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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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"Final report on the quantification of environmental indicators for sustainability assessment of future electricity supply options "

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	Dissemination Level	
PU	Public	**X**
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

I Contents

II List of Tables and Figures in the text

Tables

Figures

1 Introduction

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

The results of Research Stream RS2b will illustrate each technology’s performance in terms of its sensitivity to sustainability criteria. The sustainability criteria are weighted according to the preference profiles of individual stakeholders (electricity suppliers, electricity users, scientists, industry representatives, individuals, etc.) to give a broad representation of the many different viewpoints and priorities held by members of our society.

Two approaches will be used for the evaluation of the options. The first approach is based on total costs calculations (direct + external); estimation of total costs will be based on the information that is expected to be available from other research streams. The second approach will utilise Multi-Criteria Decision Analysis (MCDA), which combines specific attributes of the various technologies in a structured manner with knowledge of stakeholder preferences. The main efforts undertaken in RS2b concern the development of a framework for the implementation of MCDA. The approach is based on measuring the performance of competing technologies by different decision-making criteria. Performance for each criterion is judged by what may be called “indicators” or “measures” or “metrics.” Such indicators may be either quantitative or qualitative. Quantitative measures can be ascertained with relative objectivity, given stated contributing assumptions. Qualitative measures must still be assigned a value for the multi-criteria assessment, but are based on subjective judgement. Each indicator attempts to quantify a certain aspect of a given sustainability criterion.

Using the widely recognised ‘three pllar’ interpretation of sustainable development, the NEEDS project defined a range of criteria and indicators in order to assess the environmentally, socially and economically sustainable aspects of future electricity generating technologies and their associated fuel cycles (see Hirschberg et al., 2007, Deliverable No 3.1). The main objective of this report (Work Package 6) is to provide a description of the criteria and resulting indicators used to assess the potential environmental impacts of each technology, as well as to display the results for each of the four countries used in the assessment; France, Germany, Switzerland and Italy. The country-specific environmental burdens associated with the power generation are calculated using Life Cycle Inventories (LCI) established within RS1a of the NEEDS project. Certain technology characteristics are modified according to country-specific boundary conditions. The report builds on the conclusions achieved and documented in a number of other Work Packages within RS2b, which in turn profited from a variety of experiences with criteria and indicators, and which are accounted for in the literature. For the details we refer to the supporting RS2b publications[1].

The report firstly gives a review of the characteristics required of an indicator to support a clearly defined and necessary criterion in the environmental as well as the overall sustainability assessment. It then goes on to present an overview of the environmental impact indicators, together with an explanation of the structuring of the criteria hierarchy employed in the assessment. A description of the technologies considered in the assessment is also given in order that the impacts resulting from the energy chains of each technology can be more easily related to specific characteristics. Chapter 8 then provides a more concise description of each indicator followed by the graphical illustration of the results for each of the four countries and an interpretation of the predominat observations.

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[1] Available from the NEEDS Project website:

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

2 Requirements of indicators for sustainability assessment

The use of indicators is a common way to describe and monitor complex systems, and to provide information to decision makers and the public. Generally, indicators have three important functions in sustainability assessment (McCool & Stankey, 2004);

1. Description of the existing conditions and performance of a system
2. Measure of the effectiveness of actions and policies to move a system towards a more sustainable state.
3. Indicators allow the users to detect changes in economic, environmental, social and cultural systems.

Indicators need to be selected and defined with great care to fulfill these requirements. In the case of poorly chosen and applied indicators a variety of severe problems can occur, including (1) overaggregation, (2) measuring unimportant parameters, (3) dependence on a false model, (4) deliberate falsification, (5) diverting attention from direct experience, (6) overconfidence and (7) incompleteness (Meadows, 1998).

The development and selection of indicators often results in long lists of indicators selected on the basis of subjective perception. Such indicator lists tend to treat some topics in depth while others are ignored. Having too many indicators can also result in confused priorities and overwhelming details for both developers and users. Many of these problems can be avoided by using a stringent indicator selection framework. This implies that they have to meet a number of requirements, as outlined below.

Criteria need to be formulated in such a way that they can be transformed into quantifiable indicators for which the necessary data are available. The definition of the criteria and associated indicators is influenced by and depends upon the objectives and the specific aims, which represent the boundary conditions of the sustainability assessment under study. A more detailed overview of specific indicator requirements is given in Hirschberg et al. (2004a), whereas Meadows (Meadows, 1998) and Bossel (Bossel, 1999) also cover some more general issues and for an extensive discussion of indicators related to the social dimension of sustainable development we refer to (Renn et al., 2005).

Ideally, indicators meet a number of requirements and have certain characteristics. A list similar to the following one can be found in almost every indicator report (e.g., Baltic 21, 2001; BFS et al., 2003a; Hirschberg et al., 2004a; Meadows, 1998). Depending on the specific study objectives, an indicator set should aim to meet as many of those fundamental requirements as possible.

Indicators should be:

Scientific:

- *Measurable and quantifiable:* adequately reflect the phenomenon intended to measure
- *Meaningful:* appropriate to the needs of the user
- *Clear in value*: distinct indication which direction is good and which is bad
- *Clear in content:* measured in understandable units that make sense
- *Appropriate in scale:* not over or under aggregated
- *No redundancy or double counting:* indicators are not overlapping in what they measure
- *Robust and reproducible:* indicator measurement is methodologically sound, fits the intended purpose and is repeatable
- *Sensitive and specific:* indicators must be sensitive to changes in the system under study, and ideally respond relatively quickly and noticeably
- *Verifiable:* it is possible to verify an indicator by external persons or groups
- *Hierarchical:* to allow a user to understand the level of detail necessary

Functional:

- *Relevant:* for all stakeholders involved
- *Compelling:* interesting, exciting and suggestive of effective action
- *Leading:* so that they can provide information to act on
- *Possible to influence:* indicators must measure parameters that are possible to change
- *Comparable:* if the same indicators are used in several systems, they should be comparable
- *Comprehensive:* the indicator set should sufficiently describe all essential aspects of the system under study

Pragmatic:

- *Manageable:* not too many to handle; also important in view of interactions with users and stakeholders
- *Understandable:* possible to understand by stakeholders
- *Feasible:* measurable at reasonable effort and cost
- *Timely:* compilable without long delays
- *Coverage of the different aspects of sustainability*: indicators address economic, environmental and social dimensions
- *Allowing international comparison:* to the extent necessary, i.e. in accordance with specific study objectives

3 Overview of the environmental indicators used in Research Stream RS2b

Fehler! Verweisquelle konnte nicht gefunden werden. gives an overview of the sustainability criteria selected to be relevant in the environmental assessment of energy technologies and their associated fuel chains. A more comprehensive explanation of the potential impacts that the indicators measure, together with their unit of measure, is given in section 4.

Table 1 The environmental impact indicators used in Research Stream RS2b.

CRITERION/INDICATOR	POTENTIAL IMPACT	UNIT
ENVIRONMENT		
Impact on Resources		
Energy resources		
Fossil fuel use	Total consumption of fossil resources	MJ/kWh
Uranium use	Total consumption of uranium	MJ/kWh
Non-energy resources		
Abiotic resource use	Weighted total consumption of metallic ores	kg(Sb-eq.)/kWh
Climate change		
Greenhouse gas emissions	Global warming potential for next 100 years	kg(CO_2-eq.)/kWh
Impact on ecosystems		
From normal operation		
Land use	Ecosystem impacts due to land use	PDFm^{2}a/kWh
Ecotoxicity	Ecosystem impacts due to toxic substances	PDFm^{2}a/kWh
Acidification and eutrophication	Ecosystem impacts due to air pollution	PDFm^{2}a/kWh
Waste produced		
Chemical waste	Total volume of special chemical wastes stored in underground repositories	kg/kWh
Radioactive waste	Total amount of medium and high level wastes stored in geological repositories	m^3/kWh

The criteria are structured around a four level hierarchy. The top level contains the three sustainability dimensions; in this case it is the environment. The second and third levels contain the necessary criteria which define critical aspects of energy-related impacts on the environment. These are characterized by the fourth level, the individual impact indicators for which quantifiable units are expressed. Under the “Environment” dimension, the indicator “greenhouse gas emissions” is an exception to this general rule because it is in a hierarchy of only three levels. The four-level hierarchy is also used as the basic framework for the social and economic dimensions of sustainability although with similar exceptions.

4 Methodology

4.1 Scenario modeling

In order to evaluate the potential environmental impacts arising from the generation of 1kWh of electricity from different future electricity generation technology options, the NEEDS Integrated Project required the forecasting of technological development to the year 2050. The uncertainty surrounding the individual levels of technological advancement over the next four decades therefore makes the modeling of just one development scenario an over-generalisation of the possible situation in 2050. For this reason the generation technologies were specified for three different scenarios within RS1a. These were defined as;

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

With the first and third defining and modeling the extremes of development and therefore the confines of possible advancement, the impact assessment research and the technology comparison was based on the situation defined by the realistic/optimistic scenario which therefore reflects a very possible situation.

4.2 Life Cycle Assessment (LCA)

Calculation of the potential impacts arising from the complete technology chains (production and use of fuel; construction, operation and decommissioning of power plant; handling of waste; transport of fuels, materiels; etc.) was conducted using Life Cycle Inventories established within RS1a. The ecoinvent database (data v1.3) was used as source of background LCI data (ecoinvent 2006). Cumulative LCA results per kWh electricity produced (in the ecoinvent format, i.e. with a list of more than 1000 elementary flows) were the basis for the calculation of all environmental indicators. Since RS1a generated mostly generic (and in some cases site-specific) inventories, calculation of country-specific environmental burdens required the extrapolation of this specific technology inventories to the individual situations of the four countries assessed in the project. This resulted in adjustments being made to some of the technologies in order to account for specific wind conditions and solar irradiation, energy resource densities and effects on efficiencies due to average ambient air temperatures. The country-specific environmental burdens (basis for the quantification of the environmental indicators) were calculated using the SimaPro v7.1 LCA software (PRé, 2008). Details about the country-specific modifications of the generic LCI data can be found in chapter 7.

