Project No 211859
PLANETS
Probabilistic Long-Term Assessment of New Energy Technology Scenarios

SP1 – Cooperation
Collaborative project
Small or medium-scale focused research project

DELIVERABLE No 9
[Report on "Technology: policy dimension"]

Due date of deliverable: end of May 2009
Actual submission date: 30th June 2009

Start date of project: 01/01/2008 Duration: 30 months

Organisation name of lead contractor for this deliverable: Lithuanian Energy Institute

Revision:

Project co-funded by the European Commission within the Sixth Framework Programme (2002-2006)		
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)	

Report on "Technology: policy dimension"

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1. Executive Summary

EU policy analysis was performed and the main quantitative targets were presented in the framework of social, economic and environmental indicators in this report. Electricity generation technologies were assessed in terms of sustainability and competitiveness. Several scenarios were developed for electricity generation technologies assessment. Based on integrated sustainability index and equally treating all criteria the best technology (having the lowest score in assessment) is hydro, followed by wind and the worst –lignite condensing power plant. In economy focused scenario the best technology is the natural gas combine cycle and the worst is MFSC. In environmentally focused scenario the best technology is hydro, followed by wind and the worst technology is hard coal CHP with backpressure turbine. In socially focussed scenario the best technology is solar, followed by wind and the worst technology is lignite condensing power plant. Electricity generation technologies were also assed in terms of competiveness based on the total social costs and comparativeness indicator. The most competitive electricity generation technologies after the internalization of external costs are biomass (wood chips) CHP with an extraction condensing turbine.

The assessment of electricity generation technologies based on various economic, environmental and social criteria provided in this report can serve as a complementary material to results of various policy scenarios runs providing electricity generation technology ranking according priorities of EU energy and environmental policies and can serve as guidance for further policy development in EU. However taking into account the main focus of project - climate change mitigation issues - the long-term assessment of new energy technologies in electricity and transport sectors was performed for various long-run policy scenarios taking into account 2 main criteria: private costs and external GHG emission costs. Such policy oriented energy technologies assessment based on carbon price and private costs of technologies can provide information on the most attractive future energy technologies taking into account climate change mitigation targets and GHG emission reduction commitments for world regions.

Analysis of life cycle GHG emissions and private costs of the main future electricity generation technologies performed in this report indicated that biomass technologies except large scale straw combustion technologies followed by nuclear have the lowest life cycle GHG emission. Biomass IGCC with CO_2 capture has even negative life cycle GHG emissions. The cheapest future electricity generation technologies in terms of private costs in long-term perspective are: nuclear and hard coal technologies followed by large scale biomass combustion and biomass CHPs. The most expensive technologies in terms of private costs are: oil and natural gas technologies. As the electricity generation technologies having the lowest life cycle GHG emissions are not the cheapest one in terms of private costs the ranking of technologies in terms of competitiveness highly depend on the carbon price implied by various policy scenarios integrating specific GHG emission reduction commitments taken by countries and climate change mitigation targets.

Analysis of life cycle GHG emissions and private costs of the main future transport technologies performed in this report derived that transport technologies based on biodiesel from waste vegetable oil have the lowest life cycle GHG emission followed by technologies using bioethanol from wheat. Petrol based transport technologies have the highest life cycle GHG emissions followed by diesel technologies. The most expensive in terms of fuel costs are bioethanol transport

technologies and the cheapest are transport technologies based on petrol and diesel. Therefore the transport technologies having lowest life cycle GHG emission are among the most expensive in terms of fuel costs. Therefore as in the case of electricity generation technologies the policy oriented ranking of transport technologies highly depends on carbon price developments caused by foreseen future climate change mitigation policies.

The assessment of the main selected power and transport technologies based on external costs of GHG emissions and total costs was performed in 2020 and 2050 for the first best (FB-3p2) and second best scenarios (SC1-3p2; SC2-3p2). Scenarios with more strict targets (3.2 M/m2) were selected for technologies assessment and ranking.

The ranking of energy technologies based on costs (private, external and total) points to a general problem in having costs as the main parameter for comparison of different technologies since these energy technologies do not always compete on the same markets. Energy technologies show a large span in costs, efficiencies and installed capacities therefore it is problematic to compare such processes on the cost basis alone nevertheless the comparison of different energy technologies based on total costs and carbon price enables to develop some important policy recommendations even taking into account high uncertainties in private and external costs.

11 main future electricity generation technologies were selected for technologies ranking: nuclear, oil, natural gas, hard coal including hard coal technologies with CO_2 capture and various biomass technologies (wood chips combustion, gasification, CHP, straw combustion, biomass IGCC with CO_2 capture). For all policy scenarios electricity generation technologies ranking in 2020 and 2050 based on external GHG costs provides the same results as the same data on life cycle GHG emissions were applied for technologies ranking. The most competetive technology according all policy scenarios based on external GHG costs in 2020 and 2050 is biomass IGCC with CO_2 capture biomass followed by other biomass technologies. Nuclear is ranked in the middle.

Though quite different ranking of electricity generation technologies is obtained for various scenarios and time frames the results obtained in technologies ranking based on external GHG emission costs and total costs are similar just for FB-3p2 scenario in 2050 because of very high carbon price (375 EUR/tCO_2 eq). External costs of GHG emissions in FB-3p2 scenario in 2050 overweight impact of private costs in technologies ranking.

The most expensive technology in terms of total costs for all main policy scenarios in 2020 and 2050 is oil. The most competitive technology for all scenarios in 2020 is nuclear followed by large scale wood chips combustion technologies and in 2050 - biomass IGCC with CO_2 capture followed by biomass wood chips gasification CHP small scale. The hard coal and natural gas technologies are among the most expensive for all policy scenarios. In 2050 because of the high carbon prices in all policy scenarios natural gas technologies are more competitive than coal and in 2020 coal technologies are more competitive than natural gas technologies as private costs overweight external costs of GHG emissions in comparative assessment of technologies.

The ranking of biomass technologies based on total costs is different for specific scenarios and time frames and depends on carbon price obtained by specific scenarios. Very high carbon prices make more competitive technologies

having low life cycle GHG emission such as biomass IGCC with CO_2 capture and biomass wood chips gasification technologies though these technologies in terms of private costs are more expensive than other biomass technologies nevertheless the external costs of GHG emissions in high carbon price scenarios overweight the private costs in technologies ranking.

Policy oriented comparative assessment of transport technologies based on carbon prices performed in this report indicated that the most competitive transport technologies based on external GHG costs are technologies having the lowest life cycle GHG emissions, i. e. biodiesel from waste vegetable oil based technologies followed by bioethanol from wheat and from sugar beet based transport technologies. The same ranking of transport technologies is achieved for all policy scenarios considered and for both time framewoks: 2020 and 2050.

Because of very high carbon prices in 2050 in first best policy scenario FB-3p2 the ranking of transport technologies based on total costs and on GHG emission costs are very similar for this scenario but very different for all other policy scenarios especially in year 2020 where fuel costs are dominating in transport technologies ranking because of comparatively low carbon prices in second bets policy scenarios. However in 2050 the carbon price is the main determinant in transport technologies ranking and there are no big differences in transport technologies ranking in this year for all policy scenarios. Transport technologies having low life cycle GHG emissions are the most competitive. Especially first best policy scenario provides for the competitive advantage of low carbon transport technologies such as biodiesel and bioethanol.

The ranking of biomass technologies in transport and electricity generation based on total costs is different for specific scenarios and time frames and highly depends on carbon price obtained by specific scenarios. Very high carbon prices make more competitive technologies having low life cycle GHG emission such as based on biomass though these technologies in terms of private costs are more expensive than other technologies but external costs of GHG emissions in high carbon price scenarios in 2050 usually overweight the private costs in technologies ranking.

2. Introduction

Within EU collaborative Project Planets (Probabilistic Long-term assessment of New Energy Technologies), the objective of Work Package 3 „Technology assessment: policy dimension“ is to assess the possible impact of new energy technologies on competitiveness and export opportunities in the EU-27 in the short term and on sustainability including job creation opportunities in the longer run, that is up to 2050.

Work Package (WP) 3 comprises of 3 main tasks: EU policy assessment; technologies assessment based on EU policy assessment and uncertainty assessment of major physical and economic characteristics of energy technologies.

The main goal of EU energy policy assessment is to review EU and world energy and environmental policies and corresponding energy and environmental targets. The goal of Technology assessment is to develop a framework for comparative analysis of energy technologies and scenarios in the electricity, transport and building sector in a dynamic way. The methodological framework for energy technologies assessment is based on short-term competiveness assessment and sustainability assessment.

Over the last decade, the impact of “sustainability” on the development of national and international policy has increased. Efforts towards a sustainable energy system are progressively becoming an issue of paramount importance for decision makers. Efficient production, distribution and use of energy resources and provision of equitable and affordable access to energy while ensuring security of energy supply and environmental sustainability are the main energy policy objectives towards a sustainable energy system. Implementation of new energy technologies is a key mean towards a sustainable energy system. Technological advances are of critical importance for the improvement of living conditions, the production and the transportation of the energy and the efficiency of its use thus it is expected to produce major public benefits. New energy technologies can be considered to be an important bridge between the Lisbon Strategy objective of making the European Union “the most competitive and dynamic knowledge-based economy in the world” and the EU Sustainable development strategy agreed at the Goteborg European Council.

Therefore decision makers have to decide from an increasingly diverse mix of new energy technologies, the ones which warrant support, including funding (e.g., R&D support) and other incentives for private sector efforts. However, the identification of these technologies that can comply with the emerging needs and opportunities in the three sustainable development dimensions, namely the economic, environmental and social is a very complex process. Therefore, methods and tools are needed to assist policy design, in terms of establishing technological priorities towards a sustainable energy system. The multi-criteria methods can be an important supportive tool in decision making, providing the flexibility and capacity to assess the technologies’ implications to the economy, the environment and the social framework. Especially, this is true taking into consideration that many of the key attributes of energy technologies, which are not market-valued and concern the social and environmental dimension of sustainable development, are often excluded from the analysis.

EU and member states have carried out national Technology Foresight Programmes, given the importance of research priorities for supporting the new and innovative energy technologies. European Strategic Energy Technology Plan (SET-Plan) aiming to facilitate the innovation challenges of the energy related sectors, which arise from concerns about climate change and supply security was proposed in 2007. The plan proposes joint strategic planning, effective implementation and sharing resources for research and international cooperation for accelerating market introduction and take up of low-carbon and efficient energy technologies.

The future development and deployment of new energy technologies highly depends on energy and environmental policies taking into account sustainable development principles and their established binding targets for GHG and other pollutants emissions, renewable energy sources, energy efficiency improvements etc. Most of the policies focusing on these respective issues are interrelated. Therefore the review of EU policies and systematization of targets set by these policies would allow developing the comprehensive indicators framework of technologies sustainability and competitiveness assessment.

The assessment of innovative energy technologies will be performed based on the economic, environmental and social criteria by applying quantitative and qualitative indicators. Therefore assessment of new energy technologies through a number of criteria is a complex and time consuming task, since the analysis has to face a series of uncertainties such as fossil fuel price, environmental regulations, market structure, technological, and demand and supply uncertainty. Furthermore, sustainability is an inherently vague and complex concept and the implications of sustainable development as a policy objective is difficult to be defined or measured. In particular, the information needed for the evaluation of technologies in terms of their sustainability may be unquantifiable due to its nature or even unavailable. Therefore, appraising energy technologies in terms of their sustainability and competiveness is a really complex task, considering the series of uncertainties and implications that have to be encountered so as to obtain realistic and transparent results.

3. EU Policy assessment

The future development and deployment of new energy technologies is defined by priorities and targets set by energy and environmental policies. Therefore very important task is to review EU sustainable development policies in energy sector and to systematize their targets set for energy sector. These targets expressed in quantitative and qualitative indicators can be applied or developing indicators framework for technologies assessment.

The aim of this chapter is to review EU energy and environmental policies targeting various energy sectors and to select the most important targeted indicators for sustainability and competitiveness assessment of energy technologies. The main tasks of this chapter are:

- To review EU policy documents and binding targets set by these policy documents;
- To systematize targets set by EU policy documents and develop indicators framework for sustainability assessment.

3.1 EU policy documents targeting energy efficiency, renewables, climate change mitigation and pollution reduction

The main EU policy documents and directives which have impact on sustainable energy development are directives promoting energy efficiency and use of renewable energy sources, directives implementing greenhouse gas mitigation and atmospheric pollution reduction policies and other policy documents and strategies targeting energy sector. Promotion of use of renewable energy sources especially biomass and energy efficiency improvements are among priorities of EU energy policy because use of renewables and energy efficiency improvements has positive impact on energy security and climate change mitigation. The directives targeting energy efficiency, renewables and climate change mitigation indicates the EU energy policy priorities: reduction of energy impact on environment, improvements in energy generation and energy use efficiencies, increase in reliability and security of energy supply, promotion of renewables use and climate change mitigation. All these directives have specific targets which can be addressed by quantitative indicators. As targets set by specific directives are related the use of interlinked indicators framework to address these targets can be useful tool for energy policy analysis and monitoring. Such tool applied by EU member states can help to harmonize EU energy policies and enhance its implementation on country level.

On 10 January 2007 the Commission adopted an **Energy and climate change package**, calling on the Council and European Parliament to approve: an independent EU commitment to achieve a reduction of at least 20% in the emission of greenhouse gases by 2020 compared to 1990 levels and the objective of a 30% reduction by 2020, subject to the conclusion of a comprehensive international climate change agreement; a mandatory EU target of 20% renewable energy by 2020 including a 10% biofuels target. This strategy was endorsed both by the European Parliament and by EU leaders at the March 2007 European Council. The European Council invited the Commission to come forward with concrete proposals, including how efforts could be shared among Member States to achieve these targets. This package is the reply to that invitation. It comprises a set of key policy proposals that are closely interlinked. They include: (1) a proposal amending the EU Emissions Trading Directive (EU ETS); (2) a proposal relating to the sharing of efforts to meet the Community's independent greenhouse gas reduction commitment in sectors not covered by the EU emissions trading system (such as transport, buildings, services, smaller industrial installations, agriculture and waste); (3) a proposal for a Directive promoting renewable energy, to help achieve both of the above emissions targets. Other proposals that are also part of the package include a proposal for a legal framework on carbon capture and storage, a Communication on the demonstration of carbon capture and storage and new guidelines for environmental state aid.

The EU Green paper on European Strategy for Sustainable, Competitive and Secure Energy (SEC (2006) 317) (EU, 2006) sets the main priorities for EU energy strategy: competitiveness of the EU economy, security of supply and environmental protection. These objectives should help to address central policy concerns such as job creation, boosting overall productivity of the EU economy, protection of the environment and climate change.

The Commission's Green Paper on energy efficiency COM (2005) 265 (EU, 2005) stresses the importance of energy efficiency improvement for the controlling of demand growth and security of supply. According to estimates, the economic potential for improving energy efficiency in 2010 for all sectors combined is 20% of the total annual primary energy consumption of the current level. There are several directives aiming to implement Commissions Green Paper on energy efficiency: 2006/32/EC Directive on energy end-use efficiency and energy services, 2002/91/EC Directive on the energy performance of buildings and 2004/8/EC Directive on the promotion of cogeneration.

The **2006/32/EC Directive on energy end-use efficiency and energy services** sets the targets for EU member states to reduce final energy consumption by 9% during the nine year period until 2015 and proposes set of measures to achieve these targets: voluntary agreements, white tradable certificates, energy service obligations, energy audits etc.

2002/91/EC Directive on the energy performance of buildings sets target to realize a savings potential of around 22 % by 2010 for energy used in heating, air – conditioning, hot water and lighting. The main measures proposed for achieving this target are: improved standards, certification of buildings and information on energy consumption in buildings disclosure, subsidies form EU structural funds for energy efficiency improvements in public buildings, the incentive billing of residents of the buildings, soft loans for energy efficiency improvements in multi-flat buildings etc.

2004/8/EC Directive on the promotion of cogeneration based on a useful heat demand in the internal energy market aims to increase energy efficiency and improve security of supply by creating a framework for promotion and development of high efficiency cogeneration of heat and power based on useful heat demand and primary energy savings taking into account the specific national circumstances especially climate and economic conditions. The strategic goal of EU-15 is to double the share of electricity produced by combined heat and power pants (CHP) by 2010. The different mechanisms can be applied to support cogeneration at the national level, including investment aid, tax exemptions or reductions, green certificates and direct price support schemes, information disclosure etc.

White Paper for a Community Strategy and Action Plan on renewable energy sources COM (97) 599 final (EU, 1997) states that member states should formulate indicative targets contribute to the ambitious indicative target of doubling the overall share of renewables in the EU by 2010. It sets an indicative target of 12% for the contribution by renewables to the total primary energy consumption within EU by 2010 and contains a strategy and action plan to achieve this target. Pursuant to the White paper on Renewables the **Directive 2001/77/EC on the promotion of electricity produced from renewable energy sources in the internal electricity market** was passed in 2001. It adds the indicative target contribution of 22.1% by renewables-based electricity to total EU electricity consumption in year 2010. The main measures foreseen in directive: Feed-in prices for electricity produced from renewables, green tradable certificates,_competitive bidding processes, voluntary agreements, generation disclosure rules, green electricity purchases, subsidies and soft loans for renewables projects etc.

The draft Directive promoting heating and cooling from renewable energy sources was put forward. The purpose of directive is to promote renewable heating & cooling. The EU target: 20% of heat & cold from renewables by 2020.

National binding targets should be established by technology. National support mechanisms should be putted in place including green tradable certificates for heat produced from renewables, Feed-in prices for heat produced from renewables etc. Removal of administrative barriers, reliable statistics and monitoring of results are necessary.

