastest response times. This assumes that in 2050 the distributed generation will be remotely controlled either directly or by price signals. The coal and lignite technologies were next in their response time, followed by the IGCC units and nuclear. The IGCC units were assumed to be slower in their response times than pulverized coal plants due to increased time lags due to the gasifier, rather than in the combined cycle generation portion of the plant. The biomass gasification cogeneration units were assumed to have similar response times to the IGCC plants. The distributed fuel cell plants were also assigned relatively slow response times due to concerns about thermal cycling in the molten carbonate fuel cell and thermal stresses in the solid oxide ceramic fuel cells. Offshore wind was judged to be more predictable than solar power (ignoring the predictability of day and night), and the solar thermal technology indicator was based on the resource without consideration of thermal storage. This indicator did not include a differentiation by country.

Figure 8 – Flexibility of Dispatch

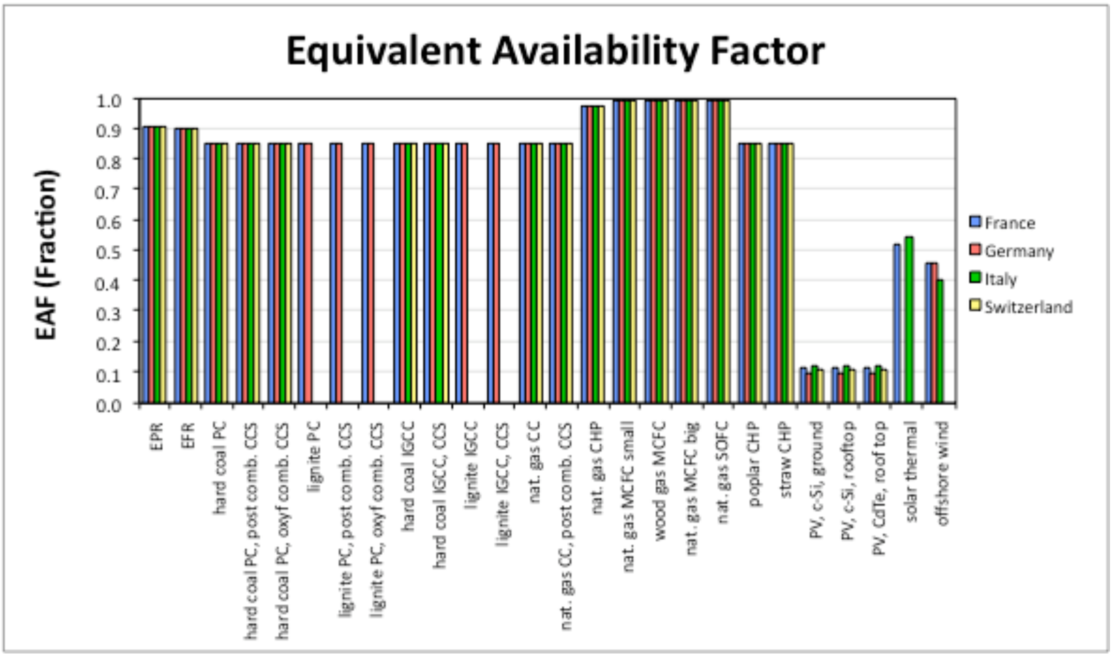


4.9 Equivalent Availability Factor (Factor)

The equivalent availability factor measures the average degree to which a plant is *available* to generate electricity over the course of the year. It can also be regarded as the full year (100%) minus the time out of service for unplanned outages and scheduled maintenance (note that a plant may be available even if it is not generating). This factor forms the upper bound to the plant's capacity factor (annual generation divided by capacity (MW) times 8760 hours per year). The term equivalent refers to the fact that the factor is adjusted for outages that are partial reductions in generation capacity instead of complete shutdowns. For technologies that are not centrally controlled (non-dispatchable), this factor depends upon the resource availability (e.g. sun and wind) specified by the contributing NEEDS partners. This indicator was not directly calculated for dispatched technologies, but rather gathered from industry sources.

The technologies that perform the best for the indicators are the distributed cogenerators (small engines and fuel cells). This is based on the fact that with many, small distributed units the total generation capacity available may be slightly adjusted downwards for individual outages or maintenance, but it will never be unavailable. It also assumes that by 2050 such units can be called upon when needed, either by price signals or direct control. Nuclear availability is next highest (based load nuclear units run full time when available, and availability is a key factor in reducing cost). The large dispatchable fossil units are third; although for many of these technologies the expected capacity factor is significantly below the availability factor. The relatively high availability for the solar thermal technology (compared to solar PV) reflects its thermal storage (storage is cheaper than oversizing the turbine-generator to meet peak solar power production). And the relatively high availability for wind generation reflects its offshore location. Country differences are only visible for the renewable resources, based on resource quality.

Figure 9 – Equivalent Availability Factor



5 Summary and Conclusions

This report has reviewed the economic indicators, including indicator requirements, data scenarios for assumptions, data contributors and the differentiation of the indicator assumptions between countries. It has also very briefly reviewed the 26 different technologies contained in the NEEDS analysis, and referred the reader to other reports for further descriptions and full characterization. The report has then presented the nine individual economic indicators. A brief description of each indicator and the associated methodology used was then followed by a graph of the indicator results and discussion of the performance based on different technologies, energy resources and countries.

The average cost of generation may be regarded as the most important economic indicator. It is the internal cost of electric generation that is added to the monetized value of various externalities to form the total cost of generation. It was also the economic indicator that was most heavily weighted on average by the stakeholders during the multi-criteria analysis process that combined all the economic, environmental and social indicators. For a full discussion of the multi-criteria analysis process and the comparison of its results with the total cost results, the reader is referred to the final report on this task (Schenler, et al. (2009) “Final report on sustainability assessment of advanced electricity supply options” Deliverable D10.2 - RS2b).

In order to get an overview of the economic indicators, the following Table 7 summarizes their relative performance by technology group (the hypen sign “-“ is intended to be more neutral than negative). This table has two particular caveats - the coal gasifier units (IGCC’s), not explicitly distinguished here, tend to straddle the boundary between the coal and natural gas categories, and the distributed cogenerators and biogas units tend to blur the boundary between the natural gas and biomass categories.

Table 7 – Summary of indicator performance by technology group

Indicator	**Technology group** Nuclear	Coal/lignite	Natural gas	Biomass	Solar/wind
Average cost	+ +	+	+	-	-
Direct labor	-	-	-	+ +	+
Energy independence	+	+	-	+ +	+ +
Total capital cost	-	+	+	+ +	+ +
Fuel cost sensitivity	+ +	+	-	-	+ +
Construction time	-	+	+	+ +	+ +
Dispatch cost	+ +	+ +	-	-	+ +
Flexibility of dispatch	+	+	+ +	+	-
Equivalent availability	+	+	+	+	-

This table captures the economic strengths and risk of nuclear, the generally good performance of coal and lignite in most economic categories (their real weaknesses lie more in the environmental areas). Natural gas units are particularly good in fast response, moderate in capital and average cost, and quick to build at moderate cost. Most of their flaws have to do with the gas fuel – foreign dependence, fuel cost and hence dispatch cost. Renewables in general have a number of real strengths – employment, domestic and renewable energy sources, and low *unit* costs and construction times. Biomass differs from solar and wind chiefly in fuel costs and hence dispatch costs and fuel price sensitivity. Overall, it can be said these indicators have been successfully quantified and succeed in measuring the economic criteria that were established.

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