Besides the individual power generation technologies, selected processes in the general LCA background data were also modified in order to reflect technology development until year 2050. These modifications concern, among others, mainly transport processes, electricity mixes and the production of (construction) materials such as steel, aluminum and copper (ESU & IFEU 2008).

5 Overview of the technologies

For the NEEDS Integrated Project 26 technologies were selected which represented a broad range of primary energy carriers and, under the ‘optimistic/realistic’ development scenario, were determined to be possible electricity generating sources in 2050. Only technologies for which suffient research and testing have been undertaken were used.

Table 2 The individual technologies and their abbreviations.

PRIMARY ENERGY CARRIER	TECHNOLOGY	ABBREVIATION
Nuclear	European Pressurised Reactor	EPR
	European Fast Reactor	EFR
Fossil	Pulverised Coal	PC
	Pulverised Coal with post combustion Carbon Capture and Storage	PC-post CCS
	Pulverised Coal with oxyfuel combustion and Carbon Capture and Storage	PC-oxyfuel CCS
	Pulverised Lignite	PL
	Pulverised Lignite with post combustion Carbon Capture and Storage	PL-post CCS
	Pulverised Lignite with oxyfuel combustion and Carbon Capture and Storage	PL-oxyfuel CCS
	Integrated Gasification Combined Cycle coal	IGCC-coal
	Integrated Gasification Combined Cycle coal with Carbon Capture and Storage	IGCC-coal CCS
	Integrated Gasification Combined Cycle lignite	IGCC-lignite
	Integrated Gasification Combined Cycle lignite with Carbon Capture and Storage	IGCC-lignite CCS
	Gas Turbine Combined Cycle	GTCC
	Gas Turbine Combined Cycle with Carbon Capture and Storage	GTCC CCS
	Internal Combustion Combined Heat and Power	IC CHP
	Molten Carbonate Fuel Cells using Natural Gas 0.25 MW	MCFC NG 0.25MW
Biomass	Molten Carbonate Fuel Cell using wood derived gas 0.25 MW	MCFC wood gas
Fossil	Molten Carbonate Fuel Cells using Natural Gas 2MW	MCFC NG 2MW
	Solid Oxide Fuel Cells using Natural Gas 0.3 MW	SOFC NG
Biomass	Combined Heat and Power using short rotation coppiced poplar	CHP poplar
	Combined Heat and Power using straw	CHP straw
Solar	Photovoltaic, ribbon crystalline Silicon - power plant	PV-Si plant
	Photovoltaic, ribbon crystalline Silicon - building integrated	PV-Si building
	Photovoltaic Cadmium Telluride – building integrated	PV-CdTe building
	Concentrating thermal – power plant	Solar thermal
Wind	Offshore Wind	Wind offshore

6 Technology characterisations

This chapter gives a brief description of the 26 individual technologies modeled for the NEEDS Integrated Project and projected under a realistic optimistic development scenario (see *Methodology*) for the year 2050. For more detailed descriptions, as well as the current status and the parameters guiding the developments of each one, please refer to the final technology reports available on the NEEDS website;

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

6.1 **Nuclear: EPR** (Lecointe et al., 2007)

This 'Generation III' design of nuclear reactor uses either uranium oxide enriched to 4.9% fissile material (uranium-235) or a mix of uranium-235 and mixed uranium plutonium oxide (MOX), with pressurised water as the moderator and cooling agent. The heat from the reaction is used to produce steam to drive a steam turbine generator. It features not only superior reliability and safety over its current 'Generation II' counterparts but also efficiency. This will result in less high-level radioactive waste requiring either reprocessing or long term storage in geological repositories per unit of electricity generated.

EPR's are currently undergoing intensive development with the first two reactors being under construction in Finnland and France, and with other countries involved in planning processes. Once operational, an EPR is expected to have a lifetime of 60 years. EPR technology does not completely rule out the risks of a severe accident or the possibility for the proliferation of fissile material to unauthorized third parties. Visual disturbance will not be greater than existing nuclear plants and, other than mining activities, remains most dependant on the type of end cooling used ie. cooling tower or access to a large water resource.

6.2 **Nuclear: EFR** (Lecointe et al., 2007)

The EFR is a 'Generation IV' design of nuclear reactor for which the term "fast" refers to the reduced moderation of the free neutrons. Fast neutrons do not lead to fission as efficiently as moderated free neutrons and which allows a greater quantity of fissile material to be used. This causes around 25% more neutrons to be produced in each fission reaction, a fraction of which are absorbed by some of the non-fissile uranium-238, thus converting it into fissile plutonium-239. By 'breeding' fissile material, a fast neutron reactor is able to operate within a closed-fuel cycle in which the spent fuel and plutonium products from co-existing Generation III reactors are recycled as MOX fuel elements, containing around 20% fissile material.

The EFR will use liquid metal (sodium) as the coolant which acts as a very efficient heat transfer medium whilst avoiding any moderational effect on the neutrons. The operational lifetime of the EFR is expected to be around 40 years. Although the inherent safety feature of a fast neutron reactor is that fission reduces with increased temperature, risk of a severe contamination release to the environment can not be ruled out completely. Visual disturbance factors are similar to the EPR.

6.3 **Fossil: PC** (Bauer et al., 2009)

Coal is pulverized and then burned in a tall boiler with watertube walls. The steam produced is then used to drive a turbine generator. The combustion of coal causes very significant quantities of carbon dioxide (CO_2) and atmospheric pollutants although sulphur dioxide and particulate emissions are almost all contained by the use of filters. These take the form of chemical scrubbers, fabric filters and/or electrostatic precipitators. The filtered materials as well as the coal ash are either recycled or landfilled. For operation in 2050, the research used a power plant net efficiency of 54% in order to follow a 'realistic-optimistc' technology development scenario until that time.

The transportation of the large amounts of fuel necessary to run a coal-fired power plant can be a cause of significant noise pollution in rail-freight transit regions whilst the power plant and atmospheric emissions in particular can be visible from considerable distance. The operational lifetime of a PC power plant is around 35 years.

6.4 **Fossil: PC-post CCS** (Bauer et al., 2009)

This technology uses the same coal combustion and electricity generation technique as for PC but the carbon dioxide CO_2 is separated from the other flue gases. This is achieved by cooling the flue gases to around 50°C and then using a solvent containing absorber. The most common solvents used for neutralizing CO_2 in chemical absorption systems are alkanolamines such as monoethanolamine (MEA), diethanolamine (DEA), and methyldiethanolamine (MDEA). The solvent-bound carbon dioxide is then re-heated to around 120°C in order to enable the solvent to be stripped from the CO_2 inside a regeneration vessel. This uses steam generated in the process as the stripping gas. The stripped solvent is cooled and returns to the absorber whilst the steam is condensed and returns to the regeneration vessel. The separated CO_2 can then be dehydrated and compressed for efficient transportation and sequestered in various types of geological formations, on deep ocean sea beds or converted to solid mineral form.

For the NEEDS Integrated Project, the scenario of transportation via pipeline to a geological sequestration site[2] was used. This involves a 400km pipeline requiring one recompression process at the half-way point. Transport of CO_2 in pipelines is cheaper than shipping over short distances due to relatively high fixed costs for harbors, loading and unloading. Shipping only becomes competitive at distances between 1000 km and 2000 km. The CO_2 gas is then injected into a saline aquifer approximately 800m below the earth's surface. Deep saline aquifers are widely distributed below the continents and the ocean floor and are within easy access to a number of power plants. It is currently being demonstrated and has proven to be technically feasible.

The major drawbacks of CCS are the significant costs involved as well as the overall efficiency reduction effects on the power plant as some of the energy from the combustion process is required in the capture of the CO_2. The overall net efficiency of the PC-post CCS power plant was determined to be 49% whilst the plant lifetime is also 35 years.

6.5 **Fossil: PC-oxyfuel CCS** (Bauer et al., 2009)

Oxyfuel combustion involves burning the pulverized coal in an environment of oxygen instead of ambient air. However, with pure oxygen the combustion temperature would be too high so therefore oxygen derived from an air separation unit is mixed with CO_2 recycled from the exhaust in order to control the combustion temperature. The exhaust from oxyfuel combustion is flue gas with very high CO_2 concentration (no nitrogen oxides are formed) which enables simple and low cost CO_2 purification methods to be used and a more efficient CCS process. Particles are removed from the flue gas using an electrostatic charge before entering a flue gas desulphurization process requiring inputs of limestone and water (produces gypsum as a marketable by-product). Furthermore, the volume of inert gas is reduced which can increase the thermal efficiency of the boiler. Although the oxyfuel combustion technique can be applied to conventional boilers, the major drawback of this approach is that the production of oxygen typically involves an air separation unit with a complex, costly and energy-intensive super-cooling (cryogenic) process to extract oxygen from the air. For the NEEDS Integrated Project, the same scenario of 400km transportation via pipeline to a saline aquifer sequestration site was used.

Oxyfuel combustion with CCS suffers similar drawbacks to that of post combustion with CCS but due to the necessary production of oxygen the overall net efficiency of the PC-oxyfuel CCS technology was determined to be marginally lower at 47% although with the same plant lifetime of 35 years.

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[2] Due to the highest potential in Europe, saline aquifers were chosen as the reference storage medium.

6.6 **Fossil: PL** (Bauer et al., 2009)

This used larger but similar power plant technology as for the PC plant and with the same power plant net efficiency. An important additional impact from the use of lignite as opposed to coal is the effect on the landscape due to large open pit mining activities. Lignite also contains a larger proportion of uncombustable impurities which must be removed as ash and disposed of. However, the transportation of fuel over long distances, such as is the case with hard coal, are not necessary since lignite power plants are operated mine-mouth.

6.7 **Fossil: PL-post CCS** (Bauer et al., 2009)

This used larger but similar power plant technology as for the PC plant with post-combustion CCS and with the same power plant net efficiency. Modeling of CO_2 transport and storage is identical.

6.8 **Fossil: PL-post CCS** (Bauer et al., 2009)

This used larger but very similar power plant technology as for the PC plant with oxyfuel combustion CCS and with the same power plant net efficiency. Modeling of CO_2 transport and storage is identical.

6.9 **Fossil: IGCC-coal** (Bauer et al., 2009)

Integrated Gasification Combined Cycle (IGCC) is an emerging advanced power generation system having the potential to generate electricity from coal with high efficiency and lower air pollution (NO_x, SO_2, CO and PM_{10}) than other current coal-based technologies.