In the EU, bio-energy resources such as forestry and agriculture crops, biomass residues and wastes already provide around 5% of all energy and 65% of renewable energy. And the potential of bio-energy is huge. In the EU it has been estimated that it could be capable of supplying more than 235 Mt of oil equivalent in 2020 without environmental damage. The EC acknowledges this potential and adopted the **European Biomass Action Plan** in December 2005 to ensure that biomass plays an increasingly important role in our energy mix in view to meet our 2010 renewables target. Also important is to mobilise our agricultural and forestry sectors. It is necessary to make such resources available for energy use while ensuring that conflicts between the different types of biomass are avoided. Therefore Member States are encouraged to develop their national biomass action plans and to subsequently exchange information and best practices for better utilisation of wood resources. Countries such as Finland, Sweden and Austria successfully use some of their wood supply for energy. A key factor in these countries has been co-ordination between forest owners; energy, wood-processing, harvesting and logistical industries; and public authorities. This might be an example to follow in many Member States where better co-ordination is still needed, both at national and regional levels.

In 2007, the EC proposed an **European Strategic Energy Technology Plan** which will address the development of second generation biofuels to become fully competitive alternatives to hydrocarbons. The Plan will consider how to better coordinate existing resources, how to use them in a more targeted and focused manner and where to invest more. An EU Strategy for Biofuels adopted on 2006 aims to further promote biofuels in the EU and developing countries, ensure that their production and use is globally positive for the environment and to prepare for the large-scale use of biofuels by improving their cost-competitiveness and support for market penetration by scaling up demonstration projects and removing non-technical barriers. The exploration of the opportunities for developing countries for the production of biofuel feedstock and biofuels is also proposed in the strategy.

2003/30/EC Directive on the promotion of the use of biofuels or other renewable fuels in transport (*RF Directive*) sets that Member States must ensure by end of 2005 a 2 % minimum proportion of biofuels of all gasoline and diesel fuels sold on their market. In longer term the target is to achieve a share of 5.75 % of biofuels for transport in the total amount of fuels in Europe by 2010 and 20 % by 2020. The main measures foreseen in directive include: excise, VAT, pollution and other tax exemptions for biofuels, financial (subsidies or soft loans) assistance for the processing industry and the establishment of a compulsory rate of biofuels for oil companies etc.

All these directives and policy documents described above have positive impact on greenhouse gas emission reduction and achieving of Kyoto target. EU has ratified Kyoto Protocol committing itself to 8% greenhouse gas emission reduction in the period 2008-2012 from the 1990. Equally the New Member States are determined to meet their individual targets under the Kyoto Protocol. Baltic States have the same target as EU-15.

Therefore the main targets of EU energy policy which can be addressed by selecting the appropriate indicators are: to increase security of energy supply, promotion of renewable energy sources and cogeneration and increase of end-use energy efficiency. All these policies have positive impact on greenhouse gas emission reduction which is also the priority issue of EU energy policy (Jaccard and Mao, 2002) however the positive impact on other sustainable energy development targets is not so obvious and needs to be assessed.

In addition there are several EU environmental policy goals related to sustainable energy development, i.e. air pollution reduction set by EU Thematic strategy on Air Pollution and National emission ceilings, Large combustion source directives which do have impact on greenhouse gas emission increase in member states therefore the contradiction between these policies can be noticed.

In its **Thematic Strategy on Air Pollution (COM (2005 446 final**), the European Commission outlined the strategic approach towards cleaner air in Europe and established environmental interim targets for pollutants contributing to acidification, eutrophication and the formation of ground-level ozone in year 2020 compared to year 2000 levels. As one of the main policy instruments, the Thematic Strategy announced the revision of the Directive on National Emission Ceilings (2001/81/EC) with new emission ceilings that should lead to the achievement of the agreed interim objectives. In the meantime European Commission started the process to develop national ceilings for the emissions of the relevant air pollutants. The EU global goal in 2020 would make for SO2 - reduction by 87%, for NOx- reduction by 50%, for PM2.5 by 41%, for NH3 - by 25% and for VOC- by 46% compared to 2000. The main EU legislation for pollutants contributing to acidification, eutrophication and the formation of ground-level ozone relevant to energy production sector are Large Combustion plant directive (2001/80/EC), Sulphur Content of Liquid Fuels Directive (1999/32/EC), and National emission ceilings directive (2001/81/EC) etc.

2001/81/EC Directive on national emission ceilings for certain atmospheric pollutants sets since 2010 the national emission ceilings for SO_2, NO_X, VOC and NH_3 which are very close to the limits of the same pollutants established by Gothenburg protocol to Long Range Transboundary Air Pollution Convention. This directive establishes national emission ceilings for EU member states for SO_2, NO_X, VOC and NH_3.

Directive 1999/32/EC relating to a reduction in the sulphur content of certain liquid fuels (Sulphur directive) is to ensure that as from 1 January 2004 the heavy fuel oil (HFO) used within territories of EU Member States do not exceed the sulphur content of 1,00 % by mass. The requirement do not exceed the sulphur content of 1% shall not apply to HFO used in (large and small) combustion plants where the emissions of sulphur dioxide from the plant are less than or equal to 1700 mg/Nm3 and for combustion in refineries, where the monthly average of emissions of SO_2 averaged over all plants in the refinery shall not exceed 1700 mg/Nm3. According the requirements of EU Directive 88/609/EEC it is possible to burn HFO with a sulphur content exceeding 1% if it is co-combusted with either natural gas or with biomass. Thus, HFO - having a sulphur content of 2.2% - can be used by large combustion plants if it is co-combusted with at least 55% natural gas or 55% biomass (in terms of energy input). In this case, the concentration of SO_2 in the flue gas will be kept below 1700 mg/Nm^3.

In addition since 2008 the new norms for SO_2 emission will be established for large combustion plants based on **Directive 2001/80/EC on the limitation of emissions of certain pollutants into the air from large combustion plans (LCP Directive).**

Besides that the implementation of all these directives and policy documents targeting specific but interrelated sustainable energy development targets described above and measures foreseen in these directives would interact with each other and this interaction is necessary to evaluate and address in setting harmonized reinforcing each other energy policies and achieving synergy effect implemented measures. Therefore before the implementation of policies and measures the evaluation of these policies impact on sustainable energy development targets needs to be addressed. The multi criteria decision aiding analysis would allow assessing impact of various energy technologies on sustainable energy development targets imposed by various EU policy documents. Sophisticated modelling tools (General Equilibrium Modelling, Partial Equilibrium Modelling including just energy sector etc.) can be used to assess the impact of various policies on sustainable energy development targets set by directives and Green papers described above.

3.2. Indicators for monitoring implementation of EU directives targeting energy efficiency, renewables and greenhouse gas and other atmospheric emission reductions

Achieving requirements of EU directives targeting sustainable energy development requires regular monitoring of impacts of selected policies and strategies to see if they are furthering sustainable development or if they should be adjusted (Faure and Skogh, 2003). It is important to be able to measure a country's state of implementation of EU directives aiming at sustainable development and to monitor its progress or lack of progress towards achievement of the main targets set by these directives. First of all it is necessary to know the country's current status concerning the established targets, what needs to be improved and how these improvements can be achieved. Second, it is very important for policy makers to understand the implications of selected directives, energy, environmental and economic programmes, policies and plans and their impacts on achieving the main targets and goals set by the main directives. Therefore choosing energy fuels and associated technologies for the production, delivery and use of energy services, it is essential to take into account economic, social and environmental consequences. Policy makers need simple methods for measuring and assessing the current and future effects of energy use. For this purpose energy indicator establishing the aforementioned targets can be used. There are a several frameworks of indicators developed to assess the trends towards sustainable development. The Energy Indicators for Sustainable Development (EISD) have been developed by International Atomic Energy Agency (IAEA) (IAEA, 2005).

The EISD is an analytical tool developed which can help energy decision- and policy-makers at all levels to incorporate the concept of sustainable development into energy policy. The EISD set is used to present energy, economic, environmental and social data for policymakers in a coherent and consistent form, showing their linkages and their usefulness for making comparisons, trend analyses

and policy assessments. Some indicators from EISD set can be selected and applied for the analysis of the EU energy policies in Member States and for the assessing their success towards implementation of the main targets set by directives and other policies establishing goals for energy efficiency improvements, use of renewables and greenhouse gas emission reduction. Therefore indicators relevant to EU energy policies will be selected from the EISD list. The additional indicators to define targets established by EU policies will be developed as well. EISD core set is organized following the conceptual framework used by United Nations Commission on Sustainable Development. There are 30 indicators, classified into three dimensions: social, economic and environmental. The scheme of core EISD is presented in Figure 1.

SOCIAL		
Equity		**Health**
Accessibility SOC1 Affordability SOC2 Disparities SOC3		Safety SOC4
ECONOMIC		
Use and production patterns		**Security**
Overall use ECO1 Overall production ECO2 Supply efficiency ECO3 Production ECO4 and ECO5 End use ECO6-EC10 Diversification ECO11-ECO13 Energy prices ECO14		Imports ECO15 Strategic fuel stocks ECO16

ENVIRONMENTAL		
Air	**Water**	**Land**
Climate change ENV1 Air quality ENV2-ENV3	Water quality ENV4	Soil quality ENV5 Forests ENV6 Solid waste ENV7-ENV9

Figure 1. EISD indicators set

Trends in overall energy productivity, supply efficiency, end-use productivity, and fuel mix and energy security will be analysed using economic dimension indicators. Climate change mitigation issues will be addressed by environmental dimension indicators.

The appropriate EISD were selected to address requirements of EU directives targeting security of supply (ECO 15), energy efficiency improvements (ECO2), promotion of renewables (ECO 11, ECO 13) and greenhouse gas (ENV1) and other atmospheric pollutants emissions (ENV2). The selected indicators were grouped by 4 priority areas established by EU energy policy: increase of energy efficiency, use

of renewables, increase of energy security and greenhouse gas and other atmospheric emission reduction. Additional to EISD framework indicators were developed to address targets of EU relevant to energy efficiency and renewables. The indicators framework for EU energy policy analysis and monitoring of targets by EU directives are presented in Table 1.

Table 1. Indicators selected for EU energy policy analysis

Indicators	**Acronym**	**Subtheme**	**Directive or policy document**	**Target**	**Date for achie-vement**
Energy efficiency (EE)					
End-use energy intensity of GDP	EE1 (ECO2)	Energy efficiency	Directive 2006/32/EC on end-use efficiency and energy services	To reduce by 9% the current level (2006)	2016
Energy saved in buildings	EE2	Energy efficiency	2002/91/EC Directive on the energy performance of buildings	22% of energy used in buildings	2010
Savings of primary energy supply	EE3	Energy efficiency	The Commission's new Green Paper on energy efficiency COM (2005) 265	20% from year 2005 level	2020
The share of CHP in electricity production	EE4	Energy efficiency	2004/8/EC Directive on the promotion of cogeneration national energy strategy	Double the current share	2010
Use of Renewables (RES)					
The share of renewables in primary energy supply	RES1 (ECO13)	Renewables	The White Paper on renewable sources	12%	2010
The share of renewables in electricity generation	RES2 (ECO 11)	Renewables	Directive 2001/77/EC on the promotion of electricity produced from renewable energy sources in the internal electricity market	22,1%	2010
The share of renewables in heat production	RES3	Renewables	Proposal for Directive promoting the renewable heating and cooling	25%	2020

The share of renewables in fuel used in transport	RES4	Renewables	2003/30/EC Directive on the promotion of the use of biofuels or other renewable fuels in transport	2% 5.75% 20%	2005 2010 2020
The share of renewables in final energy	RES5	Renewables	EU energy and climate package: proposal for a Directive of EP and EC on the promotion of the use of energy from renewable sources {COM(2008) 30 final}	20%	2020
Security of Supply (SS)					
Energy independency	ES1 (ECO15)	Security of supply	The EU Green paper on European Strategy for Sustainable, Competitive and Secure Energy	50%	2030
Atmospheric pollution reduction					
Greenhouse gas emissions (CO2 emissions from energy sector)	GHG1 (ENV1)	Climate change	Kyoto protocol	Reduction by 8% of year 1990 level Reduction by 20% of year 1990 level	2008-2012 2020
SO2 emissions, NOx emissions, VOC emissions, NH3 emissions SO2 emissions, NOx emissions, VOC emissions, NH3 emissions	ACD (1-5) (ENV2)	Acidification and eutrophication	Gothenburg protocol NEC directive 2001/81EC	Reduction by 35%, 30 %, 11% 0% comparing to 1990 level, Reduction by 87%, by 50%, by 46% by 41% compared to 2000 level	2010 2020

All these EU energy policy indicators can be connected to each other via the chain of mutual impacts seeking to develop comprehensive policy framework for monitoring implementation of EU directives and tracking various interacting policy measures targeting relevant indicators. The last indicator in EU energy policy

indicators framework is greenhouse gas emission indicator as all other EU policies (targeting energy efficiency improvements, promotion of renewables, and increase in energy supply security) in the end have positive impact on greenhouse gas emission reduction (Streimikiene, Sivickas, 2008).

4. ENERGY TECHNOLOGIES ASSESSMENT FRAMEWORKS AND TOOLS

Energy technologies are vital in reaching sustainable development and all energy, environmental and climate change policy objectives including newest one developed by EC in **Energy and climate change package**: to reduce greenhouse gas emissions by 20% and ensure 20% of renewable energy sources in the EU energy mix; to reduce EU primary energy use by 20% by 2020. Seeking to develop framework for sustainability assessment of energy technologies

The aim of this chapter is to review various concepts and tools form sustainability assessment based on recent scientific articles, books and documents and to discuss their application issues in terms of energy technologies assessment. The main tasks are:

- To review concepts of sustainability assessment;
- To review and compare tools for sustainability assessment;
- To discuss results of recent EU projects dealing with sustainability assessment;
- To analyse energy technologies assessment approaches and indicators for technologies assessment.

4.1 Sustainability assessment

Sustainable development currently is the main concept of development in all levels of economic activity. However giving a clear definition for sustainability assessment can be difficult. Several works on the area already show a wide variety of different interpretations of sustainability assessment. One of the clear reasons for this is that there is no single definition for what is meant by SD. The standard definition of sustainable development provided by the Brundtland Commission “to make development sustainable — to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs” (Brundtlan, 1987) is a starting point for most that set out to define the concept. Many authors have discussed sustainable development. The so-called 'three-pillar' or 'triple bottom line' (TBL) concept has become common to describe sustainable development. The idea is that equal weight is laid on economic, environmental and social considerations in decision-making. Kasemir et al. (2003) describe this research area as combining work in the area of environmental science with work in economic, social and development studies to better understand the complex dynamic interactions between environmental, social and economic issues. However for the transition to sustainability, goals must be assessed. This has posed important challenges to the scientific community in providing efficient but reliable tools. As a response to these challenges, sustainability assessment has become a rapidly developing area. The numbers of tools that claim that they can be used for assessing sustainability have grown; simultaneously many of the tools have developed, providing better application guidelines, data and case study experiences. Sustainability assessment has increasingly become associated with the family of

impact assessment tools consisting of e.g. Environmental Impact Assessment and Strategic Environmental Assessment (Pope, 2004), or EU Sustainability Impact Assessment. (Devuyst et al., 2001).

Sustainability assessment is a tool that can help decision-makers and policy-makers decide what actions they should take and should not take in an attempt to make society more sustainable" (Devuyst et al., 2001); or "The aim of sustainability assessment is to ensure that plans and activities make an optimal contribution to sustainable development" (Verheem, 2002).

Sustainability assessment is a tool that can help decision-makers and policy-makers decide which actions they should or should not take in an attempt to make society more sustainable. Kates et al. (2001) provides that the purpose of sustainability assessment is to provide decision-makers with an evaluation of global to local integrated nature–society systems in short and long term perspectives in order to assist them to determine which actions should or should not be taken in an attempt to make society sustainable.

In 2001, the Gothenburg European Council Conclusions stated in the part on the EU Sustainable Development Strategy (EU SDS) for the introduction of "mechanism to ensure that all major policy proposals include sustainability impact assessment covering their potential economic, social and environmental consequences". The renewed EU SDS particularly stresses the need for impact assessment (IA) in order to evaluate the major policy decisions in relation to sustainable development (SD) dimensions. Similarly, it is stated that the EU member countries should also adapt such methods for example when developing strategies and projects. (Wilkinson et al., 2004).

Assessment process is an example of “horizontal integration”. Horizontally integrated assessment processes for sustainability reflect the widely-recognised principle that sustainability assessment requires the consideration of environmental, social and economic issues, and reflect a triple bottom line approach to sustainability. There are several approaches used for sustainability assessment: “sustainability appraisal”, as defined by Sheate et al (2003) and “integrated sustainability appraisal” as discussed by Partidario (1999) or “integrated impact assessment” (Sheate et al., 2003). The term 'integration' implies that integrated assessment should be more than the sum of separate environmental, social and economic assessments Partidario (1999). Brookes (2002) supports this view, suggesting that integrated assessments should demonstrate added value; that is they should be more than the sum of their parts. In other words, integrated assessment should consider the relationships, synergies and conflicts between the impacts (Pope et al., 2004).

The aim of integrated assessment is articulated by Post et al (2004): "It aspires to describe - from the perspective of an identified problem or proposed project - the relations between the human communities concerned, their economic organization and their actual resource base. It qualifies, quantifies, and, as far as possible, values the effects of proposed and alternative interventions on the three (economic, social and natural) subsystems and their intersystem relations. It attempts to identify beneficial interventions and to fully expose unavoidable trade-offs". Therefore integrated assessment should not only consider the environmental, social and economic implications of proposals, but should also examine the interrelations between these three pillars of the triple bottom line (Francis, 2001).

Traditionally impact assessment tools aim to assess separately environmental, economic and to lesser extend social aspects. Newer assessment tools, on the other hand, have been developed to combine these three aspects of sustainable development. In general sustainability assessment is commonly viewed as a part of impact assessment process tools. Moreover, it is an integrated assessment tool in the sense that different dimensions of SD are counted together in close relationship. The inventory of sustainability assessment tools will be performed in the following section seeking to select relevant tools for sustainability assessment of energy technologies in this project.

4.2 Sustainability assessment tools and approaches

Assessment tools in our inventory are divided into four categories (see Table 2) in which **sustainability assessment** refer to SIA and different concepts of it. The other three are **product-related assessment, project-related assessment** and **sector and country-related assessment.** Additionally, **indicators/indices** are classified. The purpose categorizing is to, on the one hand, to see which of the three aspects of SD (economic, environment and social) do different assessment tools fulfil and, on the other hand, which kind of elements should be taken into consideration for the best SIA practices (Rorarius, 2007).