An IGCC power plant consists of a gasification unit in which the quantity of oxygen is insufficient to completely burn the coal and, due to the high temperature and pressure, the resulting gas has a high level of hydrogen (H_2), carbon monoxide (CO). Oxides of nitrogen and sulphur are not formed in the (reducing) environment of the gasifier but, instead, react with hydrogen to form ammonia and hydrogen sulphide. The ammonia and sulphur are then easily extracted to become marketable byproducts. The synthesis gas (syngas) is cleaned before being fired in a gas turbine to generate electricity. The high temperature exhaust of the gas turbine still has enough heat to produce super-heated steam in a steam generator as part of a conventional steam cycle. It is this use of two thermodynamic cycles in cascade which gives the name "combined cycle".

Minerals in the fuel (i.e., the rocks, dirt and other impurities that don't gasify like carbon-based constituents) separate and for the most part leave the bottom of the gasifier either as an inert glass-like slag or other marketable solid byproducts. Although oxygen-blown coal gasifiers can be more efficient and pure oxygen is not diluted by the large quantities of nitrogen present in air, making oxygen using conventional cryogenic air separation plants is expensive; both in terms of capital cost and energy consumption (see also oxyfuel combustion technologies). IGCC power plants are also relatively inflexible in that they have to be designed for a specific type of coal or solid fuel in order to provide a high reliability. On the other hand, IGCC technology offers the environment related advantages of high efficiency and very low emissions of SO_2, NO_x and particulates. The power plant net efficiency of this technology was determined to be 54.5%.

6.10 **Fossil: IGCC-coal CCS** (Bauer et al., 2009)

IGCC technology lends itself very well to carbon capture and storage (CCS) due to the higher pressure of the gas stream and the possibility to achieve the highly concentrated formation of CO_2 prior to combustion. For this to be possible then after having been cleaned of particulates the syngas enters a shift reaction unit in which the methane is reacted with steam to produce hydrogen and CO_2. The preferred technique for CO_2 sepapration in applications at higher pressure (i.e. IGCC) is currently physical absorption using solvents commonly used in commercial processes. Once captured, the CO_2 can then be treated in the same way as for the other technologies incorporating CCS. The resulting power plant net efficiency for this technology scenario is 48.5%. CO_2 transport and storage is modeled in the same way as for PC power plants.

6.11 **Fossil: IGCC-lignite** (Bauer et al., 2009)

This used a larger but very similar power plant technology as for the IGCC-coal plant but with a marginally lower overall efficiency of 52.5%. An important additional impact from the use of lignite as opposed to coal is the effect on the landscape due to large open pit mining activities as well as the higher quantity of ash requiring disposal. However, the transportation of fuel over long distances are not necessary, because lignite power plants are operated mine-mouth.

6.12 **Fossil: IGCC-lignite CCS** (Bauer et al., 2009)

This uses a larger but very similar power plant technology as for the IGCC-coal plant but with a marginally lower overall efficiency of 46.5%. CO_2 transport and storage is modeled in the same way as for PC power plants.

6.13 **Fossil: GTCC** (Bauer et al., 2009)

A gas turbine combined cycle (GTCC) power plant involves the direct combustion of natural gas in a gas turbine generator. The waste heat generated by this process is then used to create steam for use in a steam generator, in a similar manor to that of IGCC technologies. In this combined cycle power plant around two-thirds of the overall plant capacity is provided by the gas turbine. Further efficiency developments of the gas turbine will be mainly driven by material research in order to increase the firing temperature and the pressure ratio. Although GTCC plants have relatively low CO_2 emissions per unit of generated electricity compared to other fossil power plants, they can be the source of significant NO_x emissions due to the high combustion temperature which is desirable for high efficiencies. Therefore, whilst primary fuel prices will remain to be the decisive factor in the development and future of natural gas generated electricity, political decisions regarding environmental targets will also play a decisive role in their economic competetiveness.

One of the main advantages of a GTCC power plant is its flexibility of operation. This means that it can provide both base load power as well as being available to cover the shorter duration peak loads and unexpected shortfalls in supply. The net power plant efficiency of this technology is predicted to be 65% in 2050.

6.14 **Fossil: GTCC CCS** (Bauer et al., 2009)

The electricity generation aspect of this technology is exactly the same as the GTCC without CCS. The flue gas from the GTCC then enters the same CO_2 separation, stripping, drying, transportation and sequestration process to that used for coal and lignite CO_2 capture. However, CO_2 is assumed to be stored not in aquifers, but in depleted gas fields with a depth of 2500m. Owing to the energy requirements of the CCS process the net power plant efficiency of this form of electricity generation is 61%.

6.15 **Fossil: IC CHP** (Bauer et al., 2009)

This is a decentralized form of co-generation for use in situations where not only the electricity but also the heat produced in the combustion process is a desired product. Using an internal combustion engine as opposed to a turbine generator, this technology is suited to provide heat and power to single buildings such as public buildings, small industry, etc. or to groups of residential buildings sharing a distribution network where the product in most demand can be the heat produced. They are most efficiently used to cover a simultaneous electricity and heat demand rather than for use to meet peak in only electricity demand. Heat produced by combustion of the gas can be transferred to a water or air medium depending on the specific requirement. The electricity is generated by a direct generator coupling to the internal combustion engine. The efficiency of electricity generation is 44%.

6.16 **Fossil: MCFC NG 0.25 MW** (Gerboni et al., 2008)

Molten carbonate fuel cells are a moderately high temperature form of fuel cell and can achieve a relatively high overall efficiency compared to those operating at lower temperatures. In a molten carbonate fuel cell, the electrolyte is made up of lithium-potassium carbonate salts heated to about 650°C. At these temperatures, the salts melt into a molten state that can conduct charged particles, called ions, between two porous electrodes. The high concentration of methane (CH_4) in natural gas is combined with steam and converted into a hydrogen-rich gas within the fuel cell. At the anode, hydrogen reacts with the carbonate ions to produce water, carbon dioxide, and electrons. The electrons travel through an external circuit creating electricity and return to the cathode. There, oxygen from the air and carbon dioxide recycled from the anode react with the electrons to form carbonate ions that replenish the electrolyte and provide ionic conduction through the electrolyte, completing the circuit (DOE, 2009). A fuel cell therefore uses an efficient electro-chemical reaction to convert the chemical energy of the natural gas into electricity rather than the less efficient and more polluting combustion of the natural gas. This also means that the energy conversion process is very quiet as well as being dependable and stable due to the non-mechanical nature of the process.

For the NEEDS project, the insufficiently high temperature of the exhaust gas as well as the small decentralized scale of this technology meant that the waste heat from the fuel cell would be used as useful heat rather than to create steam for a steam generator. The efficiency of electricity generation is 50% for this particular technology.

6.17 **Biomass: MCFC wood gas** (Gerboni et al., 2008)

Using a gasification process similar to that for previously described fossil fuel gasification, this technology uses gas generated with sustainable sources of harvested wood or from waste wood streams. Cleaned of particulates the methane rich synthetic natural gas (SNG) can be used in the same way as natural gas and fuels the MCFC in the same way as with natural gas. The efficiency of generating electricity with this form of gas is then the same as when using natural gas (50%). The conversion efficiency from potential energy in the wood to potential energy in the wood gas is not included in this determination because obtaining the wood gas is considered as an economic consideration similar to obtaining natural gas. Here, the waste heat is also used for space heating, drying, etc.

6.18 **Fossil: MCFC NG 2MW** (Gerboni et al., 2008)

The same decentralized technology as for the 0.25 MW plant but scaled up to deliver an electricity generation capacity of 2MW. Due to the size of plant and technological advancement by 2050, it is expected that the MCFC will be part of a hybrid plant which features the use of the waste heat to power steam turbine as a secondary electricity generation method. At 55%, the energy conversion to electricity is therefore slightly higher than for the smaller plant.

6.19 **Fossil: SOFC NG** (Gerboni et al., 2008)

Although they also use an electrochemical conversion process Solid Oxide Fuel Cells (SOFC's) operate at a relatively high temperature (1000°C) and use a semi permeable solid oxide (ceramic) electrolyte rather than a liquid one. Furthermore, an SOFC is able to be fuelled by liquid or gaseous fuels and which are reformed into a hydrogen rich gas within the cell. Although a small decentralized scale plant, the higher operating temperature means that the exhaust gas can be used to power a steam generator giving the SOFC a better electricity generating efficiency (58%) than even a larger MCFC.

6.20 Biomass: CHP poplar (Gärtner, 2008)

As has been previously described, combined heat and power is a co-generational form of converting the potential energy stored in the fuel. The power plant is designed to generate electricity whilst the waste heat produced is provided to an external heat demand in close proximity to the plant. Whereas the small scale IC CHP used a gas fired internal combustion engine, the CHP plant modeled here uses the direct feed of woody biomass and is significantly larger. Here, then, the use of short rotation coppiced (SRC) poplar as the biomass feed stock is modeled and the conversion efficiency of the potential energy in the wood to electrical energy is determined.

Poplar can be commercially grown as an energy crop using the practice of SRC. Within 1-2 years of the initial planting of poplar cuttings, they are cut back to encourage the growth of multiple stems from a stool at ground level. Further cultivation for 2-4 years results in the growth of sufficient woody material for it to be mechanically harvested by clear cutting the stems above the stool. The development of the root system encourages the further shooting of new stems and the harvesting of these after the same time period. It is this continuous cycle and the periodic harvesting of naturally regenerating biomass on the same area of land which enables the sustained supply of this commercial fuel source (Tubby and Armstrong, 2002).

Once dried and chipped, the biomass is fed into a gasification process very similar to those previously described. The scale is smaller however, with the gas turbine of the biomass CHP plant having a capacity of 9MW of electricity. The overall conversion efficiency into electricity is 30%.

6.21 Biomass: CHP straw (Gärtner, 2008)

Straw accumulates as a co-product with the harvest of feed and food grain as well as oil producing plants. It often remains on the field as a soil and nutrient enhancer, but in many cases it is also used as litter or fodder for animals. It is therefore not considered as an energy crop because it is not specifically cultivated for this purpose and which means that the transportation distances of straw to a CHP plant are less predictable than for energy crops such as SRC poplar. Straw can be crushed and then fed into a biomass gasifier in the same way as for the poplar and the processes from here on are the same with the same overall efficiency of conversion to electricity of 30%.

6.22 Solar: PV-Si plant (Frankl et al., 2006)

Currently, around 85 to 90% of the total installed global photovoltaic (PV) capacity uses wafer-based crystalline silicon semi-conductor technologies. Wafer-based cells are ether a single, homogenous slice of a grown silicon crystal ingot known as mono- or single-crystalline silicon and which deliver the highest efficiencies. More commonly, they are the single slice from a casted block of many small silicon crystals known as poly- or multi-crystalline silicon and which are slightly less efficient. An alternative and advancing method for producing crystalline silicon semi-conductors, however, is ribbon technology. Here, a ribbon of substrate material is pulled directly from a bath of molten silicon causing the silicon to crystalise on the ribbon. There is therefore no requirement to produce an ingot and to saw it into wafers which avoids significant material losses. This technology has tendentially similar efficiencies to multi-crystalline silicon wafers but a much better utilisation rate of the silicon feedstock. For the NEEDS Integrated Project it was determined that under a realistic-optimistic development scenario until 2050, ribbon technology will advance sufficiently to occupy a significant share of the crystalline silicon market and offers advantages due to its efficient use of resources. For this particular technology scenario a centralized power plant size was modeled with an electricity generating capacity of 46.6MW using an average PV module efficiency of 22%.

6.23 Solar: PV-Si building (Frankl et al., 2006)

Here the PV technology is exactly the same as for 22 but the size of the installation is significantly smaller and integrated onto a new or existing building. At 420 kW, this is suited to the roof of a public or commercial building and is too large for most domestic residences.

6.24 Solar: PV-CdTe building (Frankl et al., 2006)

It has been described that 85 to 90% of the total installed global photovoltaic (PV) capacity uses wafer-based crystalline silicon semi-conductor technologies. The remaining 10 to 15% is largely made up of thin-film technologies. These are manufactured by depositing extremely thin layers (less than half the thickness of a silicon wafer) of photosensitive materials on a low cost backing such as glass, stainless steel or plastic. Although the first thin-film PV semi-conductors also used silicon, there are now various material compositions used. Of these, cadmium-telluride (CdTe) is depsited as a film less than one tenth the thickness of a silicon wafer and offers a relatively good resource requirement to efficiency ratio (Frankl, 2005).

Following the optimistic-realistic development scenario until 2050, a CdTe thin-film module is expected to have an operating efficiency equal to that of the ribbon crystalline silicon modules. This technology is also at the buiding integrated scale.

6.25 Solar: Solar thermal (Viebahn et al., 2008)

There are now several large-scale solar thermal power generation systems installed, mainly in Europe and the U.S., which use a variety of methods to capture energy from solar radiation, transform it into heat, and generate electricity from the heat using either steam turbines, gas turbines, Stirling engines, or pressure staged turbines. Only locations with irradiations of more than 2,000 kWh/(m^2a) are suited to a reasonable economic solar thermal performance. For the NEEDS Integrated Project, the optimistic realistic scenario development for 2050 used a 400MW parabolic trough collector system in combination with an overnight thermal energy storage system for 24 hour solar-only power generation.

Parabolic trough systems consist of trough solar collector arrays, at the horizontal focal point of which is a fluid filled pipe. This heat transfer fluid (HTF) is heated to around 400 °C which is sufficient to power a conventional steam turbine and generator, and by 2050 the HTF will be steam (currently synthetic thermo oil).

The use of steam as the HTF would enable the direct propulsion of the turbine by the solar heated fluid without the use of an intermediary exchange medium whilst presenting a high cost reduction potential. The implimentation of direct steam technology, however, requires the development of a new latent heat storage medium for the evaporation process of the cycle and which necessarily means the use of phase change materials (PCM). A PCM based storage system for this application would consist of salt, concrete, and aluminium. Furthermore, to have the ability to continue electricity generation overnight and through the hours of insufficient solar radiation, the concrete and PCM based storage must be have the capacity to maintain 16 hours of high pressure steam.

Based on laboratory-scale trials, a concrete/PCM storage system operates in three steps:

- During the *preheating* step a conventional thermal mass storage unit of concrete is heated up (sensible heat storage).
- This step is followed by the *evaporation* phase. The increasing heat causes the salt to undergo phase changes (e.g. from solid to liquid) but does not increase the storage temperature. Aluminium plates in the salt increase the thermal conductivity.
- In the last step, the *superheating* phase, a concrete storage is again used to heat the steam to the required temperature.

The net power plant efficiency of this technology is expected to be 18.5%.

6.26 Wind: Wind offshore (Dong, 2008)

The exploitation of wind energy has increased exponentially during the last decades, and there is still large unexploited wind energy potential in many parts of the world – both onshore and offshore. However, the success story of onshore wind energy has led to a shortage of land sites in many parts of Europe, particular in northwestern Europe, and has spurred the interest in exploiting offshore wind energy. Regarding offshore wind farms particularly, economies of scale mean that farms consisting of multiple wind turbines all connected to a single transformer station are more financially viable than individual turbines. Off-shore sites also enjoy the advantage of having significantly more stable and higher wind speeds than onshore sites and which leads to a longer turbine life. In addition, modern offshore wind turbines can also be remotely monitored and controlled, which gives unique advantages when regulating the power output.

The size, capacity, material structure and anchoring of offshore wind turbines in 2050 can only be extrapolated from recent developments as well as logistical and financial parameters. The emphasis will be on reducing weight, material consumption, handling costs and production costs, whilst the individual capacities of wind turbines will continue to grow, potentially reaching 30 – 50 MW by 2050 (by comparison, largest currently available are in the 5-6MW range). As the development moves further off shore and into water depths of more than 30 metres, the monopile design used most often up to now will need to be replaced by other designs including floating turbines.

For the NEEDS project, a realistic/optimistic development scenario resulted in a turbine capacity of 24MW and which is located in a farm of around 80 turbines. The foundation system is a guyed steel monopile for an unspecified water depth. It is expected to have an operational lifetime of 30 years.

7 Country Specific Adjustments

The generic Life Cycle Inventories generated by the individual work packages of RS1a for the individual technologies (as shortly described in the previous chapter) were adjusted where applicable in order to consider country specific parameters, which have an influence on the cumulative LCA results. This includes the impact of ambient air temperature on net power plant efficiencies of thermal units, differing wind conditions and solar irradiation, and country-specific energy content of lignite.

Table 3 summarizes the country specific modifications of the generic LCI data provided by RS1a for the technologies concerned.

Table 3 Country specific modifications of the generic LCI data provided by RS1a.

Technology	country specific parameter	generic from RS1a	Switzerland	Germany	France	Italy
Solar Photovoltaic	yearly average yield [kWh/kW$_p$] (solar irradiation)	1496	922	809	984	1032
Solarthermal	yearly average yield [kWh/kW$_p$] (solar irradiation)	6400	n.a.	n.a.	4518	4738
Offshore wind	yearly average yield - full load hours [h/a] (wind conditions)	4200	n.a.	4000	4000	3500
Advanced fossil	reduction in power plant efficiency (due to higher ambient temperature)	n.a.	0	0	0	3.2%
	energy content of lignite [MJ/kg]	8.8	n.a.	8.7	16.6	n.a.

8 Environmental indicators and results

8.1 Fossil fuel use (MJ/kWh)

This indicator measures the total primary energy in the fossil resources used for the production of 1 kWh of electricity. Due to the use of fossil fuels in many industrial processes, even if they are not directly part of the electricity generation chains in focus, they will contribute to energy requirements in manufacturing, transportation and other processes necessary for the technology to function. This requires the energy contained within the total amount of coal, natural gas and crude oil used for each complete technology chain to be modelled and is known as the "cumulative energy demand (CED)" (Frischknecht et al., 2004).

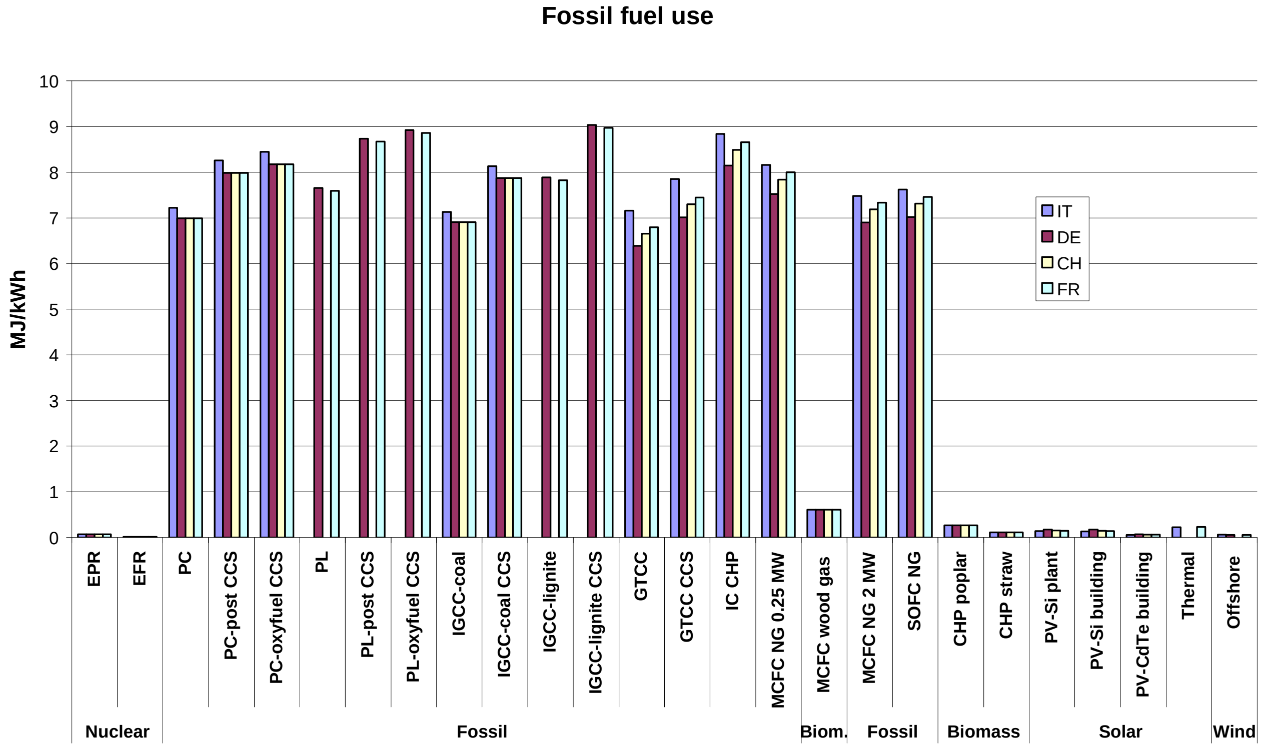

Figure 1 Results of the environmental impact indicator: fossil fuel use.