Table 2. Sustainability assessment tools

	INDICATORS/ INDICES	***Product-Related Assessment***	***Project-Related Assessment***	***Sector and Country-Related Assessment***
Environmental	Environmental Pressure Indicators (EPIs) Ecological Footprint (EF)	Life Cycle Assessment (LCA) Material Input per Service (MIPS) Unit Substance Flow Analysis (SFA) Processes energy analysis Exergy analysis Emergy analysis	Environmental impact assessment (EIA) Environmental Risk Analysis (ERA)	Environmental Extended Input-Output (EEIO) Analysis Input-Output Energy Analysis Strategic Environmental Assessment (SEA) Regional emergy analysis Regional exergy analysis
Economic	Gross National Production (GNP)	Life Cycle Costing (LCC)	Full Life Cycle Cost Accounting (FCA)	Economy-Wide Material Flow Analysis (EW-MFA) Economy wide substance flow analysis Economic Input-Output (EIO) analysis
Social	Social Indicators		Social Impact Assessment (sIA)	Social Input-Output (SIO) analysis

Integrated	Human Development Index (HDI) Environmental Sustainability Index (ESI) Wellbeing Index (WI) Sustainable National Income (SNI) Genuine progress indicator (GPI), ISEW, Genuine Savings		Cost-Benefit Analysis (CBA) Risk Analysis (RA)	Multi-Criteria Analysis (MCA) Uncertainty analysis Vulnerability analysis
Sustainable Development	Sustainable Development Indicators (SDI) Sustainable energy development indicators (SEDI)			Conceptual modelling System dynamics Sustainability Impact Assessment (SIA) Integrated Sustainability Assessment (ISA)

4.2.1 Indicators

The first umbrella of sustainability assessment tools consists of indicators and indices. Indicators are simple measures, most often quantitative that represent a state of economic, social and/or environmental development in a defined region—often the national level. When indicators are aggregated in some manner, the resulting measure is an index. Harger and Meyer (1996) suggest that indicators should contain the following characteristics: simplicity, (a wide) scope, are quantifiable, allow trends to be determined, tools that are sensitive to change, and allow timely identification of trends. Indicators and indices, which are continuously measured and calculated, allow for the tracking of longer-term sustainability trends from a retrospective point of view. Understanding these trends allows making short-term projections and relevant decisions for the future. The tools in the category of indicators and indices are either *non-integrated*, meaning they do not integrate nature–society parameters, or *integrated*, meaning the tools aggregate the different dimensions. There is also a subcategory of non-integrated tools that focuses specifically on regional flow indicators (Ness et al, 2007).

An example of non-integrated indicators is Environmental Pressure Indicators (EPIs) developed by Statistical Office of the European Communities (Eurostat). The EPI set consists of 60 indicators, six in each of the ten policy fields under the Fifth Environmental Action Programme. It is also possible to aggregate the six indicators in each policy field into an index, which in total makes up ten environmental pressure indices. The intention with these indicators, which consist of for example forest damage, fishing pressure, tourism intensity, waste landfilled, is to provide a common and comprehensive set of indicators for EU member states to evaluate and measure environmental sustainability. These indicators permit a comparison of the environmental situation in different EU member countries, and an evaluation of trends in member states and in the EU as a whole.

Even though EPI is striving to solve the problem with data by cooperating closely with the statistical offices in the member and accession countries it has three main weak points. First, it includes only environmental pressure indexes but sustainability goal includes also social and economic aspects. Secondly, it is very EU centred and even though EPI group suggests that similar index should be worked out for the rest of the world with the same goal to overcome the problem with insufficient data it remains a problem until the results of such a work are visible. Thirdly, it also looks only the current state in the countries without long-term perspective.

Another example is the set of 58 national indicators used by the United Nations Commission on Sustainable Development (UNCSD). The UNCSD was created to carry out the priorities of the United Nations Conference on Environment and Development in Rio de Janeiro, Brazil in 1992. In order to arrive at “a broader, more complete picture of societal development” these indicators extend further than just the common economic indicators, to include, social, environmental and institutional monitoring mechanisms (UNCSD, 2001). The indicators are not integrated or aggregated in any manner. Examples of the UNCSD indicators include water quality levels for the environmental category, national education levels, and population growth rates as social determinants, GNP per capita for the economic sphere, and the number of ratified global agreements in the category of institutional sustainability (Ness et al., 2007).

Analysis of material and energy flows allows an overview of the structure of resource flows and identification of inefficiencies within a system. Such studies may be used both for reconstructing historical flows and emissions and for forecasting and decision support. Material Flow Analysis (MFA) analyses the physical metabolism of society in order to support dematerialisation and reduction of losses to the environment connected to the extensive societal resources. MFA studies have been performed in many countries and the numbers of regional MFA studies have increased during the last decades. Regional flow indicators are also non-integrated as they only focus on physical flows, thus environmental aspects. Economy-wide MFA developed by Eurostat is the most standardised tool for MFA for regions. It is mainly used at the national level with the possibility of being applied at other spatial levels (Ness et al, 2007).

4.2.2. Product-related assessment

The second umbrella consists of product-related tools that focus on flows in connection with production and consumption of goods and services. Built on a

similar flow perspective, they are closely related to the regional flow indicators of the previous category. But the tools in this category focus on evaluating different flows in relation to various products or services instead of regions. They evaluate resource use and environmental impacts along the production chain or through the life cycle of a product (from cradle to grave). The aims of identifying particular risks and inefficiencies to support decision-making are similar to the regional flow indicators, but in this case in connection with design of products and production systems. These tools do not integrate nature–society systems as they are mainly focusing on environmental aspects. However, life cycle costing tools may integrate environmental and economic dimensions. Product-related tools allow both retrospective and prospective assessments that support decision-making.

The most established and well-developed tool in this category is Life Cycle Assessment (LCA). LCA has been used in varying forms over the past 35 years to evaluate the environmental impacts of a product or a service throughout its life cycle. It is an approach that analyses real and potential pressure that a product has on the environment during raw material acquisition, production process, use, and disposal of the product. LCA results provide information for decisions regarding product development and eco design, production system improvements, and product choice at the consumer level (Ekvall, 1999), the waste and energy field, as well as a multitude of other product and service areas.

Life cycle costing (LCC) is an economic approach that sums up “total costs of a product, process or activity discounted over its lifetime” (Gluch and Baumann, 2004). In principle LCC is not associated with environmental costs, but costs in general. A traditional LCC is an investment calculation that is used to rank different investment alternatives to help decide on the best alternative. There are many different tools for life cycle costing analysis, but only two of them include environmental costs — Life Cycle Cost Assessment and Full Cost Environmental Accounting.

Monetary valuation is also often referred to as shadow pricing or non-market valuation. This group consists of tools that are not sustainability assessment techniques themselves, but rather an important set of tools that can be used to assist other tools when monetary values are needed for goods and services not found in the marketplace. Tools, for example, Cost–Benefit Analysis, Genuine Savings, and Life Cycle Cost Assessment require such values to be used. With monetary valuation there are different ways to assign values. There is for example the Contingent Valuation method (previously called the Survey Method), which uses surveys to estimate people's willingness-to-pay for certain nature's goods and services. The Travel Cost method uses the price paid for travelling as a basis of its monetary value (Johansson, 1996), and the Hedonic Pricing method that focuses mainly on property markets through analysing prices influenced by its surrounding, which can be either positive (near beach or park) or negative (close to highway, airport or industrial area) (Pearce et al., 1994). There also are additional techniques for monetary valuation including Factor Income, Avoided Cost and Replacement Cost that can be used (see Pearce et al., 1994).

Analysis of material and substance flows is also used for product systems. The Wuppertal Institute for Climate, Environment and Energy has developed a product Material Intensity Analysis based on the Material Input per unit of Service (MIPS) index (expressed in weight). This analysis considers all the material flows connected to a particular product or a service including the so called *ecological rucksack*. Product energy analysis measures the energy that is required to manufacture a

product or a service (Herendeen, 2004). It includes both direct and indirect energy flows.

4.2.3 Integrated assessment

Tools under the third umbrella are integrated assessment tools; they are used for supporting decisions related to a policy or a project in a specific region. Project related tools are used for local scale assessments, whereas the policy related focus on local to global scale assessments. In the context of sustainability assessment, integrated assessment tools have an ex-ante focus and often are carried out in the form of scenarios. Many of these integrated assessment tools are based on systems analysis approaches and integrate nature and society aspects. Integrated assessment consists of the wide-array of tools for managing complex issues (Gough et al., 1998). There are many examples of integrated assessments of major environmental problems, but also established tools such as Multi-Criteria Analysis, Risk Analysis, Vulnerability Analysis and Cost Benefit Analysis that do not necessarily pertain directly to only sustainability issues, but can be extended to a variety of other problem areas across disciplinary thresholds (Ness et al., 2007).

Conceptual Modelling analyses qualitative (causal) relationships and often makes use of stock and flow diagrams, flow charts, or causal loop diagrams. Conceptual Modelling can be used for visualising and detecting where changes in a given system can be made for increasing sustainability or as the initial conceptualisation mechanism in a larger computer modelling approach. Systems Dynamics refers to “the building of computer models of complex problem situations and then experimenting with and studying the behaviour of these models over time”. Examples of models related to sustainability assessment include IIASA's air pollution model (RAINS, MESSAGE), the IMAGE model created to analyse social, biosphere, and climate system dynamics, and the Wonderland model designed to illustrate economic–environmental interactions.

Multi-Criteria Analysis (MCA) is used for assessments in situations when there are competing evaluation criteria. MCA identifies, in general, goals or objectives and then seeks to spot the trade-offs between them; the ultimate goal is to identify the optimal policy. This approach has the advantage of incorporating both qualitative and quantitative data into the process (Wrisberg et al., 2002; Walker, Johnston, 1999). The alternative to MCA is Cost Benefit Analysis (CBA). CBA is an applied welfare economics tool with roots reaching back to the early 20th century (Johansson, 1996). It is used for evaluating public or private investment proposals by weighing the costs of the project against the expected benefits. In the realm of sustainability assessment, CBA can be an effective tool for weighing the social costs and benefits of different alternatives in connection with e.g. energy and transports (Wrisberg et al., 2002).

Risk is defined as “the possibility that certain losses or damages occur as the result of a particular event or series of events” (Rotmans, 1998; Rotmans, 2006). Risk Analysis is the assessment of these potential damages. The process begins with identification of the risk, and moves on to a qualitative and/or quantitative assessment of the risk—leading to certain management decisions regarding the minimisation of that risk. The final stage of the Risk Analysis includes communication with stakeholders concerning the assessment and the corresponding decisions involved with minimising the risk (Vose, 2000). Since risk is closely related

to uncertainty, risk analysis cannot be separated from uncertainty analysis (Rotmans, 1998). There are two types of uncertainties: stochastic uncertainty refers to natural variability of the system, fundamental uncertainty is the inability to predict due to lack of knowledge about the system (Kann and Weyant, 2000). Uncertainty and Risk Analysis involve both types of uncertainty. They estimate the probability of events and predicting the events using the knowledge that is available. These aspects of natural variability and lack of knowledge are also the reason why societal and environmental risk analyses are forms of sustainability assessments (Ness et al, 2007).

Some tools may be integrated within their specific assessment dimensions. Efforts have been made through combining two or more different tools to extend the focus of analysis (Wrisberg et al., 2002). Examples of this tendency are the simultaneous analysis of a product or service function using Life Cycle Assessment (environmental impact tool), Life Cycle Costing (economic tool) and/or the Social Life Cycle Assessment. A shortcoming of such an approach is that the overall results of the study are not presently integrated in any manner.

For sustainability assessment of energy technologies integrated tools need to be applied. The combination of indicators framework, LCA, LCC, MCA and integrated indicators approach might be useful for energy technologies assessment including application of conceptual modelling tools and uncertainties analysis therefore in Planets project for probabilistic long-term assessment of new energy technologies scenarios the assessment framework will be developed based on these tools. However application of reviewed tools was already applied in some EU funded projects therefore the critical review of the approaches and tools applied in these projects is necessary.

4.3 Sustainability assessment in EU funded and other projects

There are several important projects dealing with sustainability assessment being developed in EU recently:

- **The MATISSE** (Methods and Tools for Integrated Sustainability Assessment) project, funded by the European Commission, seeks to examine ISA's possibilities for the process of developing and implementing policies for more sustainable Europe. In the project the main task is to develop, test and demonstrate new and improved methods and tools for conducting ISA. The project is still ongoing (until March 2008) http://www.matisse-project.net/projectcomm/
- **The Sustainability A-Test project,** funded by the EU, seeks to evaluate tools that can be used for assessing sustainability. Instead of developing new tools it concentrated on already existing tools and their contribution to assessment process, i.e. to strengthen the analysis. http://ivm5.ivm.vu.nl/sat/
- **The TRIAS** (Sustainability Impact Assessment of Strategies Integrating Transport, Technology and Energy Scenarios) project aims to develop sustainability impact assessment of strategies integrating transport, technology and energy scenarios. The view point is from the transportation and energy sector. http://www.isi.fhg.de/trias/index.htm
- **GaBE** (Comprehensive Assessment of Energy Systems) project was developed by Paul Scherrer institute (PSI). PSI conducted several studies on energy technologies assessment, i.e. “Comprehensive Assessment of Energy Systems” (GaBE) study was conducted in 2000. "Integrated Assessment of Sustainable Energy

Systems in China -The China Energy Technology Program (CETP) - A Framework for Decision Support in the Electric Sector of Shandong Province" was developed by PSI in 2003. "Sustainability of electricity supply technologies under German conditions: A comparative evaluation" the extension of GaBE study was performed in 2004. Detailed environmental inventories for current and future energy systems during normal operation established at Swiss Centre for Life Cycle Inventories. The *ecoinvent database* for the average German and Union for the Co-ordination of Transmission of Electricity (UCTE) was developed. www.ecoinvent.org.

- **EUSUSTEL-** European Sustainable Electricity- Comprehensive analysis of future European demand and generation of European electricity and its security of supply. The strategic objective of the project is to provide the Commission and the member states with coherent guidelines and recommendations to optimise the future nature of electricity provision and the electricity generation mix in Europe so as to guarantee a sustainable electricity supply system. http://www.eusustel.be/
- **ECLIPCE-**Environmental and ecological lifecycle inventories for present and future power systems in Europe project completed in 2003 provides with application-dependent methodological framework and guidelines related to the quantification over the life cycle of environmental impacts from power generation in Europe. http://cordis.europa.eu/data/PROJ_FP5/ACTIONeqDndSESSIONeq112362005919ndDOCeq692ndTBLeqEN_PROJ.htm;
- **TRANSUST-SCAN** – Scanning Policy Scenarios for the Transition to Sustainable Economic Structures is EU funded project with the main focus on wide range of policy scenarios relevant to EU Sustainable development strategy. The main objective of this research project is to scan a wide range of policy scenarios as to their relevance for the European Sustainable Development Strategy in view of Extended Impact Assessment. http://www.transust.org/events/ws_madrid.htm
- **NEEDS-** New Energy Externalities for Sustainability Developments. The ultimate objective of the NEEDS Integrated Project is to evaluate the full costs and benefits (i.e. direct + external) of energy policies and of future energy systems, both at the level of individual countries and for the enlarged EU as a whole. In this context NEEDS refines and develops the externalities methodology already set up in the ExternE project, through an ambitious attempt to develop, implement and test an original framework analysis to assess the long term sustainability of energy technology options and policies. http://www.needs-project.org/.
- **CASES**- Cost Assessment for Sustainable Energy Systems. The CASES project aims to compile coherent and detailed estimates of both external and internal costs of energy production for different energy sources at the national level for the EU-25 Countries and for some non-EU Countries under energy scenarios to 2030; to evaluate policy options for improving the efficiency of energy use, taking account of full cost data and to disseminate research findings to energy sector producers and users and to the policy making community, through events that serve to validate and disseminate the projects outputs. http://www.needs-project.org/.

The MATISSE (Methods and Tools for Integrated Sustainability Assessment) project, funded by the European Commission, seeks to examine ISA's possibilities for the process of developing and implementing policies for more sustainable Europe. In the project the main task is to develop, test and demonstrate new and improved methods and tools for conducting ISA. The project is still ongoing (until March 2008) and thus no specific guidelines or experiments for

conducting ISA exist yet. However, there are several studies carried out by the MATISSE research group. Based on these studies some suggestive entry-points for ISA can be identified. ISA should be used in ways that put pressure on mainstream policy paradigms. Scoping and envisioning stages should be more clearly performed. Moreover, there should be a clear institutional entry point (e.g. the Prime Minister's Office) which can minimize influences from current policy paradigms (i.e. market-liberalism). In terms of the length of the assessment process, it should be a continuous rather than temporally delimited project. This also refers to learning process, in which short-term interests can be diminished and long-term visions are emphasized.

The Sustainability A-Test project, funded by the EU, seeks to evaluate tools that can be used for assessing sustainability. Instead of developing new tools it concentrated on already existing tools and their contribution to assessment process, i.e. to strengthen the analysis. Hence, ways of assessing sustainability is similar to that in ISA. Sustainability A-Test realizes that assessing sustainability it involves multiple generations (i.e. longer time scales), multiple geographical scales (i.e. from local to global), multiple domains (i.e. economic, environmental and social) and multiple perspectives (i.e. different ideas about how to develop sustainable)". Ways of including such wide aspects are carried out with using different tools. These include:

1. Physical assessment tools (e.g. EF, LCA, EW-MFA)
2. Monetary assessment tools (e.g. CBA)
3. Models (various computer models)
4. Scenario analysis (tools with prospective character)
5. Multi-criteria analysis (helps criteria analysis)
6. Sustainability/environmental appraisal tools (SIA, SEA)
7. Participatory tools (aiming to involve stakeholders)
8. Transition management

The TRIAS (Sustainability Impact Assessment of Strategies Integrating Transport, Technology and Energy Scenarios) project, funded by the European Commission, aims to develop sustainability impact assessment of strategies integrating transport, technology and energy scenarios. The view point is from the transportation and energy sector. It is stated that the "future framework of the transport system is intimately linked with energy supply". TRIAS uses an integrated assessment by combining already established models that cover the three dimensions of SD. These should be applied in an interlinked manner in order to analyze the whole scenario of impacts induced by strategies. Indicators are helped indicate a consistent picture. Public participation is encouraged in the assessment process. These are carried out in workshops as well as discussion forums in the internet.