Figure 1 shows very clearly the demand that the use phase of a technology has on overall fossil fuel consumption. For non-fossil fuelled technologies their demand on fossil fuels for all other life cycle aspects is minor in comparison. The graph also shows for which countries a particular technology is expected to be relevant. For example, lignite power plants were only modeled for Germany and France due to the poor accessibility to the lignite fuel in Switzerland and Italy. Italy consistently requires more fossil fuel because thermal power plants in Italy function with marginally lower net efficiencies due to the higher average ambient air temperature (See chapter 7 - *Country Specifiec Adjustments*). Also evident from Figure 1 is that the integration of carbon capture and storage (CCS) in to a power plant causes a significant increase in the overall fuel use. The separation, compression and injection of CO_2 requires large quantities of power which means that to deliver 1 kWh to the electricity grid it must consume larger quantities of fossil fuel resources.

8.2 Uranium use (MJ/kWh)

This indicator quantifies the primary energy from natural uranium resources used to produce 1kWh of electricity and also uses CED methodology (Frischknecht et al., 2004). Even if the technology in question is not a nuclear one, it is likely that electricity inputs to various aspects of the complete technology chain will have featured nuclear power in the electricity mixes, i.e the results for non-nuclear technologies are a measure for nuclear electricity consumption throughout the complete energy chains.

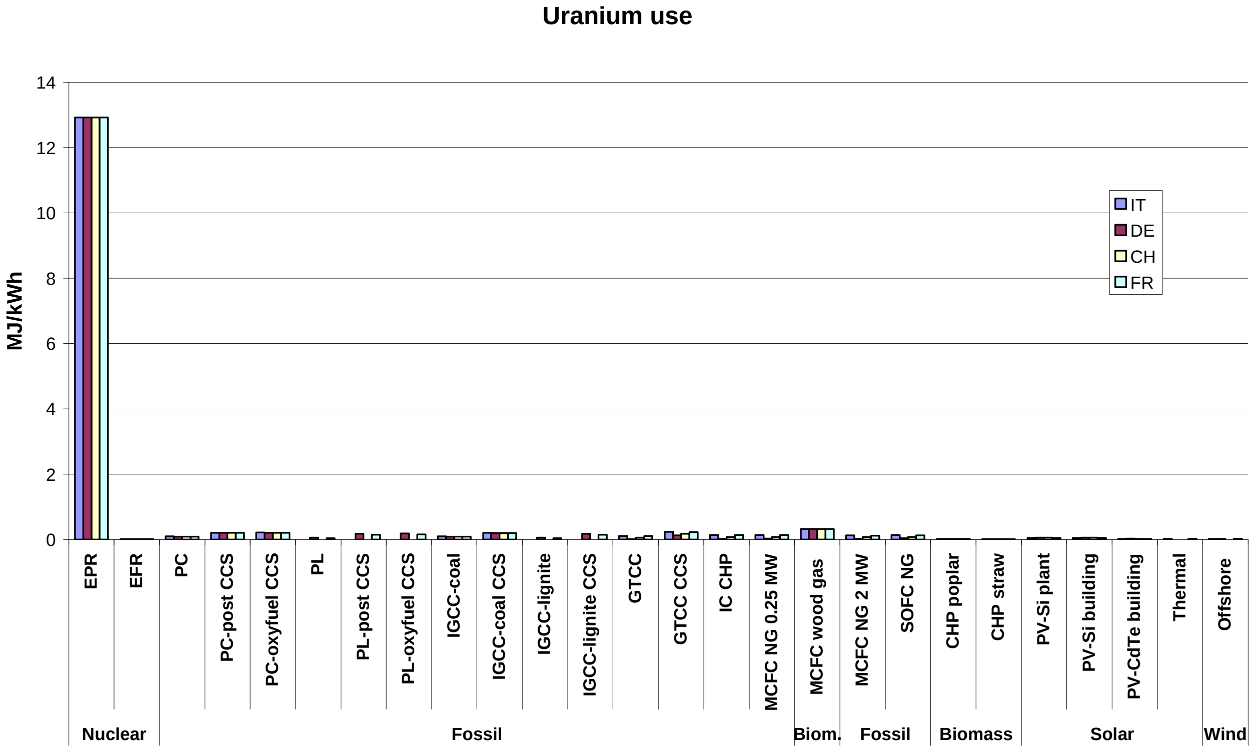

Figure 2 Results of the environmental impact indicator: uranium use.

The results are dominated by the Generation III European Preasurised Reactor (EPR) but the uranium use by generating 1kWh from the Generation IV European Fast Reactor (EFR) is shown to be less than many of the other technologies. For the NEEDS project a scenario for 2050 was adopted in which the nuclear power plant parks would consist mainly of Generation III with Generation IV plants only having recently (post-2040) become commercially available. Therefore the electricity mixes use a higher proportion of nuclear power plants burning enriched natural uranium and this demand is then reflected in the electricity demands from the complete energy chains of all plants. The EFR on the other hand, does not burn enriched natural uranium but uses MOX fuel elements consisting of reprocessed spent fuel.

8.3 **Abiotic resource use** (kg (Sb-eq.)/kWh)

This indicator quantifies the total amount of non-energy mineral resources used in the complete technology chain in order to produce 1 kWh of electricity. It is based on the impact assessment methodology ‘CML 2001’ (Guinée et al., 2001) but is modified to model the use of abiotic metal resources only. The measurement of single metals is based on the scarcity of their ores and expressed with reference to an equivalent use of the metal antimony (Sb).

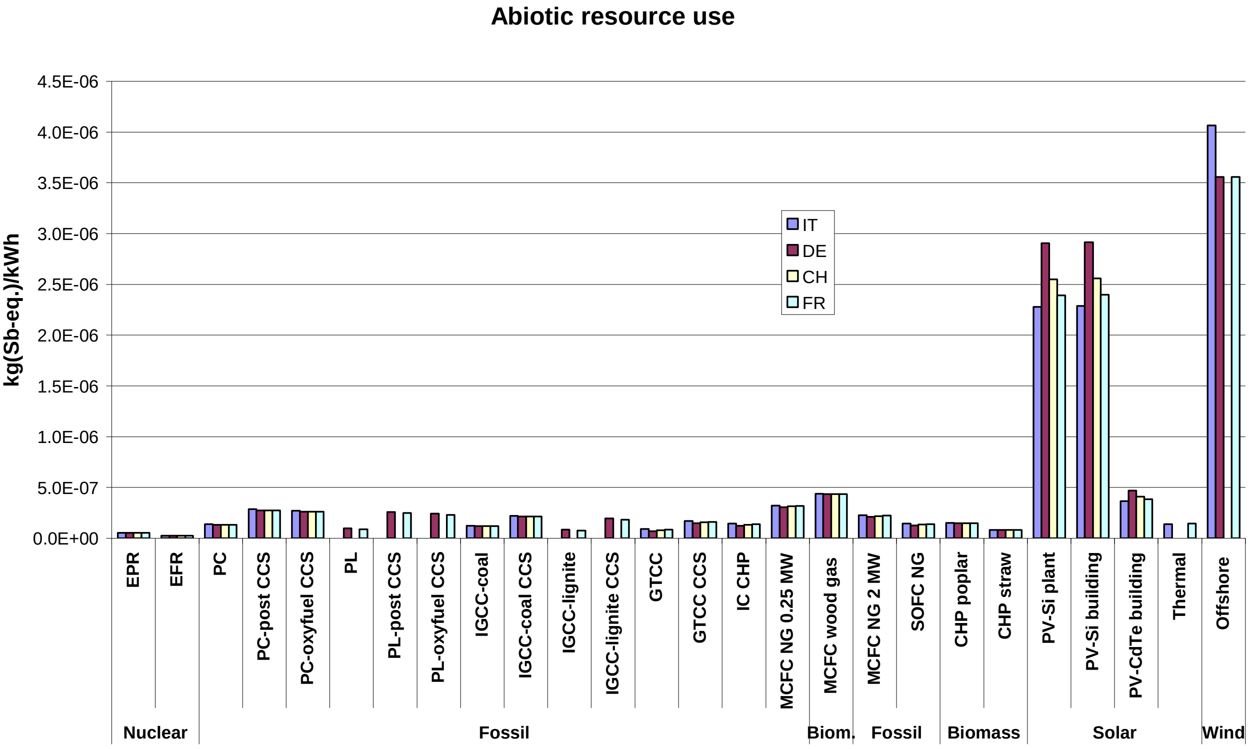

Figure 3 **Results of the environmental impact indicator: abiotic resource use.**

Although the nominal capacity of an offshore wind turbine is determined to grow significantly, the large amounts of metallic materials necessary for construction and anchoring remain comparatively high. With less wind availability, Italian offshore wind power requires slightly more of these resources per unit of electricity generated than for French or German wind power. With reference to solar PV technologies, the extent to which thin film (PV-CdTe) technologies reduce the consumption effect of metals is very evident and, for this particular indicator, places this technology on a relatively similar ranking with some fuel cell and fossil fuel technologies. The large output capacities of nuclear technologies mean that the overall consumption effect of metals is relatively low. The application of CCS technologies is shown to have a significant effect on the demand for these resources in a comparison of fossil fuel technologies.