EUSUSTEL, ECLIPCE; TRANSUST-SCAN, NEEDS, CASES and PLANETS are projects dealing directly with sustainability assessment issues in energy sector therefore need more attention in this project.

EUSUSTEL is EU funded project aiming to develop coherent guidelines and recommendations to optimise the future nature of electricity provision and the electricity generation mix in Europe so as to guarantee a sustainable electricity supply system. A first concrete objective is to make a review of the current electricity provision and the regulatory framework in the EU-25 countries. Further objectives are to define a sustainability framework, to figure out a reasonable evolution of

demand of electricity and to make an analysis of electricity generation technology in order to optimise the electricity provision from a total social cost perspective. The time horizon is 2030. The project entails a major effort of reviewing and evaluating existing studies and publications, carefully complemented with the project participants own expertise and views. The methodology used mixes two directions of analysis. In a first (horizontal) one, the existing electricity systems of the 25 EU countries are analysed and national policy choices and future projections are studied. Next, vertically then, a subject-wise treatment is considered, whereby both the demand side as well as the supply side technologies and system integration are treated. Furthermore, the regulatory and liberalised market framework for an integrated European electricity market is carefully examined and appraised. Based on these analyses, it is then in a combined approach attempted to summarise the 'static' overall social cost (private cost plus external cost) for electricity generation. Subsequently, these cost figures are used as input in carefully screened simulation models in order to perform some well-defined and contrasting scenarios, but in line with the regulatory framework of the energy market. From these results, it must be possible to obtain the 'most optimal solution' (from an economic-effectiveness point of view -including environmental burdens) for the electricity provision in Europe. The project provided conclusions on the possible future of electricity demand and supply in Europe, well embedded in a properly functioning liberalised electricity market. A possible most optimal mix for electricity generation, compatible with existing EU directives, regulation and guidelines, was proposed based on the simulations (EUSUSTEL, 2007).

The general objective of ECLIPCE **project** is to overcome current limitations of the use of Life Cycle Inventories (LCI) for energy modelling and planning and other uses. Users of project results are provided with application-dependent methodological framework and guidelines related to the quantification over the life cycle of environmental impacts from power generation in Europe; a harmonised and methodologically coherent set of data on new and decentralised power systems. Data is provided in a format that makes them comparable to existing data of other energy technologies, easily adaptable to local conditions and technological improvement, and updatable. Explicit user-oriented examples for a correct use of LCI of present and future power systems in Europe. Project results contributed to the increase of the credibility, diffusion and exploitation of LCI.

TRANSUST-SCAN – Scanning Policy Scenarios for the Transition to Sustainable Economic Structures is EU funded project with the main focus on wide range of policy scenarios relevant to EU Sustainable development strategy. The main objective of this research project is to scan a wide range of policy scenarios as to their relevance for the European Sustainable Development Strategy in view of Extended Impact Assessment. Embedded in the TranSust network of researchers, with its expertise in modelling the transition to sustainable economic structures, the project links and expands an extensive set of available models. Using a scenario approach in cooperation with stakeholders, these models will address the strategic policy options. In a first step, existing models are extended to reflect the multifunctionality aspect of sustainability policies and their trade-offs with other policies. In addition to the traditional economic, environmental and social issues, the expanded models address the new policy agenda as put forward by the Lisbon Strategy of the European Union and the World Summit for Economic Development. The models will therefore be able to deal with: Competitiveness; Economic

development; Security; The preparations for Beyond-Kyoto policies; The interaction between technological change and the use of natural resources. In a second step, this enhanced set of models is used for a comprehensive analysis of a wide range of policy scenarios. In designing the scenarios, a participatory approach emphasises close cooperation with stakeholders, Commission services, and international organisations. By backcasting the path dependency and by simulating the range of assumptions, the scenario analysis will reveal the sensitivity of forecasts. The methodology and databases will be made available to institutions involved in policy decision-making. http://www.transust.org/events/ws_madrid.htm

In CASES project sustainability assessment of climate change mitigation policies and electricity generation technologies was performed based on results of external costs of electricity generation obtained in NEEDS project. http://www.feem-project.net/cases/. The main criteria for electricity generation technologies applied in CASES are: private costs, health external costs, CO_2 eq emissions, environmental external costs, radionuclides external costs, fatal accidents from past experience, severe accidents perceived in future, food safety risks and grid costs. The private costs include investment and operation costs based on the assessments in previous EU studies. Health external costs estimates include external costs estimates for damages to health due to emissions to air, soil and water of particles, N2O, SO2, the formation of ozone and the emissions of metals. Environmental external costs include estimates of damages to ecosystems due to emissions to air, soil and water of particles, gases like N2O, SO2, the formation of ozone, and the emissions of metals. The external costs estimates for damages to health due to emissions of radionuclides in the life cycle, including indirect use of nuclear electricity in the production of the technologies. Risk of a fatal accident using the frequency of occurrence of a severe accident in the past and the number of fatalities involved in previous accidents. The qualitative assessment of risk of severe accidents in future was applied in for technologies assessment in CASES project (2007, 2008). The higher the score the more people perceive that accident will happen. Qualitative assessment of risk that using biomass fuels will put a stress on food supply safety and food prices. Qualitative assessment of risk was performed based on assumption that a certain technology will include high cost for grid connection.

In **NEEDS** the sustainability assessment of electricity generation technologies was performed seeking to define the effect of energy and environmental policies on technological development in energy sector. In NEEDS project analysis of the technical, environmental and economic performance of future power plants, taking into consideration various energy policy framing conditions (NEEDS, 2005, 2006, 2007). The technology clusters include advanced power plants, hydrogen technologies, fuel cells, offshore wind, PV, concentrating solar thermal power plants, biomass technologies, advanced nuclear and ocean energy technologies. Technical reports providing details on technical characteristics, costs and LCA data are available for download from NEEDS website: http://www.needs-project.org/. The technology foresight methodology was applied to assess emerging energy technologies. Technology foresight can be defined as systematic analysis and discussion about possible technology futures.

4.4 Recent approaches used for energy technologies assessment

NEEDS project developed technology foresight methodology aiming to analyse expected energy technology futures. Over the last 10 years the technology foresight projects become increasingly usual as an instrument in public governance of research, innovation and technology development. A large number and EU have established technology foresight projects and emphasised the need of a stronger future orientation in policy development and strategic planning. The technology foresight projects become increasingly usual as an instrument in public governance of research, innovation and technology development.

Technology foresight works systematically with the long-term perspective and tries to position the different developments on a time scale. In practice, the time perspective in technology foresight studies is 10, 20 or 30 years. The purpose of technology foresight is not in itself prediction of the future. Technology foresight differs from forecasting. The purpose is not to identify data about technology in the long-term future but to establish a fuller understanding off the possible technology futures and the forces shaping the future developments. Foresight helps to be ready for the future as no-one can predict the future but the future is shaped by the decisions we make today. Therefore there are many possible futures behind us and dependent on how actors choose to act, different futures are possible thou not all of them will become reality. Technology foresight reflects that there are considerable uncertain aspects concerning the future technology. Foresight recognizes that addressing the future necessitates acknowledgement and management of uncertainty. Technology foresight is a set of methods and techniques that helps to assess possible energy futures.

Planning and decision-making represent important challenges in the realm of technology development programs. Whether projects involve incremental improvement or technology breakthrough, there typically are significant uncertainties and interrelationships which complicate the environment of competing priorities and limited funding. Technology Roadmaps are used to identify precise program and project objectives and requirements, create a consensus vision of R&D needs, focus R&D resources, facilitate informed decision making, provide a structured defensible decision program and project plan, accelerate application of new technologies, expedite new systems deployment, and minimize project costs and schedules. Technology road mapping approach was also applied in NEEDS projects. Technology road mapping is a forward-looking approach developed and widely used to support strategic long-term planning within organizations like industrial companies. Roadmap studies analyse and discuss the road ahead for the development of a specific industrial product or a specific technology. Roadmaps seek to capture the surrounding landscape, threats and opportunities for a particular group of stakeholders in a technology area or in an area of technology application.

The technology road mapping approach is increasingly applied in foresight studies, especially in those exercises that are focused upon particular industrial sector like energy sector. It is characteristic of traditional technology road mapping that it describes a specific, partial perspective of energy technologies development with a clearly defined goal. This approach can lead to a comprehensive and multi-facetted understanding of a desirable development path for a technology and of the interplay between different kinds of activities (market, scientific or industrial activities), different drivers of change etc. In NEEDS project the technology foresight

and Life Cycle Assessment (LCA) approaches were combined for technology assessment. The developed methodological framework comprises three main steps: technology scanning or information gathering; analysis and discussion of the future technology or visioning and synthesis by developing energy technology road map and description of results or LCA scanning. The purpose of the methodological framework developed in NEEDS was to analyse the likely long-term future of an energy technology with respect of LCA relevant issues. The output of the method was qualified description of the characteristics of the energy technology in **2025** and **2050** and important uncertain aspects in the technology's future and in its' environmental relations.

Strategic Technology Roadmap is navigation tool for strategic planning and implementation of research and development investments. Ministry of Economy, Trade and Industry of Japan (2006) formulated "Strategic Technology Roadmap" for energy sector consisting of technology overview and the roadmap (. The "Strategic Technology Roadmap" of the energy sector was developed by backward examination (backcasting) of the technology portfolio to overcome constraints in resources and the environment, which will become a big concern in the future globally, on a long-term basis until **2100**. The object of this Roadmap was to prioritise long term based research and development, and to contribute to the discussion based on the long-term and global point of view such as post Kyoto international framework. The challenging technology portfolio was developed based on the following assumptions: constraints on energy connect directly to the level of human utility; consideration of future energy supply-demand structure should take into account both resource and environmental constraints; based on the long-term scope, the key to achieve truly sustainable energy supply-demand structure is technology; in order to establish technology, a long lead time is required for R&D, introduction and promotion, the establishment of related infrastructure and also there is actually great uncertainty. Three cases were developed as technological scenarios: a) Maximum use of fossil resources such as coal combined with CO2 capture and sequestration; b) maximum use of nuclear energy and c) maximum use of renewable energy combined with ultimate energy saving. According first case, while supplying energy by fossil resources such as coal or non-conventional fossil fuels of which reserves are comparably rich, generated CO2 is captured and sequestrated. However it is supposed that capacity for geological sequestration is limited and realization of ocean sequestration is an essential condition. In second case, energy for all sectors is supplied by nuclear power which emits no GHG. Electricity and hydrogen are assumed to be the energy carriers for sectors including transport and industry. If depending on nuclear power largely, based on resource limitations of uranium ore, acquisition of non-conventional nuclear fuel such as recovery of uranium from seawater, or establishment of a nuclear fuel cycle is an essential condition. In third case, as well as maximizing the use of renewable energy, energy demand will be reduced as much as possible by energy-saving, highly efficient utilization, self-sustaining, improvement of conversion efficiency to control required energy supply, and to maintain or improve the quality of life at the same time. It is essential that both renewable energy technologies and energy-saving technologies are fully established and deployed. Measures such as energy saving, highly efficient utilization, self-sustaining and improvement of conversion efficiency are essential to the third case, but also employed in both other cases. However the energy saving in the first two cases was not applied to so large context

in order to identify technologies required for preparation for the future. The significance, potential, technical feasibility, applicability and other constraints were defined for three cases in Japan study. In order to bring the constraints into shape as technological specifications, the examination of demand sectors was performed.

European Strategic Energy Plan (EU, 2007a; 2007b) presents a vision of EU energy future based on efficiency, diversification, decarbonisation and liberalization and identifies those energy technologies for which it is essential that EU finds more powerful way of mobilising resources in ambitious result-oriented actions to accelerate their pathway to the market. The technology map for the European Strategic Energy Plan was created. It is a brief and comprehensive description of the current status and prospects of key energy technologies aiming to provide information for the identification of potential European initiatives that could be considered as a part of a European Strategic Energy Technology Plan (SET-Plan). This was achieved by assessing the potential of a set of technologies and barriers and needs for their further development and deployment, highlighting the role of energy technology innovation in support of achieving the EU energy policy goals. The Technology Map addresses the following technologies:

Power and heat

- Wind power generation;
- Solar photovoltaic power generation;
- Concentrated solar power generation;
- Solar heating and cooling;
- Hydro power generation;
- Geothermal;
- Ocean wave power generation;
- Cogeneration of heat and power;
- Zero emission fossil fuel power generation;
- Nuclear fission power generation;
- Nuclear fusion.

Energy infrastructures

- Electricity networks (Smart Grids)

Transport

- Biofuels;
- Hydrogen and fuel cells.

The Technology Map describes for each technology: the current status and anticipated technical developments, the current and future share in the European energy demand, the quantified impacts of technology penetration on GHG emissions, measured through quantities of CO2 avoided, security of supply, through quantities of fossil fuel saved; competitiveness, through changes in the overall cost of energy production due to the penetration of the technology; barriers to penetration in the European energy market; needs to realise its potential and synergies with other technologies and sectors.

The methodology applied in development of Technology Map for the European Strategic Energy Technology Plan is based on quantification of the effects of the penetration of the different technologies considered in the Technology Map on the EU energy policy goals. This quantification of effects is made following a common assessment framework comprising the following steps:

- The establishment of penetration levels for each technology according to the baseline scenario, which is considered as a business-as-usual;
- The assumption of two distinct penetration scenarios for each technology that represent alternative views of market potential;
- The evaluation of the effects of the additional to the baseline penetration of each technology individually through four indicators, namely CO2 avoided, carbon mitigation cost, fossil fuel saved and changes in the overall production cost of the energy carriers that the technology produces (electricity , heat or transport fuel).

It should be stressed that the assessment was not made at the energy system level. Consequently, the impacts of the various technologies cannot be added up since it is not feasible that all technologies achieve the envisaged maximum potentials simultaneously. In addition to technical and physical constraints of the energy system, social and consumer acceptance is an important barrier for the deployment of technologies. The time horizon considered for the assessment is **2030.** A key assumption of the developed assessment framework is that all technologies considered replace their fossil fuel based conventional counterpart technologies hat produce the same energy carrier. For example, wind energy substitutes electricity from fossil fuel power plants and solar heating systems replace boilers fuelled by oil or gas.

The Assessing the Value of New Energy Technologies performed by Stanford University (2002-2007) in framework Global Climate and Energy Project (GCEP) is based on assessment of the impacts of new energy technologies dependent on the assessments of both their likely costs and performance characteristics including carbon emissions and other environmental impacts, and their likely market penetration under a wide range of possible energy futures. Given information regarding the characteristics of the new energy technologies resulting from R&D (expressed via ranges or probability distributions over costs and performances at specific future dates of interest), assessments of the value of those specific new technologies depend on what other new technologies have been developed, the rate of improvement in existing technologies, and conditions in energy markets. Conditions in energy markets are reflected in energy prices and depend on many factors including population levels, economic output, and the structures of the world's economies, resource availabilities, and energy producer behaviour, the set of available technologies for producing, transforming and consuming energy and state energy, economic and environmental policies. The project conducted by Stanford University experimented with assessing the impacts of new energy technologies using wide range of different probability distributions and different levels of structural modelling of future energy devices and processes. The key factors that determine the future value of new energy technologies are highly uncertain and the relationships between them are quite complex. One approach to energy policy assessment is to run sensitivity analysis of external factors through models of the energy system. Results from these types of exercises are extremely illuminating but generally consider only reference scenario for one basic set of input and parameter values for each model. There are extremely large uncertainties about both sets of inputs over the course of time and these uncertainties have a significant impact on how to value the impact of R&D on new technologies. During the project it was recognized that large-scale energy system models are often designed for purposes other than long-term energy technology assessment and

therefore include a level of complexity that makes extensive sensitivity analysis, let alone formal uncertainty analysis, infeasible. Therefore the approach employed in GCEP was based on reduced-form energy models calibrated to the more large-scale models as the central element of an uncertainty-oriented technology evaluation approach. The set of integrated probabilistic scenarios were developed during the project representing a wide range of future states of the world enabling to calculate impact values for the new technologies across a wide range of possible technological and socio-economic futures. The time frame used in the study is **2050.**

4.5 Indicators used for sustainability assessment of energy technologies

There are many examples of energy technologies assessment. Based on the results of survey of energy technologies assessment found in the recent literature and results of EU funded projects, a methodological framework based on indicators set for energy technologies assessment was developed seeking to address goals of PLANETS project.

In an interagency effort led by the IAEA in cooperation with UNDESA, IEA, the Statistical Office of the European Communities (Eurostat) and the European Environment Agency (EEA) a core set of energy indicators for sustainable development(EISD) has been established (IAEA et al., 2005). By mutual consent, the original set of 41 indicators was reduced to a final core set of 30 indicators. Although the original framework used the DSR approach, it has been modified to follow the recently adopted theme and subtheme framework of UN CSD. The 30 energy indicators for sustainable development presented here are classified according to the three major dimensions of sustainability: economic (16 indicators), environmental (10 indicators) and social (4 indicators). This set of indicators (Figure 1) was used for EU energy policy analysis in this report (Table 1).

There were few projects on energy technologies assessment performed in EU applying sustainable energy indicators approach and using various sets of sustainable indicators ranging from quantitative to qualitative. In EUSUSTEL project the assessment of energy technologies was based on total social costs as useful indicator to account for overall resource consumption. Private cost of electricity was calculated based on average lifetime levelised generation costs. External costs of electricity generation due to emissions of CO_2, NOx, NMVOC, CH_4, PM_{10}, N_2O and C_{14} have been taken into account. Detailed information on technical and economic characteristics of power plants was provided in EUSUSTEL (2007). There were no other environmental indicators applied for sustainability assessment of electricity generation technologies.