8.4 **Greenhouse gas emissions** (kg(CO_2-eq.)/kWh)

This indicator measures the total quantity of greenhouse gases (GHG) released into the atmosphere from the complete technology chain. Using the global warming potential (GWP) over 100 years of one kg of carbon dioxide (CO_2) as the reference impact and equal to a GWP of 1, other GHG's are quantified according to their equivalence to CO_2. For example, at the time that this study was conducted, methane (CH_4) was classified as having a GWP of 23 meaning that 1kg of CH_4 has an ability 23 times greater than that of 1kg of CO_2 to heat the atmosphere (Frischknecht et al., 2004). The GWP factors have since been slightly adjusted (Forster et al., 2007).

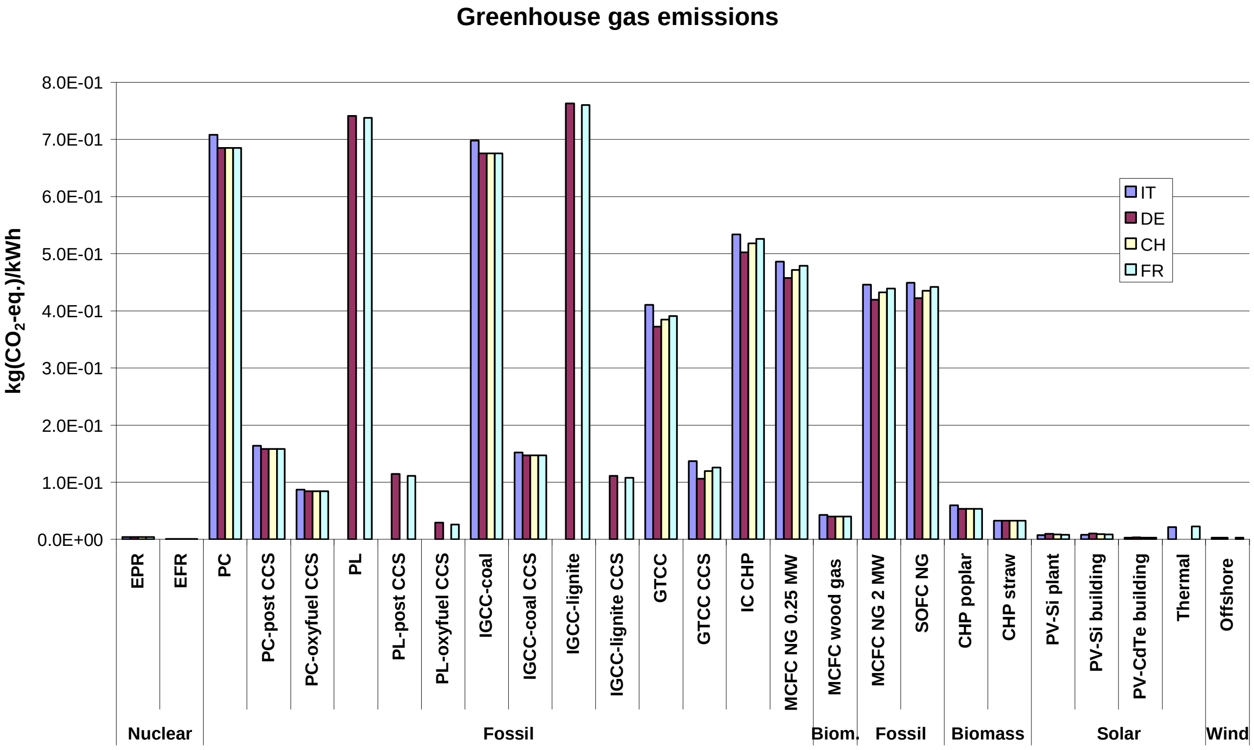

Figure 4 **Results of the environmental impact indicator: GHG emissions.**

Initial observations of Figure 4 show the clear differences in GHG emissions of fossil fuelled technologies with and without carbon capture and storage (CCS). The highly enriched CO_2 flue gas stream resulting from oxyfuel combustion enables relatively simple and low cost CO_2 purification methods to be used. For these technologies a 100% capture rate was used in the modeling of the life cycle inventory. Post-combustion and pre-combustion (IGCC) capture technologies were modeled using a 90% capture rate due to the higher flue-gas volumes and more difficult separation processes involved. The application of CCS, however, cannot remove CO_2 or other GHG emissions from other stages of the energy chain and so there are still some emissions attributed to the technology. The largest potential reductions of integrating CCS are for lignite, particularly in combination with oxyfuel and for which emissions are reduced sufficiently to be less than the highest emitting renewable technology chains (namely CHP poplar). This is due to both the different energy chains and chemical compositions of the coal and lignite fuels. Lignite power plants are operated on a mine-to-mouth basis where the power plant is situated in proximity to the mining site. The operation of a hard coal power plant requires the transportation of the fuel from various locations, including overseas, as well as its intermediary storage. So whereas the combustion of lignite produces a greater quantity of direct GHG emissions, action at this stage in the form of CCS can have a greater overall impact on reductions.

Although biogenic sources of CO_2 were not considered to increase atmospheric GHG's, the combustion of biomass also emits methane and nitrous oxides. The energy chains of the biomass-based renewable technologies also cause GHG emissions; this is mainly due to fuel transportation, crop fertilizers and the primary energy sources of electricity used.

8.5 Land use (PDFm^{2}a/kWh)

This indicator quantifies the loss of species (flora & fauna) in terms of a “potentially disappeared fraction” (PDF) due to land use in producing 1 kWh of electricity. The PDF of species is expressed according to land area and time, and is modeled as part of the Eco-Indicator 99 (EI99) impact assessment methodology. (Goedkoop and Spriensma, 1999).

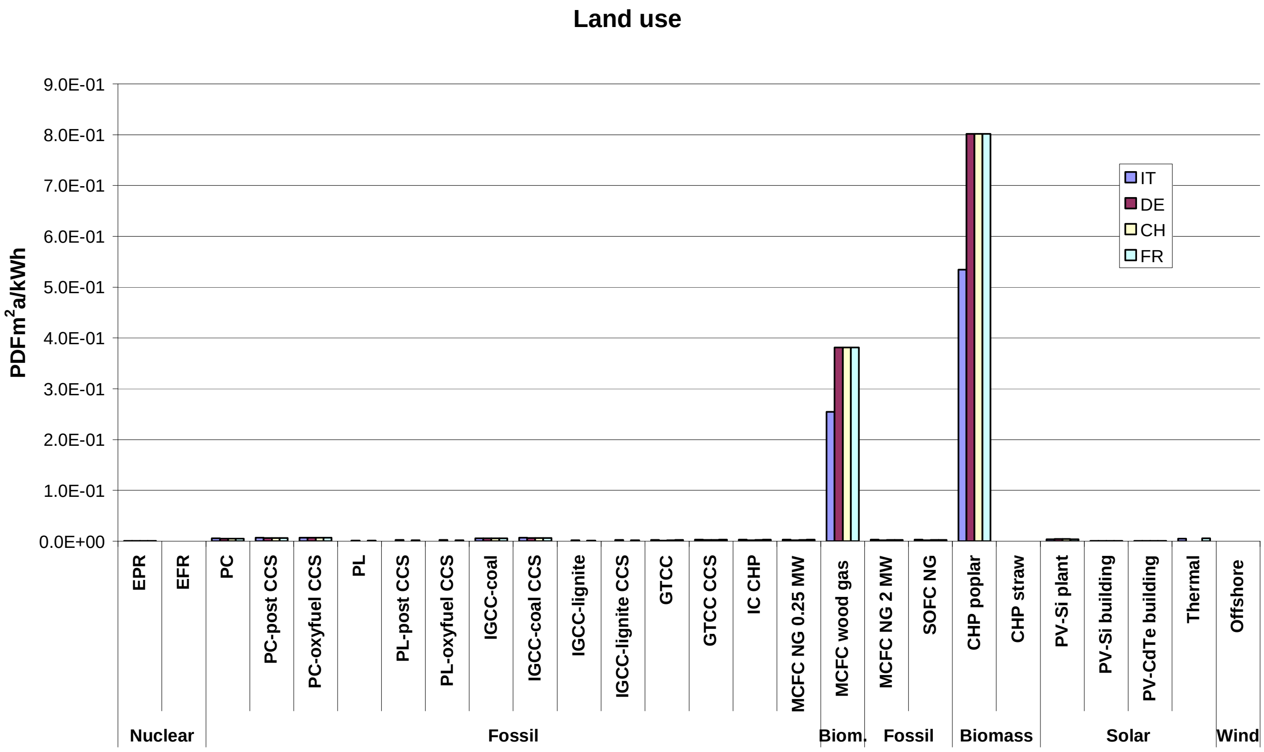

Figure 5 Results of the environmental impact indicator: Land use.

The potential impacts from land use are shown to be dominated by the land requirement for supplying wood-fuel. Whereas the CHP poplar plant receives all of its fuel from intensively cultivated short rotation practices, the supply for the wood gas fuel cell plant uses 50% waste from forestry activities which is not allocated a land use occupation. The results also reflect the energy density of the crop and the large area of land required to maintain a continuous but sustainable supply of woody biomass. The warmer climate in Italy encourages a longer growing season and so therefore a reduced land requirement per unit electricity generated. Straw is considered a waste by-product of cultivating cereals and is therefore also without the allocation of a land occupation.

8.6 Ecotoxicity (PDFm^{2}a/kWh)

This indicator quantifies the loss of species (flora & fauna), also in terms of a “potentially disappeared fraction” (PDF), due to ecologically toxic emissions in producing 1 kWh of electricity. The PDF of species is expressed according to toxic substances released to air, water and soil, and is also modeled as part of the Eco-Indicator 99 (EI99) impact assessment methodology (Goedkoop and Spriensma, 1999).

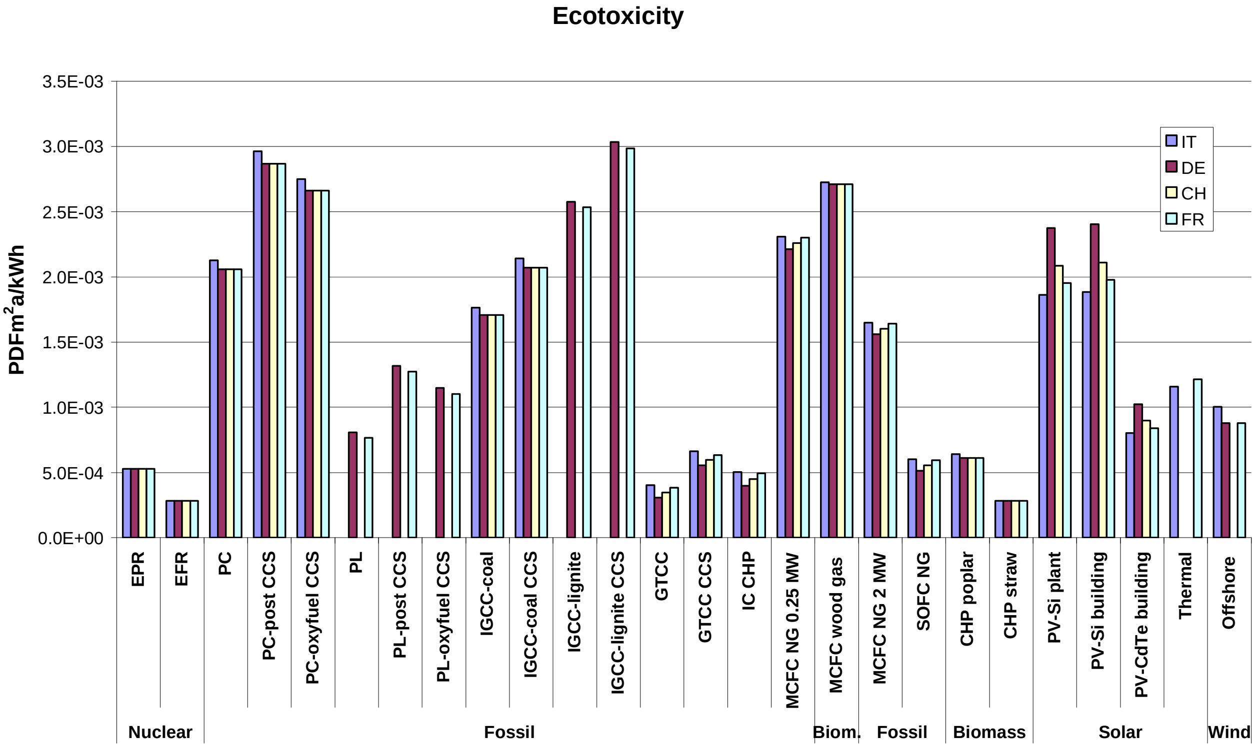

Figure 6 Results of the environmental impact indicator: Ecotoxicity.

Potential ecotoxic impacts are shown to occur in relatively similar quantites for both fossil and renewable technologies, with those from nuclear being similar to centralized gas and the biomass CHP technologies. A noteable difference is between pulverized coal and pulverized lignite. Here the ecotoxicity of the coal chain is more than twice that of the lignite chain. The transoceanic transportation of coal contributes 36% of the total impacts, an aspect of the chain which does not exist for lignite. Furthermore, although the combustion of lignite requires the disposal of greater quantities of ash and accounts for almost a half of impacts from this chain, the impact from the operation of the pulverised coal power plant is more than five times that of the lignite plant. A further significant contributor to both energy chains is due to the production of chromium steel used in construction of the power plants, of which the pulverised coal plant has a significantly greater demand. Potential impacts from centralized gas are much lower than for pulverized coal due to lower impacts from all aspects of the energy chain; fewer toxins are produced during combustion, the fuel supply is via pipeline as opposed to motorized vehicle and the power plant itself requires a less intensive use of metals.

The integration of CCS into the energy chains is shown to increase ecotxicity impacts for all fossil fuel chains. Integrating CCS as a post combustion technology necessarily means extra infrastructure and a higher consumption of fuel per kWh at the busbar. These have the effect of increasing the emissions of toxic substances. Oxyfuel combustion incorporates CSS as an integral design aspect and, although the net efficiency of the plant is lower than that of post-combustion, the additional impacts from this are much smaller than the avoided impacts from a smaller demand for overall infrastructure.

The small scale of the MCFC plants and their high level of (particularly chromium) steel components causes these technology chains to exhibit high impacts of ecotoxicit. The SOFC energy chain is significantly less impacting due in large part to a much lower use of chromium steel.

The difference between the silicon and cadmium telluride photovoltaic energy chains is accounted for by the potential impacts from processing of the different semi-conductor materials used in the PV cells.

8.7 Acidification and eutrophication (PDFm^{2}a/kWh)

This indicator also quantifies the loss of species (flora & fauna) in terms of a “potentially disappeared fraction” (PDF). The impact indicator characterises changes to land and water acidity and neutrient levels, largely as a result of airborne emissions. It is also modeled as part of the Eco-Indicator 99 (EI99) impact assessment methodology (Goedkoop and Spriensma, 1999).

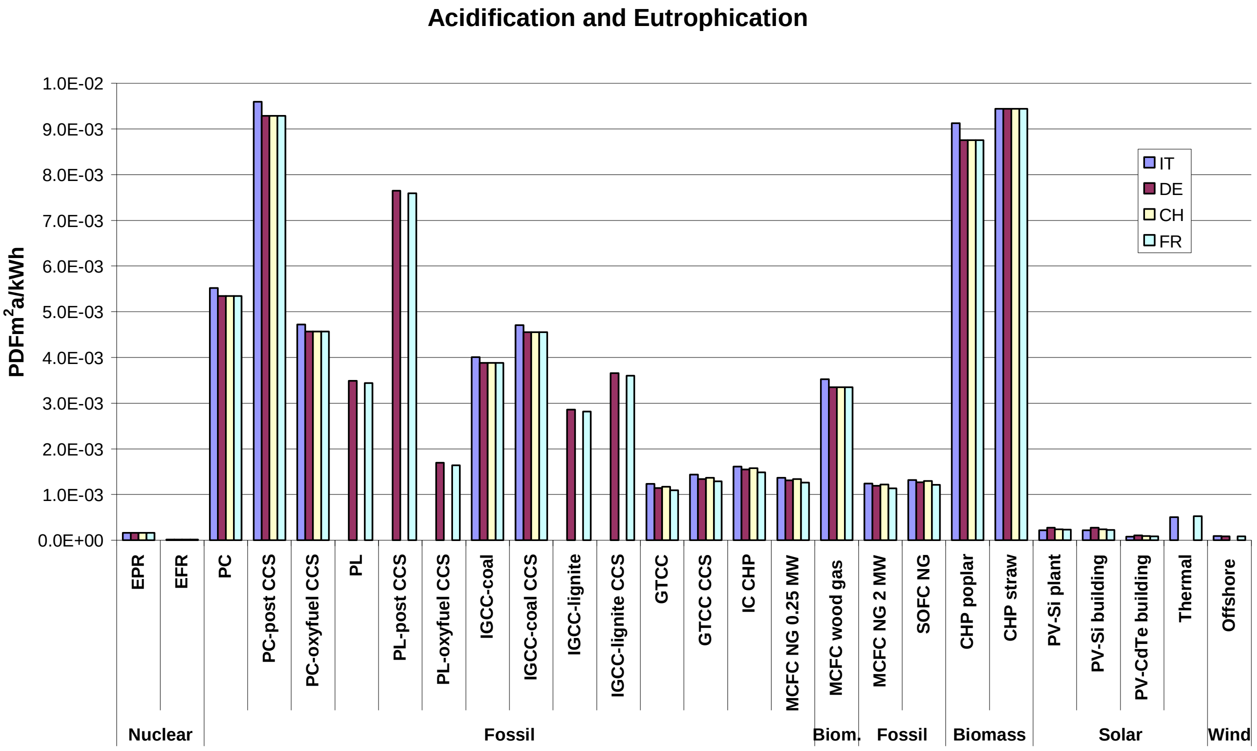

Figure 7 Results of the environmental impact indicator: Acidification and eutrophication.

The incorporation of carbon capture as a post combustion technology is shown to significantly increase the potential impacts due to acidification and eutrophication but which are not present for the oxyfuel combustion and capture process. In the post combustion capture system analysed for NEEDS, a monoethanolamine (MEA) solvent is used to scrub the flue gas and absorb the CO_2. The CO_2 is then separated from the solvent using heat and in this process ammonia is released as an emission to air. Combustion of coal and lignite as an oxyfuel, and therefore in the abscence nitrogen, requires less elaborate and chemically intensive treatment of the flue gas which has a very high concentration of CO_2.

The higher values for the biomass CHP plants are due to the emissions of nitrogen oxides during combustion and which then act as a fertilizer and increase natural nutrient levels.

8.8 Chemical waste (m³/kWh)

This indicator quantifies the total volume of chemical wastes requiring storage in underground repositories[3] due to the production of 1 kWh of electricity. Being a measurement of physical quantities, it does not reflect actual damage to humans or nature and does not reflect the confinement time required for each repository. It covers each complete electricity generation technology chain.