Quantitative indicator system that allows assessing the level of sustainability in energy policy, energy supply and use was developed In Switzerland, the Swiss Federal Office of Energy (NEEDS, 2005). The defined indicator framework distinguished four types of indicators: Impact indicators: impacts of the energy sector on environment, economy and society; Activity indicators: description of production and consumption of goods and services in the four consumer groups industry, services trade, households and transport, Energy efficiency indicators: they refer to the technical-energetic efficiency of energy extraction, conversion and use and Policy indicators: they represent the reactions, which are implemented by energy policy to achieve a more sustainable energy sector. Based on 27 criteria

a total of 60 indicators were defined however this indicator sets fits more to sustainability assessment of energy sector as a whole and can't be applied for technologies assessment within specific energy sectors such as electricity, buildings etc.

The **Paul Scherrer institut** (PSI) conducted several studies on energy technologies assessment, i.e. "Comprehensive Assessment of Energy Systems" (GaBE) study (Hirschberg et al., 2004a) was conducted in 2000 followed by other studies based on the same approach developed." The PSI approach started with a small set of basic principles resulting from a comprehensive definition of sustainable development that encompasses all three dimensions ("pillars"), i.e. economic, environmental and social aspects: "No" degradation of resources in the broadest sense. "No" production of "non-degradable" waste; High potential for robustness/long-term stability. Here "no/non" reflects the aim of being as small or as near to zero as possible. Each principle is related to a set of specific criteria and indicators, which aim at being representative rather than complete.

In Table 3 a set of representative criteria and associated indicators selected to assess energy-related technologies under the constraints of sustainability is shown. This set is the result of an iterative process, following discussions among scientists and taking problems experienced in quantifying the indicators into account The context is set to a large regional and global scale; the mid-term, i.e. the years 2020-2030 and beyond, are taken as orientation points. In applicable cases the indicators should be based on LCA and generally cover the full energy chain.

Table 3. Set of principles, criteria, indicators and corresponding units to evaluate energy-related technologies under the constraints of sustainability (NEEDS, 2005)

Criteria	Indicators
"No" degradation of resources	
Use of fuels	Depletion time [years]
Use of other materials	Amount (e.g. copper ore) [kg/GWa]
Use of land	Surface to support normal operation [km2/GWa]
Effects of water	Pollution (e.g. by zinc) or consumption [kg/GWa or m3/GWa]
Environmental impact through emission	Amount of climate relevant gases [t CO2 equivalent/GWa] Amount of gases damaging the ozone layer [t CFC equivalent/GWa]
Impact on human health	Through normal operation [years of life lost/GWa] Through accidents / collective risk [fatalities/GWa]
Impact on social aspects	Risk aversion: Land losses per accident [km2] Fatalities per accident [-] Work opportunities [Δpy/a/GWa] Proliferation threat [qualitative]
Competitiveness	Internal and external costs [currency unit/kWh]
"No" production of non-degradable waste	
Produced amount	Produced amount [m3/GWa]
Necessary confinement times	Necessary confinement times [years]
"No" high sensitiveness with respect to the environment	

Supply and disposal security	Foreign dependency [qualitative] Technology availability [currency unit]
Robustness, i.e. no necessity for…	…rapid external interventions [hours] …socio-political/financial stability [qualitative]

On behalf of the International Committee on Nuclear Technology (ILK) the Paul Scherrer Institut carried out a comparative study addressing the sustainability of electricity supply technologies operating under German-specific conditions (Hirschberg et al., 2004b). The primary objective of this analysis was to provide a support for the formulation of ILK position on the sustainability of various electricity supply technologies, with special emphasis on nuclear energy.

The evaluation covers selected current fossil, nuclear and renewable technologies, which are representative for the average conditions in Germany. As a starting point existing, representative evaluation criteria and indicators, recently proposed by competent international organisations were reviewed. Based on this survey and PSFs experience from various evaluation studies, a set of criteria and indicators for use in the present project was established. The main effort went into generation of quantitative technology-specific economic, environmental and social indicators. The set of criteria and indicators used in the full analysis of the candidate technologies for the future electricity supply in Switzerland developed by PSI is shown in Table 4 along with the basic set of used weights.

Table 4. Structure of the Base Case: Criteria, indicators, evaluation basis for their quantification, units, and weights (Hirschberg et al., 2006)

1st level	W	2nd level (evaluation basis & unit)	W	3rd level (evaluation basis & unit)	W
Economy	1/3	Financial requirements	70	Production costs [Rp/kWh]	50
				Investment [power plant, CHF/kW]	25
				Fuel price increase sensitivity [increase of production costs due to doubling of fuel costs]	25
		Resources	30	Short-medium term potential [generation potential GWh/year]	40
				Availability [load factors]	15
				Geo-political factors [estimation]	15
				Long-term sustainability [years]	10
				Peak load response [relative scale]	20
		Human health impacts	30	Mortality [EIA&LCA, Rp/kWh]	90
				Morbidity [EIA&LCA,	10

				Rp/kWh]	
Health & environment	1/3	Loss of crop [EIA&LCA, Rp/kWh]	1		
		Impact on materials [EIA&LCA, Rp/kWh]	4		
		Non pollutants effects	5	Land use [m2/kWh]	
		Greenhouse gases [LCA, gCO2equiv/kWh]	30		
		Wastes	15	Volume [LCA, m3/kWh]	
		Severe accidents	15	Fatalities [RA, fatalities/kWh]	
Social Aspects	1/3	Employment [jobs per unit of energy]	20		
		Proliferation risks [yes or no]	5		
		Local disturbance [estimation per unit of energy]	25		
		Critical waste confinement time [years]	25		
		Risk aversion [maximum fatalities per accident]	25		

The CETP framework for China Energy Technology Framework developed by PSI (2003) has also succeeded in integrating analysis of the complete electricity chain, including demand, supply, direct and indirect environmental burdens, health impacts and accident risks. This includes not just modelling the future mix of electricity supply, but also life cycle analysis of generation technology chains, detailed analysis of major environmental externalities and risks, creation of the associated datasets required, and developing a wide range of specific tools, including custom software.

In NEEDS project comprehensive assessment of electricity generation technologies was performed based on well- established indicators framework (Table 5).

Table 5. Criteria and associated indicators for three sustainability dimensions applied in NEEDS project (NEEDS, 2007)

Criterion	Indicator	Unit	Estimation Method	Input
ENVIRONMENTAL DIMENSION				
RESOURCES				
Energy Resources				
Fossil primary	Total	MJ/kWh	Life Cycle Impact	PSI

energy	consumption of fossil resources		Assessment (LCIA)	
Other non-renewable energy	Total consumption of uranium	MJ/kWh	Life Cycle Impact Assessment (LCIA)	PSI
Mineral Resources (Ores)	Weighted total consumption of metallic ores	kg(Sb-eq)/kWh	Life Cycle Impact Assessment (LCIA)	PSI
CLIMATE CHANGE	Global warming potential	kg(Sb-eq)/kWh	Life Cycle Impact Assessment (LCIA)	RS1a/PSI
IMPACT ON ECOSYSTEMS				
Impacts from Normal Operation				
Biodiversity	Impacts of land use on ecosystems	PDF*m^2a/kWh	Life Cycle Impact Assessment (LCIA)	PSI
Ecotoxicity	Impacts of toxic substances on ecosystems	PDF*m^2a/kWh	Life Cycle Impact Assessment (LCIA)	PSI
Acidification and eutrophication	Impacts of air pollution on ecosystems	PDF*m^2a/kWh	Life Cycle Impact Assessment (LCIA)	PSI
Impacts from Severe Accidents				
Release of hydrocarbons	Large release of hydrocarbons	t/kWh	Risk Assessment (RA)	PSI
Land contamination	Nuclear land contamination	km^2/kWh	Risk Assessment (RA)	PSI
WASTES				
Special Chemical Wastes stored in Underground Depositories	Total weight of special chemical wastes stored in underground repositories	kg/kWh	Life Cycle Assessment (LCA)	PSI
Medium and High Level Radioactive Wastes to be stored in Geological Repositories	Total amount of medium and high level radioactive wastes to be stored in geological repositories	m^3/kWh	Life Cycle Assessment (LCA)	PSI
ECONOMIC DIMENSION				
IMPACT ON CUSTOMERS				
Price of electricity	Average generation cost	EUR/MWh	Extrapolation of current costs	/EDF
INPACT ON OVERALL ECONOMY				
Employment	Direct labor	Person-	Labor due to fuel	PSI

		years/GWh	extraction and transport, plant construction and generation, and decommissioning	
Autonomy of electricity generation	Medium to long-term independence from foreign energy sources	Ordinal scale	Expert judgment	EDF
IMPACT ON UTILITY				
Financial Risks				
Capital investment exposure	Total capital cost	EUR	Cost estimation	EDF
Impact of fuel price changes	Ratio of the fuel cost to the generation cost	Fraction	Forecast fuel cost divided by forecast average generation cost	EDF
Risk due to changes in boundary conditions	Construction time	Years	Estimated construction time	EDF
Operation				
“Merit order” for dispatch purposes	Total average variable cost or “dispatch cost”	EUR/MWh	Forecast fuel cost and variable O&M cost	EDF
Flexibility of dispatch	Composite indicator	Ordinal scale	Expert judgment	EDF&PSI
Availability	Equivalent availability factor	Fraction	Industry statistics	EDF
SOCIAL DIMENSION				
SECURITY/RELIABILITY OF ENERGY PROVISION				
Political Threats to Continuity of Energy Service				
Diversity of primary energy suppliers	Market concentration in the primary energy supply	Ordinal scale	Expert judgment	U.STUTT
Waste management	Probability that waste storage management will not be available	Ordinal scale	Expert judgment	U.STUTT
Flexibility and Adaptation	Flexibility to incorporate technological	Ordinal scale	Expert judgment	U.STUTT

	change			
POLITICAL STABILITY AND LEGITIMACY				
Potential of Conflicts induced by Energy Systems	Potential of energy systems induced conflicts	Ordinal scale	Expert judgment	U.STUTT
Willingness to act (Mobilization Potential)	Willingness of NGOs and other citizen movements to act against realization of an option	Ordinal scale	Expert judgment	U.STUTT
Necessity of participative Decision-making Processes	Necessity of participative decision-making processes for different technologies	Ordinal scale	Expert judgment	U.STUTT
SOCIAL AND INDIVIDUAL RISKS				
Expert-based Risk Estimates for Normal Operation				
Reduced life expectancy due to normal operation	Mortality due to normal operation	YOLL/kWh	Impact Pathway Approach (IPA)	PSI
Non-fatal illnesses due to normal operation	Mortality due to normal operation		Impact Pathway Approach (IPA)	PSI
Expert-based Risk Estimates for accidents				
Expected Health effects from accidents	Expected mortality due to severe accidents	Fatalities/kWh	Risk Assessment (RA)	PSI
Maximum consequences of accidents	Maximum creditable number of fatalities per accident	Fatalities/accident	Risk Assessment (RA)	PSI
Perceived Risk				
Perceived risk characteristics for normal operation	Subjective health fears due to normal operation	Ordinal scale	Expert judgment	U.STUTT
Perceived risk characteristics for accidents	Psychometric variables such as personal control,	Ordinal scale	Expert judgment	U.STUTT

	catastrophic potential, perceived equity, familiarity			
Terrorist Threat				
Potential of attack	Potential for a successful attack	Ordinal scale	Expert judgment	PSI
Likely potential effects of a successful attack	Expected number of fatalities	Ordinal scale	Expert judgment	PSI
Proliferation	Potential for misuse of technologies and substances within nuclear energy chain	Ordinal scale	Expert judgment	PSI
QUALITY OF LIFE				
Socially compatible development				
Equitable life conditions	Share of the effective electricity costs in the budget of a social welfare recipient	%	Expert judgment	U.STUTT
Work quality	Work qualifications expressed as average years of education for workforce	Ordinal scale	Expert judgment	U.STUTT
Effects on the Quality of Landscape and Residential Area				
Effects on the quality of the landscape	Functional and aesthetic impact of energy infrastructure on landscape	Ordinal scale	Expert judgment	U.STUTT
Noise exposure	Extent to which residents feels highly affected by noise	Ordinal scale	Expert judgment	U.STUTT
Contribution to traffic	Total traffic load	tkm/kWh	Life Cycle Impact Assessment (LCIA)	PSI

However some indicators developed by NEEDS project are difficult to collect and their cover the same issues. Very complex indicators systems and therefore criteria for assessment of technologies do not allow to carry out MCDA and to rank technologies. In addition in CASES project some new indicators were proposed which fits better for sustainability assessment of energy technologies, such as total social costs of electricity generation or environmental and human health external costs. In Table 6 indicators framework for sustainability assessment of electricity generation technologies applied in CASES project is presented (CASES, 2008).

Table 6. Indicators for long-term sustainability assessment of electricity generation technologies developed in CASES project

Acronym	Indicator	Unit
PR COST	Private costs (investments and operation costs)	EURcnt/kWh
GRID COST	Costs of grid connection	Scores (1 to 5)
CO2eq	GHG emissions	kg/kWh
ENV	Environmental external costs	EURcnt/kWh
RADIO	Radionuclide external costs	EURcnt/kWh
ACC PAST	Fatal accidents from the past experience	Fatalities/GWye
ACC FUT	Severe accidents perceived in future	(Score 1 to 5)
HEALTH	Human health impact	EURcnt/kWh
FOOD	Food safety risk	(Score 1 to 5)

In CASES project these indicators set was not well established without allocation of specific indicators to specific dimensions of sustainable development. There was no clear background provided for selection of these indicators for sustainability assessment of electricity generation technologies. However valuable experience was obtained in performing MCDA based on CASES multi criteria tool developed for CASES project.

All indicators set reviewed have their weaknesses and strong points therefore for long-term sustainability assessment of energy technologies in PLANETS project the new indicators framework will be created based on the review of newest information available in this field.

Overview of indicators sets used for energy technologies assessment in previous studies allowed to develop the indicators framework for energy technologies assessment relevant to PLANETS project.

The following conclusions were drawn from the criteria and indicator survey carried out within this study.

1. The indicators frameworks applied for sustainability assessment of energy technologies have different scope and focus: sustainable development in general, sustainable development within the energy sector, and sustainable development within specific energy sources. There are wide differences in allocating specific indicators for specific dimensions of sustainable development.

2. There are just few world-wide recognized and well developed indicators for sustainability assessment of energy technologies applied in all studies. These indicators are mainly applied to electricity and heat sector and are supported by well-developed comprehensive data bases. These indicators are: private costs of electricity generation, life cycle external health costs, life cycle environmental external costs, life cycle radionuclides external costs and life cycle emissions of GHG gases.
3. There are no well-established comprehensive indicators sets supported by databases for sustainability assessment of energy technologies in transport, buildings and industry sectors;
4. The sets of indicators originating from international organizations are not suitable
for comparing the sustainability attributes of the major energy sources, in regard to
appropriate differentiation between technologies.
5. Most of the indicators sets are primarily based on directly available, simplistic indicators, and
there are major consistency problems.
6. Little effort has been made towards aggregation of indicators to support decisions.
7. Furthermore, aspects such as land use or security of supply are not addressed.
8. Earlier studies have not provided a harmonized, recognized set of technology-specific, application-specific numerical indicators. A broad knowledge base is a prerequisite for the establishment of such indicators, and the analytical framework employed in the present study can serve as a basis for this. Based on the results of the survey, the experience gained from the sustainability assessment will used for developing indicators framework for sustainability assessment of energy technologies.

The indicators set selected for electricity generation technologies sustainability assessment in GaBE study performed by PSI is the most comprehensive one from analysed frameworks and studies. This framework together with some indicators from NEEDS and CASES projects served as the background for technologies assessment in this report. Therefore based on these recent international studies on energy technologies assessment the methodological framework for long-term energy technologies sustainability assessment and short –term competitiveness and export opportunities was developed in the framework of Planets project.

5. SUSTAINABILITY ASSESSMENT OF ENERGY TECHNOLOGIES

The sustainability concept constitutes an essential background to the evaluation of energy technologies. However independently which exactly concept is chosen the objective of this work package is to differentiate between performances of the various energy technologies of interest. The concept of sustainability calls first of all for the integration of the economic, ecological and social aspects in the assessment of energy technologies. The evaluation of alternatives should be done on the basis of an agreed set of criteria and indicators covering these three dimensions. There are few ways to assess energy technologies by aggregating environmental, economic and social impacts: by applying multi-criteria decision analysis or by developing integrated indicator. Use of multi-criteria framework and

integrated indicators approach allows decision-makers to simultaneously address the often conflicting economic, ecological and social criteria.

The aim of this chapter is to develop framework for energy technologies assessment and apply this framework for sustainability and competitiveness assessment of energy technologies in electricity, transport and buildings sector.

- To develop indicators framework and integrated sustainability indicators based on this framework for sustainability and competitiveness assessment of energy technologies;
- To assess electricity generation technologies using integrated sustainability indicators;

5.1 Framework for sustainability assessment of energy technologies

The overall methodological framework for energy technologies assessment applied in PLANETS project consists of several stages and work packages. Long-term sustainability assessment based on the set of indicators and multi criteria analysis of energy technologies in 2050 according these indicators is just the first step in this assessment to be accomplished by this work package. The following probabilistic study concerning the major characteristics of the energy technologies and future states of the world (energy prices, GDP growth, policy targets set etc.) performed by stochasting models will allow to assess probabilistic long-term energy technologies scenarios. The applied methodological framework for energy technologies assessment consists of several main steps and serves for the main goal of PLANETS project:

1. The problem definition and bounding;
2. Development of tools for technologies assessment;
3. Technology description and it's anticipated evolvement over the time horizon;
4. Societal context description;
5. Long-tem sustainability assessment of energy technologies;
6. Short-term competitiveness assessment of energy technologies;
7. Comprehensive assessment of bridging technologies;
8. Integrated probabilistic assessment of energy technologies;
9. Development of probabilistic policy scenarios;
10. Policy recommendations.

The framework of probabilistic energy technology scenarios assessment performed in Planets project can be represented in the Figure 2.

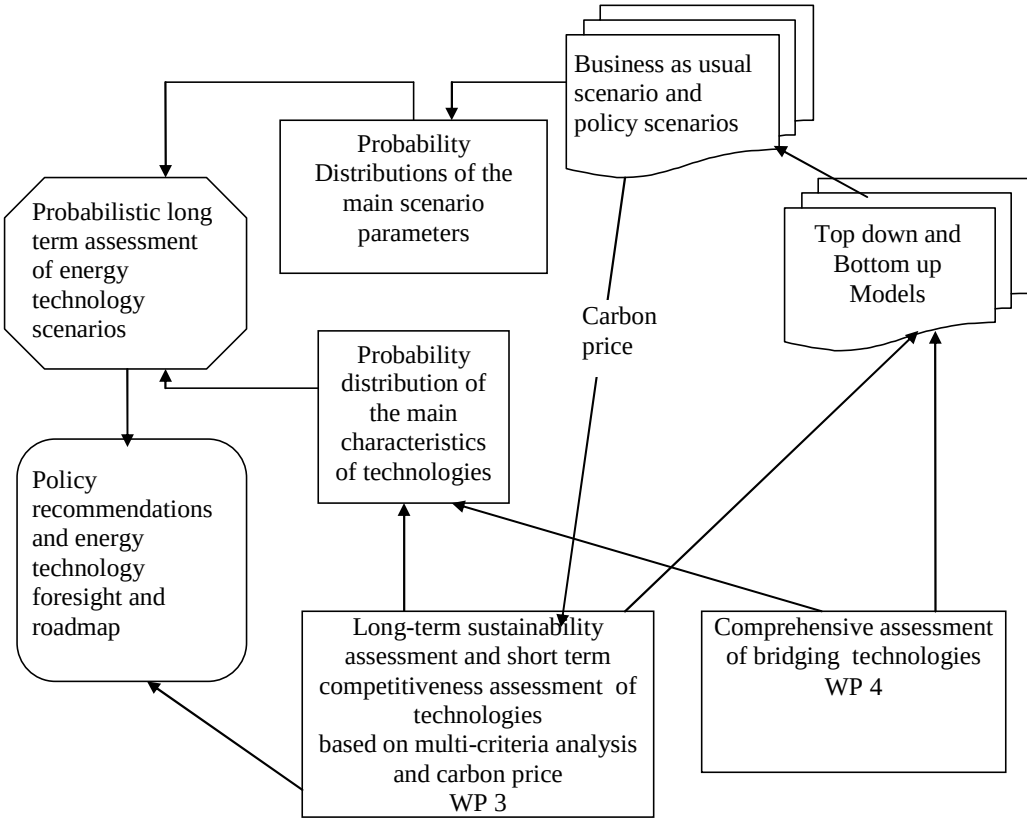

Figure 2 The framework for probabilistic long-term assessment of new energy technologies

The aim of this work package and this report is long-term sustainability assessment and short competitiveness assessment of energy technologies which constitutes just one part of probabilistic long-term energy technology scenarios assessment. In this work package relevant energy technologies will be selected based on the aim of the project and described taking into account their anticipated future development, potentials, barriers and restrictions including societal context and assessment of these technologies will be carried out based on developed indicators framework representing long-term EU energy and environmental policy goals. The assessment of energy technologies based on quantitative indicators framework enables to compare and to rank technologies based on EU sustainable development policy goals and provides useful information for other work packages aiming at representing future energy sector development in EU. The assessment of bridging technologies to be performed in parallel work package will focus on assessment on biomass based technologies and carbon capture and storage (CCS) technologies with respect to costs, maturity and risk. The bridging technologies can benefit from the existing infrastructure and can have a decisive influence on the long-term development of the energy system as a whole.

The full technology foresight exercises which are time and resource consuming projects are out of scope of this work package or PLANETS project and simplified approach for technologies assessment is required. The suggested technology assessment approach therefore, is firstly built on existing technology

foresight and assessment studies and similar analysis instead of starting from scratch. The suggested technologies assessment exercise includes the main findings from NEEDS, CASES, EUSUSTEL and GCEP projects etc. and integrates approaches used in these projects in terms of relevance to PLANETS project and skips not relevant aspects of approaches developed in these projects.

Therefore the technologies assessment framework developed in this work package of PLANETS project includes long-term sustainability assessment and short term competitiveness assessment parts both aiming at policy dimensions. As two energy technology assessments are included in PLANETS project ranging from bridging technologies to long-term future technologies assessment the different approaches were used in each assessment.

For long-term sustainability assessment of energy technologies the quantified indicators framework was proposed based on review of various studies and projects performed in the past. Earlier studies have not provided a harmonized, recognized set of technology specific numerical indicators. As broad knowledge base is a prerequisite for establishment of such indicators system therefore before developing indicators framework for long-term sustainability assessment of energy technologies the survey of other studies dealing with technologies assessment was conducted.

The proposed indicators framework is based on a systematic, bottom-up methodology, specifically tailored to the assessment of energy systems employing LCA approach. The main aim to represent explicitly technologies covering economic, environmental and social characteristics relevant for comprehensive assessment and comparison of technologies.

There are two major approaches to use sustainable development indicators. The one approach aims to develop a single, complex index, the other one to develop a set of indicators. Developing a single composite index implies selecting a number of different components and combining them into a single unit. Single, composite indices have the advantages to be straightforward because changes in the indicators value are directly related to an improvement or impairment of sustainable development. In addition, the various components (economic, social, and environmental) of such index can be evaluated explicitly when the index is calculated. Such indices allows easy to compare technologies and to track the changes in technologies performances over time. The disadvantages of single indices include pitfalls in the aggregation process, over simplification of complex systems and possibility to result in potentially misguiding signals. In the past years, several composite sustainable development indices have been developed mostly for cross national comparisons of economic, environmental and social aspects of sustainable development (Living Planet Index, Well-being Index, eco-indicator 99 etc.).

The advantage of a set of indicators used for technologies assessment is that the changes across several dimensions of sustainable development can be separately analysed however ranking of technologies according their economic, environmental and social performance based on the system of indictors requires multi criteria analysis and trade off among criteria therefore comparison between countries or tracking changes over the time become quite complicated time and resource consuming task.

The proposed methodological framework is based on integrated sustainability assessment indices and on the set of indicators representing

economic, social and environmental performance of energy technologies in long-term and competitiveness assessment in the short term. The aim of the proposed framework is to assess energy technologies **by selecting quantitative and qualitative technology and sector specific indicators for economic (including impact on competitiveness and export opportunities in short term), environmental and social (including impact on job creation) dimensions of sustainability assessment in long-term.**

Seeking to integrate long-term technology assessment with results of long-term policy scenarios run (Figure 2) in assessing the main relevant power and transport technologies the carbon price obtained by various policy scenarios runs will be used in the calculation of the GHG emission externalities of selected energy technologies.

5.2. Indicators framework for sustainability assessment of energy technologies

The set of indicators will be further selected for long-term sustainability assessment of energy technologies and short-term competitiveness assessment of energy technologies.

5.2.1 Indicators framework for long term sustainability assessment of energy technologies

A literature survey aiming at a review of published criteria and indicators was conducted. The requirements on criteria and indicators were established, having in mind the ultimate goal to operationalise evaluation of sustainability of energy technologies. The preliminary full set of indicators covering economic, environmental and social aspects was selected for long-term sustainability assessment of energy technologies. Based on these criteria and the scope of Planets project the set of indicators for long-term sustainability assessment of energy technologies was developed (Table 7). These indicators were selected based on surveys of studies on energy technologies assessment and energy indicators frameworks used for these assessments performed during the last decade. Proposed framework of indicators addresses the EU energy and environmental poly priorities and three dimensions of sustainable development: economic, social and environmental. In Table 7 just general indicators are selected covering the most important and sensitive sustainability issues with respect to EU energy and environmental policy goals defined in the first chapter of this report.

Table 7. The general indicators framework for long-term sustainability assessment of energy technologies

Indicator	Unit
Economic dimension	
Private costs (investments and operation costs)	EURcnt/kWh or EURcnt/vehicle km

Security of supply	Scores (1 to 5)
Grid costs	Scores (1 to 5)
Peak load response	Scores (0 to 5)
Average availability (load) factor	%
Environmental indicators	
GHG emissions	CO_2 eq kg/kWh or CO_2 eq kg/vehicle km
Environmental external costs	EURcnt/kWh or EURcnt/vehicle km
Human health impact	EURcnt/kWh or EURcnt/vehicle km
Radionuclides external costs	EURcnt/kWh
Social	
Technology-specific job opportunities	Person-year/kWh; Person-year/GJ
Food safety risk	(Score 1 to 5)
Fatal accidents from the past experience	Fatalities/GWh; Fatalities/vehicle km
Severe accidents perceived in future	(Score 1 to 5)

One can notice that indicators framework for sustainability assessment of energy technologies assessment presented in Table 7 *reflects* just general frame for energy technologies assessment based on EU energy and environmental policy priorities, i.e. private costs, external health and environmental external costs, GHG emissions and issues related to security of supply, accidents and food safety risk which are common for energy technologies in electricity, transport and buildings sector. Food safety risk assessment is mainly related with biomass which is being widely applied in all energy sectors: electricity, heat and transport etc.

5.2.2 Indicators framework for short – term competitiveness assessment of energy technologies

Competition and sustainability can be seen as a first extension of the traditionally used dimensions of sustainability. In fact, the topic has been on the agendas of governments since the 1990s. Environmental policy measures are often accompanied by the fear that they will entail negative competitiveness effects and lead to financial losses of domestic firms or in the worst case a relocation of „dirty“ industries to countries with less stringent environmental regulation.

Especially with the ongoing process of globalisation, characterised (among other factors) by increasing international trade flows, the interaction between

environmental policies and international competitiveness is becoming more important, and needs to be analysed. In this context, the energy system has an important role to play in terms of improving the competitiveness of European enterprises. The task of competitiveness assessment is to investigate how the energy issue can be dealt with in an adequate analytical framework. The aim of this work package is to select meaningful competitiveness indicators and to carry out corresponding assessment of energy technologies.

There are few indicators that can serve for competiveness assessment: total social costs of energy generation; fuel price increase sensitivity or increase in production costs due to doubling of fuel costs, the changes in the overall cost of energy production due to the penetration of technology (Table 8). Total social costs of energy generation by different technologies can be used as competiveness indicator as it allows ranking technologies according their competiveness in the market. This indicator was used to assess competitiveness of energy technologies in several studies: EUSUSTEL, Comprehensive Assessment of Energy Systems (GaBE) project conducted by PSI and in CASES and NEEDS projects.

Table 8. Indicators for short term competitiveness assessment of energy technologies

Indicator	Description	Unit	Information sources
Social costs (SC)	The full cost is calculated by adding all external costs to the private cost of production	EUR/GWh	EUSUSTEL and CASES project
Fuel price increase sensitivity (S)	This indicators represents the increase of production costs due to doubling of fuel costs	The ratio of fuel cost to generation costs	PSI data
Competitiveness through changes in the overall cost of energy production (C)	This indicator reflects the change in the overall cost of production of the energy carrier in the baseline caused by the penetration of the technology considered.	$\frac{x \times COE_t + (1-x) \times COE_{bl}}{COE_{bl}} - 1$ X – the additional share of the specific technology in the baseline gross consumption of the relevant energy carrier; COE – is the production cost of energy carrier; T – the production cost of technology considered; bl –baseline costs	A European Strategic Energy Technology Plan

In the following chapters the sustainability assessment of the main electricity generation technologies in EU will be performed. Description of technologies, potentials and barriers and needs are provided in Annex I of report.

5.3. Sustainability assessment of electricity generation energy technologies

Sustainability assessment of electricity and heat generation technologies will be performed based on indicator framework for long-term sustainability assessment of electricity generation technologies and competitiveness assessment will be performed based on indicators for competiveness assessment.

5.3.1 Long-term sustainability assessment of electricity generation energy technologies

Based on sustainability assessment indicators framework presented in Table 8, specific set of 13 indicators for electricity and heat generation technologies sustainability assessment was selected (Table 9). The description of indicators is presented bellow and evaluation of electricity generation technologies is followed.

Table 9. Indicators for long-term sustainability assessment of electricity generation technologies

Acronym	Indicator	Unit	Information sources
Economic			
PR COST	Private costs (investments and operation costs)	EURcnt/kWh	CASES
AVAILAB	Average availability (load) factor	%	EUSUSTEL
SECURE	Security of supply	Scores (1 to 5)	NEEDS
GRID COST	Costs of grid connection	Scores (1 to 5)	CASES
PEAK LOAD	Peak load response	Scores (0 to 5)	PSI data, NEEDS
Environmental			
CO2eq	GHG emissions	kg/kWh	CASES
ENV	Environmental external costs	EURcnt/kWh	CASES
RADIO	Radionuclide external costs	EURcnt/kWh	CASES
HEALTH	Human health impact	EURcnt/kWh	CASES
Social			
EMPL	Technology-specific job opportunities	Person-year/kWh	PSI data

FOOD	Food safety risk	(Score 1 to 5)	CASES
ACC PAST	Fatal accidents from the past experience	Fatalities/kWh	PSI data
ACC FUT	Severe accidents perceived in future	(Score 1 to 5)	CASES

Economic indicators

The Economic dimension in sustainability assessment of energy technologies is very important as energy supply cost is the main driver for energy technologies penetration in the markets. There are 6 indicators selected to address economic dimension of sustainability assessment in electricity and heat sector: private costs, fuel price increase sensitivity, average availability factor, costs of grid connection, peak load response, security of supply. The most important indicators are: private costs, availability factor and costs of grid connection.

The private costs in EURcnt/kWh are based on the Average Levelised Generating Costs (ALLGC) methodology. The methodology calculates the generation costs (in EuroCents/kWh) on the basis of net power supplied to the station busbar, where electricity is fed to the grid. This cost estimation methodology discounts the time series of expenditures to their present values in 2005, which is the specified base year, by applying a discount rate. According to the methodology used in the IEA study in 2005, the levelised lifetime cost per GWh of electricity generated is the ratio of total lifetime expenses versus total expected outputs, expressed in terms of present value equivalent. The total lifetime expenses include the value of the capital, fuel expenses and operation and maintenance expenses, inclusive the rate of return equal to discount rate. The formula to calculate average lifetime levelised generating costs is:

$$ALLGC = \sum_{t=o}^{T} \frac{[I_t + M_t + F_t]}{(1+r)^t} \Bigg/ \sum_{t=0}^{T} \frac{[E_t]}{(1+r)^t} \qquad (1)$$

Where I_t is the investment expenditures in year t; M_t is the operation and maintenance expenditure in year t; Ft is the fuel expenditures in year t; E_t is the electricity generation in year t and r is the discount rate.

The capital (investment) expenditures in each year include construction, refurbishment and decommissioning expenses. As suggested by OECD the methodology used defines the specific overnight construction cost in €/kW and the expense schedule from the construction period. The overnight construction cost is defined as the total of all costs incurred for building the plant immediately.

The operating and maintenance costs (O&M) contribute by a small but no negligible fraction to the total cost. Fixed O&M costs include costs of the operational staff, insurances, taxes etc. Variable O&M costs include cost for maintenance, contracted personnel, consumed material and cost for disposal of normal operational waste (excluding radioactive waste).

The fuel price assumptions for fossil and nuclear plants are based on results from EUSUSTEL project. The technical life time for various types of power plants are also obtained from EUSUSTEL project. Since lignite and biomass are local energy carriers, which are not included in an international price mechanism, then the fuel prices of these two types of energy carriers are assumed to be constant. The price projections for the other fuels are determined by taking into account the international market mechanism. Of particular noteworthiness for nuclear power is that the total fuel cycle costs are considered (natural uranium, conversion, enrichment, intermediate and final disposal).

The ALLGC for combined heat and power plants (CHP) does not take into account the fact that the plant is used also to produce heat, in addition to electricity. The value of heat recovery can be measured by the cost avoided in using recovered thermal energy for a specific purpose, as opposed to using another source of energy. The value of recovered thermal energy is equivalent to the cost of fuel energy that would have otherwise been consumed, which is referred to as an energy credit or fuel credit. A gas boiler, with an efficiency of 90 percent, gives the alternative heat generation technology in this report. Then in the computation of full cost the fuel credit is subtracted from the ALLGC.

An adjustment of the ALLGC should be made also for wind and solar technologies. Due to the fluctuation caused by producing energy with wind and solar plants, which are intermittent energy sources, a back-up technology is necessary for compensating this. The back-up cost of uncertain generating power of solar and wind plants are calculated with the equation estimated in (Friedrich et al, 1994). In this equation, the provision of the back-up power is reduced by a capacity factor (P) for the renewable technologies. In the calculation of full costs the ALLGC is summed to the back up cost of a gas-fired CCGT plant for maximum back-up costs. The methodology described determines for each technology a private cost of electricity production levelised for all Europe. To reach the objective of comparability, country specific cost components are not considered. In particular the estimation is not influenced by the capital market's differences across Europe since overnight investments costs are considered. In addition all costs are considered net of taxes, which change from country to country. To assess full costs of electricity production a discount rate of 5 percent is considered. The basis year for the analysis is 2005. This indicator was applied in all studies on energy technology assessment reviewed in report. European values for 2030 will be applied for electricity generation technologies assessment in this report.

Costs for grid connection (Score 1 to 5) indicator is additional qualitative indicator to assess the risk that a certain technology will include high cost for grid connection as private costs of electricity generation do not include costs related to grid connection. The higher the score the higher risks of high cost for grid connection, for example wind off-shore electricity generation has the highest grid connection costs. This indicator was used in just in CASES project to assess electricity generation technologies.

Peak-load response (Score 0 to 5) is qualitative indicator which reflects the technology-specific ability to respond swiftly to large temporal variations in demand. This capability is particularly attractive in view of market liberalization. Base-load technologies, and those renewables which strongly depend on climatic conditions, are not suitable in this context and has very low score. This indicator was applied in NEEDS, GaBE studies just other scales for scoring were applied. In GaBE (Score 0

to 100) and in NEEDS flexibility to dispatch was evaluated based on ordinal scale from 1 to 10. For the dispatchable technologies, such as hard coal, lignite, natural gas, oil based and hydro technologies a score between 1 and 5 is allocated and for non-dispatchable technologies such as solar and wind – 0 score is allocated.

Table 10. Values for the indicator peak load response

Fuels	Value
Nuclear	0,5
Fuel cells	0,5
Hard coal	2,5
Lignite	1
Oil	5
Natural gas	5
Hydro	1,5
Biomass	5
PV	0
Wind	0

Average availability factor (%) is based on typical load factors. This information for specific power plants is presented in EUSUSTEL project and available in NEEDS, GaBE projects.