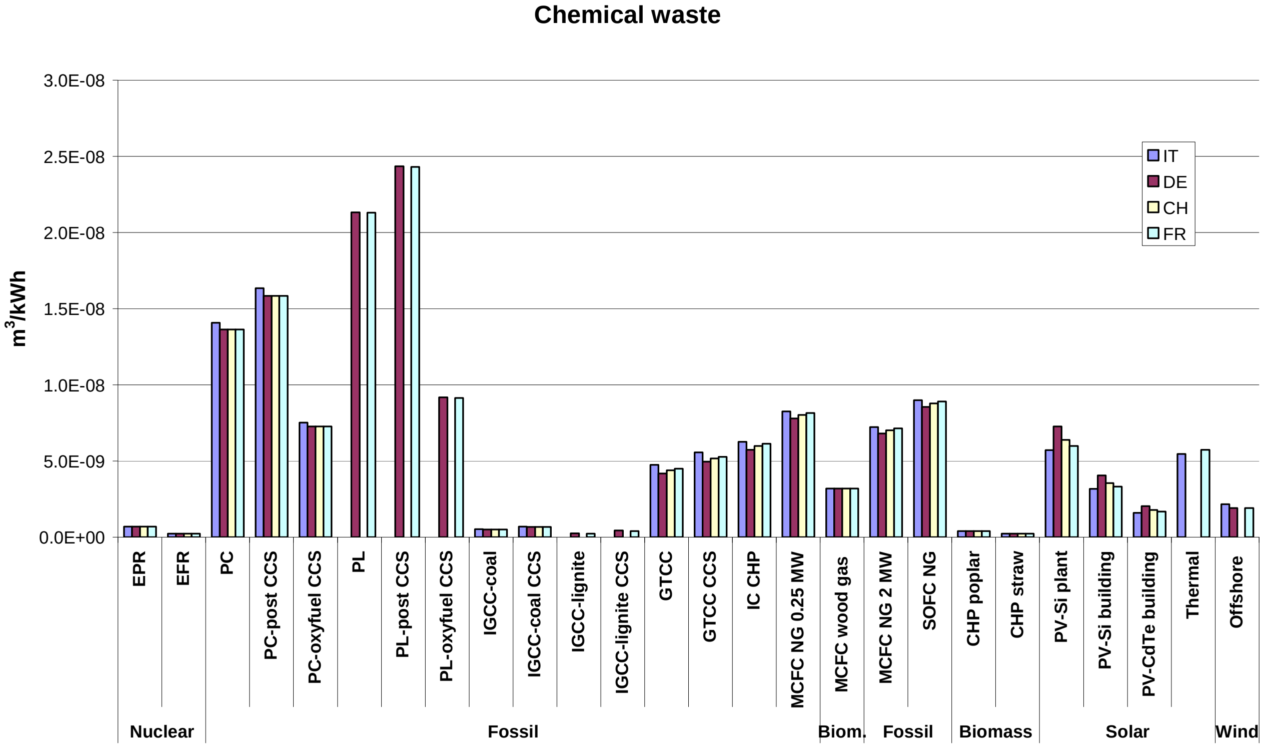

Figure 8 Results of the environmental impact indicator: chemical waste.

Increases in the quantities of chemical waste produced by coal and lignite with post combustion CCS are caused by the reduced efficiency of the plants as well as the requirement for disposal of the solvents used in the CO_2 scrubbing process. More than 90% of the total volume of chemical waste is from the catalytic converters used in the reduction of nitrogen oxides (NO_x). The oxyfuel combustion technologies use a cryogenic air separation unit prior to combustion and therefore do not need to separate NO_x from the flue gas and which explains the significantly lower values for these technologies. The chemical wastes from the lignite energy chains are higher than for their pulverised coal counterparts because the lignite fuel contains higher levels of nitrogen than hard coal. IGCC technologies produce relatively small quantities of chemical waste because the gas produced through gasification of the hydrocarbon fuel is primarily hydrogen (H_2) and carbon monoxide (CO). Oxides of nitrogen and sulphur are not formed in the (reducing) environment of the gasifier but, instead, react with hydrogen to form marketable byproducts of ammonia and hydrogen sulphide. In this way as much as 95 to 99% of NO_x and SO_2 emissions are removed and so do not cause chemical wastes. IGCC technologies using lignite are shown to cause slightly less chemical waste because, at such relatively small amounts compared to non-IGCC fossil fuels, there are no demands made from transportation and storage of the lignite.

Differences between fuel cell technologies using natural gas and the fuel cell using gasified wood stem from the chemical wastes caused at the natural gas extraction sites.

Although on a larger scale, the energy chain of the ground level PV-Si system requires the long-term storage of more chemical waste than the smaller, building mounted PV-Si system because of the larger amounts of aluminium used to construct the free standing ground system. Chemical waste from aluminium production is

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[3] Represented by the elementary flow „Volume occupied, underground deposit“.

mainly caused by the reprocessing of scrap aluminium (used consumer products) which requires the containment of dust, the exchange of filters and the collection of sediment. The quantity of secondary aluminium recycled into the production mix is around 32% (Classen et al., 2004).

8.9 Radioactive waste (m^3/kWh)

This indicator quantifies the volume of intermediate and high level radioactive wastes requiring storage in geological underground repositories[4] due to the production of 1 kWh of electricity. Being a measurement of physical quantities, it does not reflect actual damage to humans or nature and does not reflect the confinement time required for each repository. It covers each complete electricity generation technology chain.

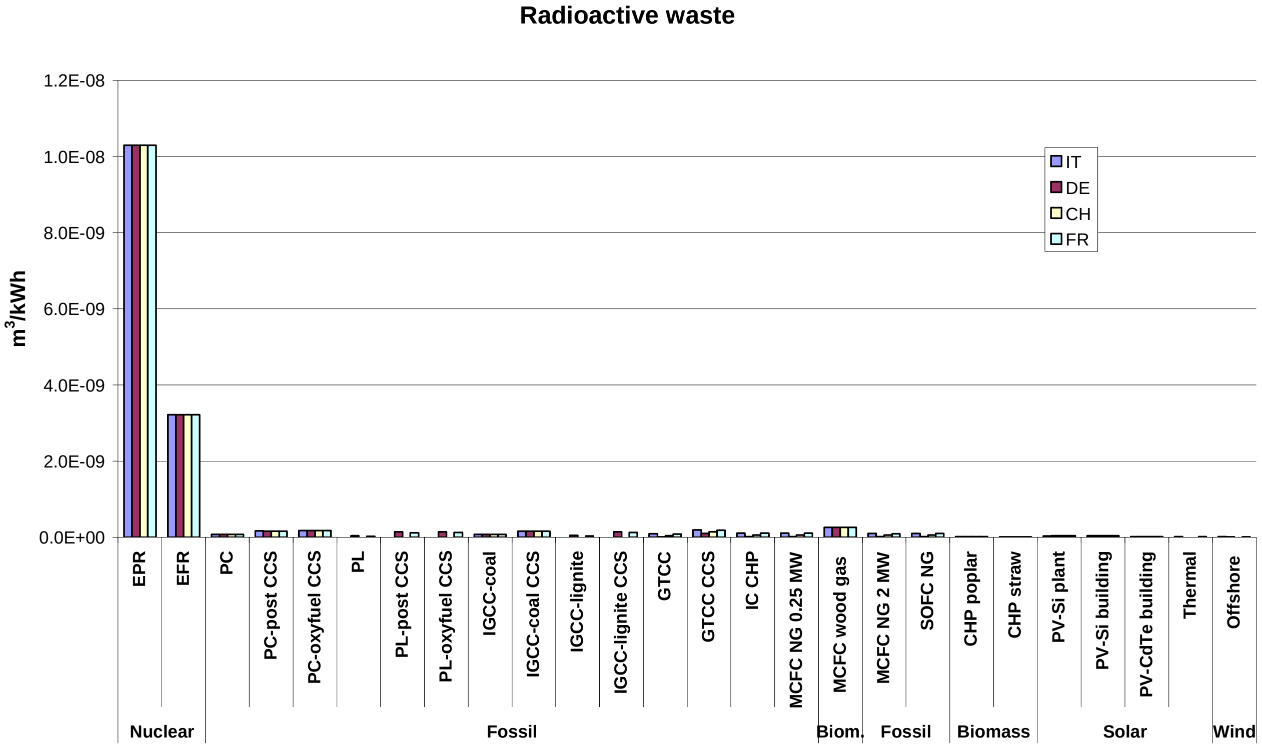

Figure 9 Results of the environmental impact indicator: Radioactive waste.

The quantity of intermediate and high level waste produced by the EFR is foreseen to contain far less spent fuel per kWh generated than for the EPR, as well as producing far less long-lived waste due to the transformation of plutonium. Figure 9, however, only shows a reduction of around 70% which is due to the other active wastes requiring storage. These are the fuel element casing materials as well as high level wastes from the reprocessing stages and preparation of the MOX elements prior to use in the EFR. Some of these processes and associated wastes also result from the EPR energy chain.

The other, non-nuclear, energy chains are shown to have differing but much smaller quantities of radioactive waste associated with them. Here, the electricity used in these energy chains originates from electricity mixes for which nuclear power is a contributor. The use of electricity therefore has the allocation of a volume of radioactive waste.

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[4] Represented by the elementary flow „Volume occupied, final repository for radioactive waste“

9 Summary

This report has given a review of the procedures used in selection of the environmental impact indicators as well as the life cycle assessment (LCA) methodologies employed for their assessment within the NEEDS Integrated Project. The basic charateristics of the 26 technologies and associated energy chains have been described. These were defined as being appropriate in 2050 according to “realistic/optimistic” development scenarios and the assessment methodologies were applied according to the various specific characteristics relevant to the four countries of Switzerland, Italy, Germany and France.

The environmental assessment showed that the nuclear technologies cause relatively very low impacts for most of the indicators. The Generation IV, European Fast Reactor (EFR), has significant advantages over the European Pressurised Reactor (EPR) because it recycles some of the spent fuel products of the EPR and other reactors, and which significantly reduces the quantity of high level radioactive waste needing long-term underground storage. However, the uncertainties associated with its technology development are comparatively much higher than for the EPR.

An overall distinction of the fossil fuelled technologies was shown to be far less clearly possible according to the indicators used. Concerning the application of CCS technologies, the large reductions in GHG emissions from the entire energy chains of fossil fuelled technologies was shown to be counteracted in a number of other indicators due to the reduced efficiencies of the power plants and, specifically for the post combustion and IGCC technologies, the pollution effects of the CO_2 separation mechanisms. Integrating gasification prior to the combustion of coal and lignite was only shown to have significant potential benefits due to the reduction of chemical wastes and with slight reduction in the impact on natural acidity and nutrient levels. On the other hand, the potential impacts caused by toxic releases were seen to be larger by integrating gasification. For most of the indicators, electricity from natural gas combined cycle power plants performs better than from coal and lignite power plants.

The distinction of characteristic impacts is however easier for the cogeneration technologies either using fuel cells or combustion and with similarites between wood based fuels. If they are fuelled with natural gas then they cause the typical impacts of fossil fuel resource depletion, GHG emissions and slightly higher chemical wastes but do not have the impacts from NO_x emissions and land use as do wood based fuels.

In a similar manor to nuclear technologies, the remaining renewable technologies of PV and wind perform well, with only very few indicators reflecting significantly larger impacts; specifically the depletion of metal resources (with the exceptions of PV thin film and solar thermal) and, to a lesser extent, ecotoxicity and the production of chemical wastes. The development of novel PV technologies is also associated with much higher uncertainties compared to the other renewables.

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