Security of energy supply is a qualitative indicator (score 1 to 5) and it is very important from the point of view of EU energy policy priorities. The security of supply in electricity sector can be expressed by Long-term independence from foreign energy source. This indicator was applied for evaluation of autonomy of electricity generation in NEEDS project.

Utility companies and the societies they serve may be vulnerable to interruptions in service if imported fuels are unavailable due to economic or political problems related to energy resource availability. It combines consideration of energy autonomy and sustainability, based on whether the energy resource for a specific technology is imported, domestic and finite, or domestic and renewable, with some weight given to the relative size of different finite resources. The quantification of this indicator is proposed to follow an ordinal scale, as given in Table 11 below.

Table 11 Values for the indicator "very long-term independence from foreign energy sources (NEEDS, 2006)

Group name	Value	Description
Imported energy carrier	0	Technologies that rely on fuels or energy sources that must be imported
Domestic oil	1	For oil-fired technologies in countries where domestic oil resources are available
Domestic gas	2	For gas-fired technologies in countries where domestic gas resources are available
Domestic coal	3	For coal-fired technologies in countries where domestic coal resources are available
Domestic uranium	4	For nuclear technologies in countries where

		domestic uranium resources are available
Fuel cells	3	Fuel cells are based on natural gas or biogas therefore average score can be applied
Domestic renewable resource	5	For technologies which rely on renewable energy fluxes present in a given country (hydro, solar, wind, wave, geothermal)

The scale given runs from zero for energy carriers that must be imported, to 5 for renewable resources that are domestically available. Intermediate values for domestic fossil or nuclear resources are based on judgement of the relative time scales for the availability of different fuel types, and some consideration of domestic interaction with global markets. For this indicator, the fuel refers to the primary energy carrier, e.g. synthetic gas made from biomass would be scored a 5, while synthetic gas made from coal would be scored a 3, and natural gas would be scored a 2. This distinction also applies to synthetic oil from various sources v. oil refined from domestic crude reserves.

Several possible indicators were originally proposed in various studies to measure the contribution of each generating technology to the autonomy of electricity supply. The indicator for short-term autonomy proposed in NEEDS project was the lifetime of stored reserves (i.e. short-term stockpiles/current resource use). Estimating future stockpiles and use for the year 2050 however was so uncertain and scenario dependent that this indicator was abandoned. An indicator for long-term autonomy based on domestic energy resources was also proposed, based on long-term reserve life (i.e. currently known and recoverable domestic reserves/current domestic use) in NEEDS project. There was still considerable uncertainty as to how well this current measure of resource lifetime would apply in the year 2050, but it was deemed acceptable due to the long-term resource life. Modifications based on the substitutability of fuels were also considered and rejected. However the main problem with using the concept of resource life as an indicator remained that it essentially produces a binary measure. That is, fossil & uranium reserves are finite, no matter how large, and renewables have a resource life that is infinite for all practical purposes. This binary separation of finite v. infinite destroys the possibility of making any discrimination between the different resource lifetimes for the different fossil and nuclear technologies, which are still of significant importance.

It was proposed to resolve this difficulty by imposing an arbitrary, large cap on the resource life of the renewable resources, but it was unclear what the rationale for this should be. Likewise, it would have been possible to use the logarithm of the resource life, which would have compressed the difference between finite and renewable resources, but not really have solved the problem. In the end, it seemed more reasonable to recognize the inherent element of judgement, and the ordinal scale given above was proposed. This element of judgement also allows some recognition of the fact that finite resources with similar resource lifetimes may still have different risks associated with geographic distribution, market forces and international politics.

The evaluation of whether domestic energy resources are available is based on expert judgment, i.e., whether it is now thought that there is sufficient domestic fuel resource to build a generation unit in 2050 and operate it economically for its life. If fossil fuels or uranium are not now domestically present, then the situation is

clear. If coal, lignite or uranium is present, then the reserves are likely to last for the commercial life of the plant (40+ years). The situation for oil and particularly gas reserves is more complicated.

Environmental indicators

The main environmental dimension indicators for energy technologies assessment are: GHG emissions, environmental external costs, radionuclides external costs, severe accidents perceived in future and fatal accidents from the past experience. Additional environmental indicators are land use and solid waste.

Life cycle emissions of GHG emissions in kg (CO2-eq.)/kWh are selected to assess electricity generation technologies according EU environmental policy priority – climate change mitigation. GHG emissions in kgCO2eq/kWh were selected instead of external costs of GHG emissions because of the large uncertainties related to evaluation of external costs of GHG emissions. Climate change is the dominating environmental concern of the international environmental political discussion of today. Global warming is not only an issue for the environment, but rather for human society as a whole, since rising global temperatures might have serious consequences not only on the environment, but on our economy and social life as well. Among the potential consequences are more frequent extreme weather events like heat waves, storms, flooding and droughts, stress due to higher temperatures for plants and humans, rising sea level, and altering occurrence of pathogenic organisms. The indicator reflects the potential negative impacts of the global climate change caused by emissions of greenhouse gases for the production of 1 kWh of electricity. It follows the methodology of (IPCC, 2001) and covers complete energy chains. This indicator was used in almost all studies on energy technologies assessment survived.

The environmental external costs in EURcnt/kWh is the estimates for damage to ecosystems due to emissions to air, soil and water of particles, gases, the formation of ozone and the emissions of metals. These costs were obtained during ExternE, NEEDS and CASES projects and were used in these projects for electricity generation technologies assessment. Environmental external costs are calculated with respect to the impact of pollutants on crops, damage to materials, and loss of biodiversity caused by acidification and eutrophication. For all these categories of impact the life cycle emissions of air pollutants are considered: Ammonia (NH3), Non-methane volatile organic compounds unspecified (NMVOC), Nitrogen oxides (NOx), Particulates (PPMco - between 2.5 and 10 um, and PPM25 - less than 2.5 um), Sulfur dioxide (SO2). In addition the cost of sulfur dioxide and nitrogen oxides emissions in the atmosphere is calculated with respect to the damage to materials. The European values for 2030 will be applied for assessment of electricity generation technologies in this report.

The external health costs in EURcnt/kWh provide the estimates for damages to health due to emissions to air, soil and water of particles, gases, the formation of ozone, and emissions of metals. Marginal external costs for classical air pollutants were calculated for CASES project by IER with the updated EcoSenseWebV1.2 tool. To estimate external costs by transforming impacts that are expressed in different units into a common monetary unit, the ExternE methodology is used. The costs of emission are calculated with respect to the impact of pollutants on human health for all these categories of impact the following air

pollutants are considered: Ammonia (NH3), Non-methane volatile organic compounds unspecified (NMVOC), Nitrogen oxides (NOx), Particulates (PPMco - between 2.5 and 10 um, and PPM25 less then 2.5 um), Sulfur dioxide (SO2). The European averaged values for 2030 will be applied for electricity technologies assessment in this project.

Radionuclides external costs in EURcnt/kWh are external costs estimates for damages to health due to emissions of life cycle radionuclides including indirect use of nuclear electricity in the production of other technologies. The release of these radionuclides and the corresponding radioactivity into the environment causes impacts to human health. The impacts considered are fatal cancers, non-fatal cancers and hereditary defects. The cost in Euro/kBq is obtained by multiplying the collective dose estimation unit (manSv) per kBq, which is specific for each pollutants, times the cases of fatal cancer, non fatal cancer and hereditary defects per manSv and the corresponding Willingness To Pay (WTP) values in Euro per endpoint. The factors relating collective dose to impact, so called risk factors, are determined by a linear dose-effect relationship. The values used in calculation are: 0.05 cases per manSv for fatal cancers, 0.12 cases per manSv for non-fatal cancers and 0.01 cases per manSv for hereditary defects. To calculate the cost in Euro/kBq for radionuclide unit of emission the respective number of cases of endpoint per kBq is multiplied by the following values for WTP per endpoint: 1.120.000 Euro for fatal cancers, 481.000 for non-fatal cancers and 1.500.000 for hereditary defects10. These WTP values are derived from estimates for different types of cancer, e.g. leukaemia, lung cancer, etc. Types of cancer differ in latency and estimated YOLL and YLD (year lost due to disability). For fatal cancers, 15.95 YOLL + 0.26 YLD are assumed. The monetary value for fatal cancer includes also an additional estimation of WTP to avoid the illness based on the costs of illness (COI) (ca. 481,050 E) The YOLL are multiplied with 40,000 Euro/year of life lost. Heredity effects have been valued at the same value as a statistical life, since there are no WTP estimates of such impacts available, and given the relevance usually attributed to such effects. Generic marginal external radionuclides cost were estimated for the following radionuclides: Aerosols, radioactive, unspecified into air; Carbon-14 into air and water; Hydrogen-3, Tritium into air and water; Iodine-129 into air; Iodine-131 into air; Krypton-85 into air; Noble gases, radioactive; unspecified into air; Radon-222 into air; Thorium-230 into air and water; Uranium-234 into air and water. The radionuclides external costs estimates are based on ExternE, NEEDS and Cases project results. The European values for 2030 will be applied for evaluation of electricity generation technologies in this report.

Social indicators

The main social indicators selected for electricity technologies assessment in this report are technology-specific job opportunities, human health impact, food safety risk and work related fatalities per accident. The most important indicators applied in almost all studies for technologies assessment are: external health costs and technology specific job opportunities.

Technology specific job opportunities in person-year/kWh indicator are based on the average amount of labour used to produce a unit of electricity. It does not give the total number of persons employed (some jobs might be part-time), or the quality of the jobs as measured either by salary or the amount of training or

education required. The quality of work issue is instead addressed by one of the social indicators (the "Work Quality" indicator is based on knowledge and training of average worker in each technology chain, using an ordinal scale indicator. The aim of the technology chain labour assessment was to estimate the life-cycle labour content of 8 technology chains for electricity generation, including lignite pulverized coal, bituminous pulverized coal (hard coal), oil, natural gas, hydro, wind and solar PV generation. In order to do this, each chain was divided into four components: 1) Fuel Extraction & Processing; 2) Fuel Transportation; 3) Generation Plant Construction; and 4) Generation Plant Operation.

It is difficult to find hard data for establishing accurate, averaged labour statistics for these technologies across the entire EU electricity sector. National electricity sector associations do not collect employment numbers by fuel-type or type of plant. The only official number from these organizations is the total employment level of 131,000 for the German electricity sector. Normalizing by the total net generation of about 520 TWh in 2002 gives an average employment of about 250 man-yr/TWh. If the more detailed US employment data ratios are applied, this would result in about 110 man-yr/TWh for generation, transmission and distribution (T&D), and about 240 man-yr/TWh for general and administrative jobs. These data can serve as an order of magnitude check against individual generation technologies, although they do include non-generation components, and do not include T&D employment.

Overall, the estimation of labour can be followed by 3 possible methods. When national data (e.g. mining jobs) were available, they were used to obtain a national sector average. If industry sources were available for specific plant types (e.g. generation labour for combined-cycle plants), these were used next. Finally, order-of-magnitude estimates were made (e.g. for average hydro construction labour) when other sources failed. Total uncertainty depends upon both the relative sizes and uncertainties of the labour estimates for the individual technology chain components. Two other factors also affect the uncertainty of labour estimates. First is the question of where the dividing boundary should be. For example, in the case of coal and nuclear generation, direct plant construction labour was estimated for on-site construction, and excluded the specific labour content of components. However, for the wind and solar technology chains, more indirect aggregate industry construction data were used, based on data availability, and the fact that more of the labour is devoted to component fabrication. Secondly, labour results have been normalized in terms of generation; i.e. they were given in man-years per TWh. This means that variable labour (e.g. fuel) depends upon plant efficiency, and fixed labour (e.g. construction) depends upon plant generation. Some electricity generation (e.g. by wind and solar) is fixed by natural availability, but most generation is based on cost-based dispatch. In this case, the generation was based on the German average generation for the technology in question. Finally, labour components for different technologies were compared and adjusted, based on our own estimates of the relative labour intensity required. It should be noted that all non-recurring labour (primarily construction labour) was amortized over the assumed life of the generation technology before adding the variable labour content for fuel, etc. This means that labour rates for the different labour components can be multiplied by the labour content to produce a total labour cost per kWh, if so desired. Finally, the relative sizes of the individual labour components and totals were compared for general consistency, and adjusted as deemed appropriate.

Food safety risk is qualitative indicator (Score 1 to 5) used for qualitative assessment of the risk that using biomass fuels will put stress on food supply safety and food prices. This indicator was applied for technologies assessment in CASES project is very relevant today as the increased use of biomass especially for biofuels production in transport cause big problems related with increase of food prices.

Fatal accidents from past experience in fatalities/kWye indicator represents the risk of fatal accident using the frequency of occurrence o a severe accident in the past and the number of fatalities involved in previous accidents. In principle, the approach used for the evaluation of severe accidents is consistent with the impact pathway method. Due to their special nature, however, accidents are treated separately. The evaluation builds on other work carried out at PSI (Hirschberg et al, 1998) and covers fossil energy sources (coal, oil and gas), nuclear power and hydropower. PSI's database ENSAD (Energy-related Severe Accidents Database was developed. This indicator was also widely applied in energy technologies assessment studies, i. e. NEEDS, CASES, GaBE etc.

Severe accidents perceived in the future is qualitative indicator (Score 1 to 5) and represents qualitative assessment of risk of a severe accidents in the future. The higher the score the more people perceive that accident will happen. This indicator is similar to risk aversion. This indicator was applied in CASES project, GaBE and NEEDS projects.

The following electricity and heat generation technologies will be assessed based on sustainability assessment indicators framework described above (Table 9). They are described in Annex I.

Table 12. Selected electricity and heat generation technologies for long-term sustainability assessment

TECHNOLOGIES AND TYPE OF POWER PLANT FOR ELECTRICITY PRODUCTION		
nuclear		EPR
		PBMR
fossil fired power plants	oil	heavy oil condensing PP
		light oil gas turbine
	coal	condensing PP
		IGCC
		IGCC PP with CO2 sequestration
	lignite	condensing pp
		IGCC
		IGCC pp with CO2 sequestration
	gas	combined cycle
		combined cycle PP with CO2 sequestration
		gas turbine
hydropower	run of river	<10 MW
		<100 MW
		>100 MW
	dam	
	pump storage	
	tidal power	

wind	on shore	
	off shore	
solar PV	roof	
	open space	
solar thermal		
TECHNOLOGIES AND PP FOR ELECTRICITY AND HEATING PRODUCTION (CHP)		
CHP with an extraction condensing turbine	gas	CC
		CC PP with CO2 sequestration
	coal	PP
		IGCC PP with CO2 sequestration
CHP back pressure	gas	
	coal	
biomass CHP with an extraction condensing turbine	straw	
	wood chips	
fuel cells	natural gas	MCFC
		SOFC
	bio gas	MCFC

In the Table 13 the long-term sustainability assessment of the reviewed electricity generation technologies is presented based on the 13 indicators (Table 9). These 13 indicators consist of 5 economic indicators (private costs, grid costs, availability factor, peak load response and security of supply), 4 environmental (environmental external costs, radionuclides external costs, human health related external costs, GHG emissions) and 4 social indicators (technology-specific job opportunities, food safety risks, fatal accidents from the past and severe accidents perceived in the future).

Table 13. The long-term sustainability assessment of EU electricity technologies in 2030

Energy technologies	Acr	HEALTH, EURcnt/kWh	CO2eq, kg/kWh	PR COST, EURcnt/kWh	ENV, EURcnt/kWh	RADIO, EURcnt/kWh	ACC PAST	ACC FUT	FOOD	GRID COST	AVAI-LAB	SECURE	PEAK LOAD	EMPL, persons-year/GWh
Nuclear power plant (Europann pressurized reactor)	NUC	0.190	0.013	2.653	0.015	0.1452	0.001	4	1	3	0.90	4	0.5	0.16
Heavy oil condensing power plant	OIL CL	2.390	0.208	7.194	0.213	0.0017	0.132	4	1	3	0.85	1	5	0.47
Light oil gas turbine	OIL GT	1.853	0.435	9.681	0.174	0.0019	0.132	4	1	3	0.85	3	5	0.47
Hard coal condensing power plant	COA CL	1.548	0.751	3.203	0.186	0.0012	0.157	4	1	3	0.85	3	2.5	0.86
Hard coal IGCC without CO2 capture	COA IGCC	0.930	0.694	3.495	0.105	0.0013	0.157	4	1	3	0.85	3	2.5	0.86
Hard coal IGCC with CO2 capture	COA IGCC CCS	1.042	0.154	4.150	0.118	0.0005	0.157	4	1	3	0.85	3	2.5	0.86
Lignite condensing power plant	LIG CL	1.134	0.817	2.135	0.130	0.0005	0.157	4	1	3	0.85	3	1	0.21
Lignite IGCC without CO2 capture	LIG IGCC	0.934	0.786	2.778	0.094	0.0005	0.157	4	1	3	0.85	3	1	0.21
Lignite IGCC with CO2 capture	LIG IGCC CCS	1.051	0.106	3.351	0.106	0.0002	0.157	4	1	3	0.85	0	1	0.21
Natural gas, combined cycle without CO2 capture	GAS STAG	0.563	0.395	4.519	0.077	0.0002	0.085	2	1	3	0.85	0	5	0.65
Natural gas, combined cycle with CO2 capture	GAS STAG CCS	0.620	0.110	5.875	0.86	0.0002	0.085	2	1	3	0.85	0	5	1.8
Natural gas, gas turbine	GAS GT	0.864	0.620	6.563	0.124	0.0002	0.085	2	1	3	0.85	0	5	0.65
Hydropower, run of river 10MW	HYD S	0.198	0.013	7.229	0.016	0.0001	0.001	1	1	3	0.57-0.80	5	1.5	1.2
Hydropower, run of river <100MW	HYD M	0.142	0.009	4.519	0.011	0.0001	0.001	1	1	3	0.57-0.80	5	1.5	1.2
Hydropower, run of river >100MW	HYD L	0.127	0.008	4.519	0.010	0.0002	0.001	1	1	3	0.57-0.80	5	1.5	1.2
Hydropower, dam (reservoir)	HYD DAM	0.245	0.015	7.350	0.020	0.0002	0.001	2	1	3	0.80-0.91	5	1.5	1.2
Hydropower, pump storage	HYD PMP	0.251	0.014	7.350	0.020	0.0005	0.001	2	1	3	0.80-0.91	5	1.5	1.2
Wind, on-shore	WIND ON	0.142	0.010	6.019	0.007	0.0004	0.001	1	1	4	0.23 0.29	5	0	0.36
Wind, off-shore	WIND OFF	0.173	0.007	6.143	0.006	0.0022	0.001	1	1	5	0.29 0.50	5	0	0.36
Solar PV, roof	PV ROOF	0.479	0.056	25.140	0.032	0.0028	0.001	1	1	3	0.15	5	0	6.6
Solar PV, open space	PV OPEN	1.082	0.108	20.829	0.064	0.0002	0.001	1	1	3	0.15	5	0	6.6
Solar thermal. parabolic trough	SOL TH	0.105	0.008	11.969	0.007	0.0002	0.001	1	1	3	0.15	5	0	6.6
Natural gas CHP with extraction condensing turbine without CO2 capture	CHP GAS	0.527	0.366	4.225	0.072	0.0002	0.085	2	1	4	0.85	0	5	0.65
Natural gas CHP with extraction condensing turbine with CO2 capture	CHP GAS CCS	0.574	0.101	5.450	0.079	0.0011	0.085	2	1	4	0.85	0	5	1.8
Hard coal CHP with extraction condensing turbine without CO2 capture	CHP COAL	1.406	0.674	0.945	0.167	0.0010	0.157	4	1	4	0.85	3	2.5	2.01
Hard coal CHP with extraction condensing turbine with CO2 capture	CHP COAL CCS	0.805	0.119	1.468	0.092	0.0002	0.157	4	1	4	0.85	3	2.5	2.01
Natural gas combined cycle CHP with backpressure turbine	CHP GAS STAG	0.612	0.424	4.134	0.083	0.0012	0.085	2	1	4	0.85	0	5	0.86
Hard coal CHP with backpressure turbine	CHP COAL BP	1.555	0.741	0.503	0.183	0.0004	0.157	4	1	4	0.85	3	2.5	0.86

Biomass (straw) CHP with an extraction condensing turbine	CHP STRAW	1.691	0.069	4.751	0.360	0.0029	0.085	2	2	4	0.95	5	5	4.4
Biomass (woodchips) CHP with an extraction condensing turbine	CHP WOOD	0.639	0.057	3.791	0.078	0.0028	0.085	2	2	4	0.95	5	5	4.4
MCFC (natural gas)	MCFC	1.958	0.184	7.300	0.167	0.0018	0.085	2	1	3		3	0.5	1.8
SOFC (natural gas)	SOFC	0.664	0.127	7.080	0.069	0.0005	0.085	2	1	3		3	0.5	1.8
MCFC (biogas)	MCFC	3.196	0.326	7.824	0.241	0.0269	0.085	2	1	3		3	0.5	1.8

The equal treatment of the three dimensions environment, economy and society is not without controversy. An alternative perspective postulates that human society has to develop within the boundaries set by the environment, and that economy has to satisfy societal needs - not the reverse. Therefore the sustainability assessment of energy technologies needs integrated indicators or MCDA for ranking technologies. Overall, a meaningful sustainability perspective implies a balanced (equal) assignment of importance to economic, ecological and social aspects. For the comparative sustainability evaluations of energy technologies will be performed further based on the aggregation of indicators. The integrated sustainability assessment indicators will be calculated for each technology by summing weighted indices of all indicators:

$$Q_j = \sum wi * Q_{ij}, \text{ where } \sum wi = 1 \qquad (2)$$

Here: Q_j integrated indicator for sustainability assessment of specific energy technology j; Q_{ij} – index of indicator i for specific energy technology j; wi – the weight of i indicator in the integrated indicator

The indices for integrated are derived by the following formula:

$$Q_{ij} = q_{ij} / qi_{vid} \qquad (3)$$

Here: Q_{ij} – index of indicator i for specific energy technology j; q_{ij} – the value of indicator i for specific technology j; qi_{vid} – the average value of indicator i for all energy technologies

If indictor decrease (for example external costs or private costs) is positive in terms of sustainability assessment the indices of such indicators are integrated as inverted indices:

$$Q_{ij} = 1/Q_{ij} \qquad (4)$$

The weights for specific criteria will be selected based on various studies carried and various weighting schemes will be assigned to accommodate the range of possible stakeholders considerations. The sensitivity of these possible choices will be also investigated. In one case the weights will be equally distributed between economic, environmental and social components, in another case which will be economy focused to the economic criteria being given a weighting of 50%, while the environmental and social criteria each have a weighting of 25%, the other cases will be defined in an analogous manner by running environmentally, socially focused cases. Multi Cases tool developed by CASES project or other tools (DAM etc.) can be also applied for MCDA.

Further performed the comparative sustainability assessment of energy technologies is based on the aggregation of economic, social and environmental indicators by developing integrated indicators. The integrated sustainability assessment indicators are calculated for each technology by summing weighted indices of all indicators. The sensitivity analysis is carried out. Several scenarios were developed. In one case (equal treatment of all criteria) the weights are equally distributed between economic, environmental and social criteria, in another cases to the economic criteria (economic focus scenarios) being given a weighting of 50% and 80%, while the environmental and social criteria each have a weighting of 25% and accordingly 10%, the other cases will be defined in an analogous manner by running environmentally, socially focused cases.

In Figure 3 the ranking of electricity generation technologies is presented based on integrated sustainability assessment indicators when all 13 criteria are being treated equally in assessment by providing the same weight to each economic, social and environmental criteria.

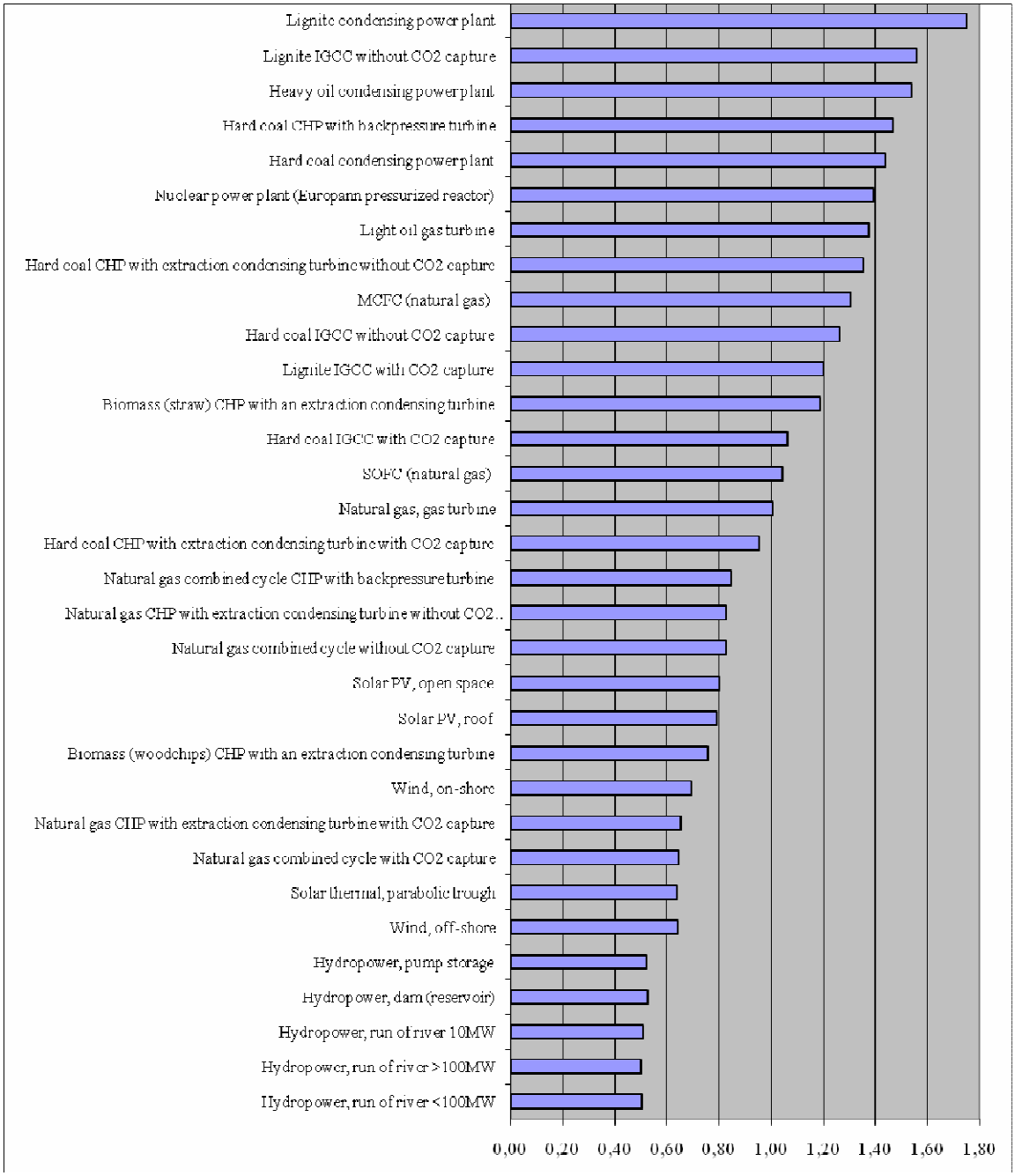

Figure 3. Ranking of electricity generation technologies: equal treatment of all criteria (Table 13)

In Figure 4 the ranking of electricity generation technologies is presented according environmentally focused scenario when for 4 environmental criteria from Table 13 the given total weigh is 80% (or 20% per each environmental criteria) and economic and social criteria are allocated with 20% weight.

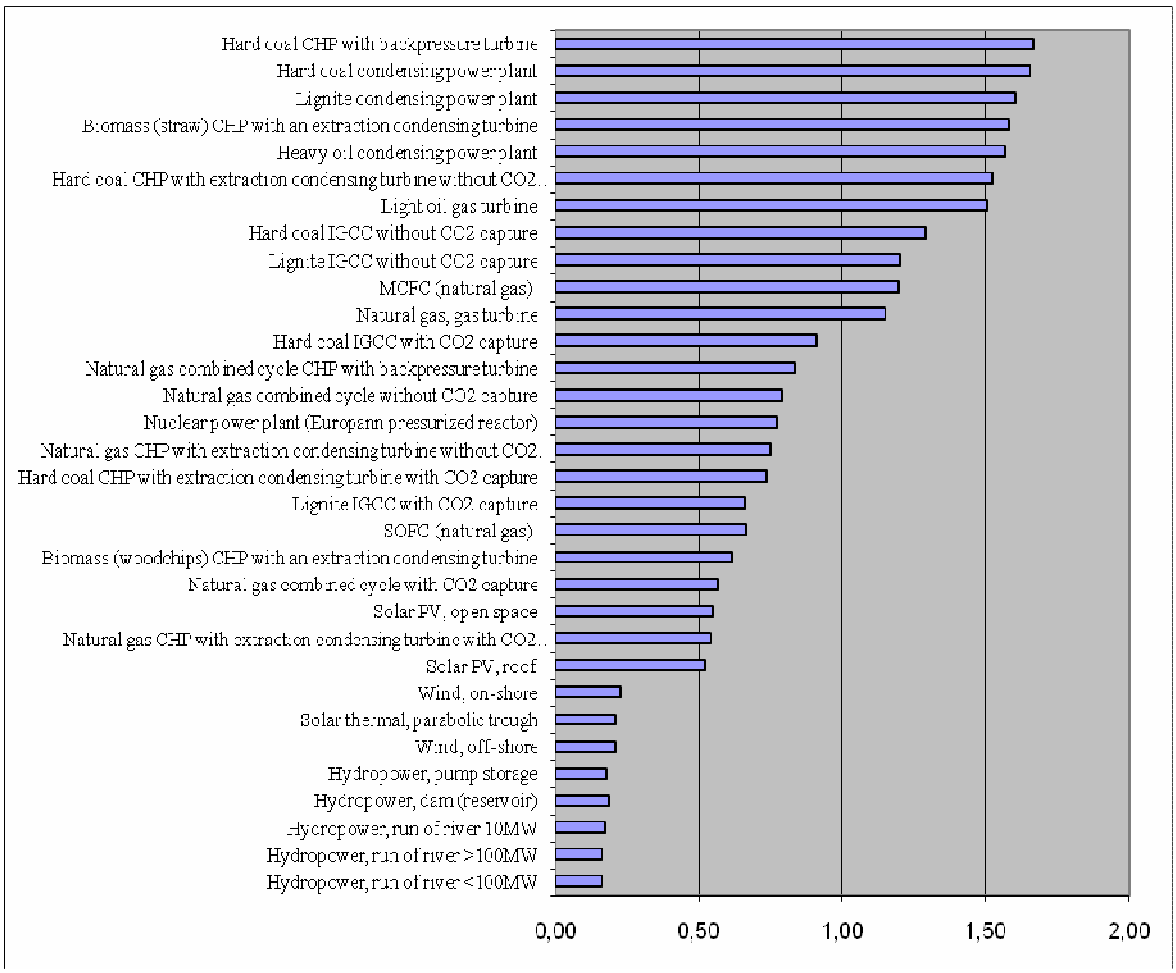

Figure 4. Ranking of electricity generation technologies: environmentally focused scenario

In environmentally focussed scenario the best technologies having the lowest score of integrated sustainability assessment indicator are renewable and the worst technologies are mainly coal based. Ranking of electricity generation technologies in economically oriented scenario is presented in Figure 5. In this scenario 5 economic criteria are weighted by 80% and social and environmental criteria are weighted by 20%. As one can see form technologies ranking in Figure 5 the best technologies according economically oriented scenario are natural gas and hydro energy technologies. The technologies having the highest score of integrated sustainability indicator or being the worst according sustainability criteria are fuel cells based technologies and mature oil and natural gas technologies.

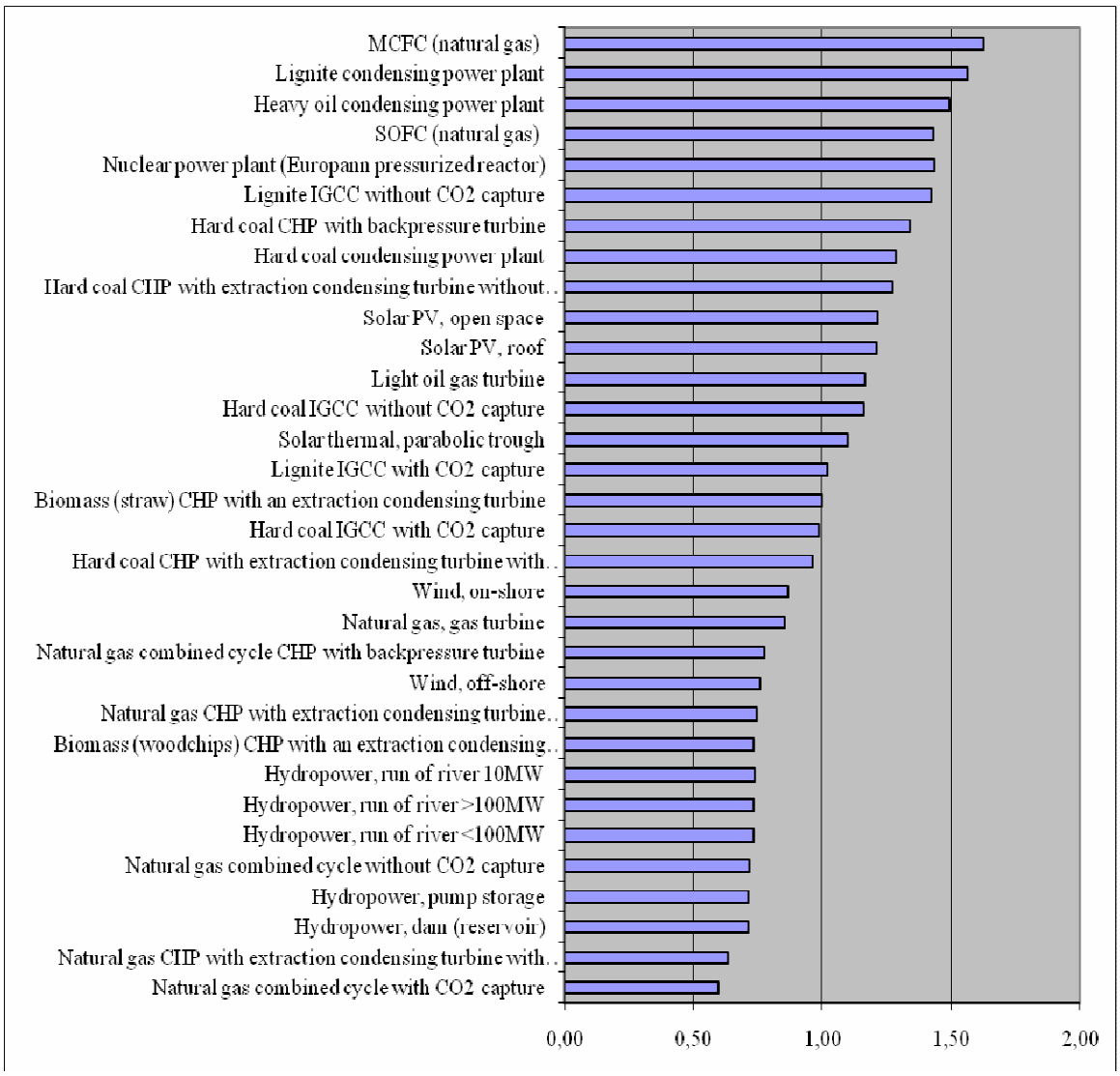

Figure 5. Ranking of electricity generation technologies according economically focused scenario

The ranking of electricity generation technologies according socially foccused scenario when 4 social criteria are weighted by 80% and economic and environmental criteria are weighted by 20% is presented in Figure 6. As one can see from Figure 6 the best technologies having the lowest score in this scenario are solar and hydro and the worst – lignite and other mature heavy oil and coal technologies.

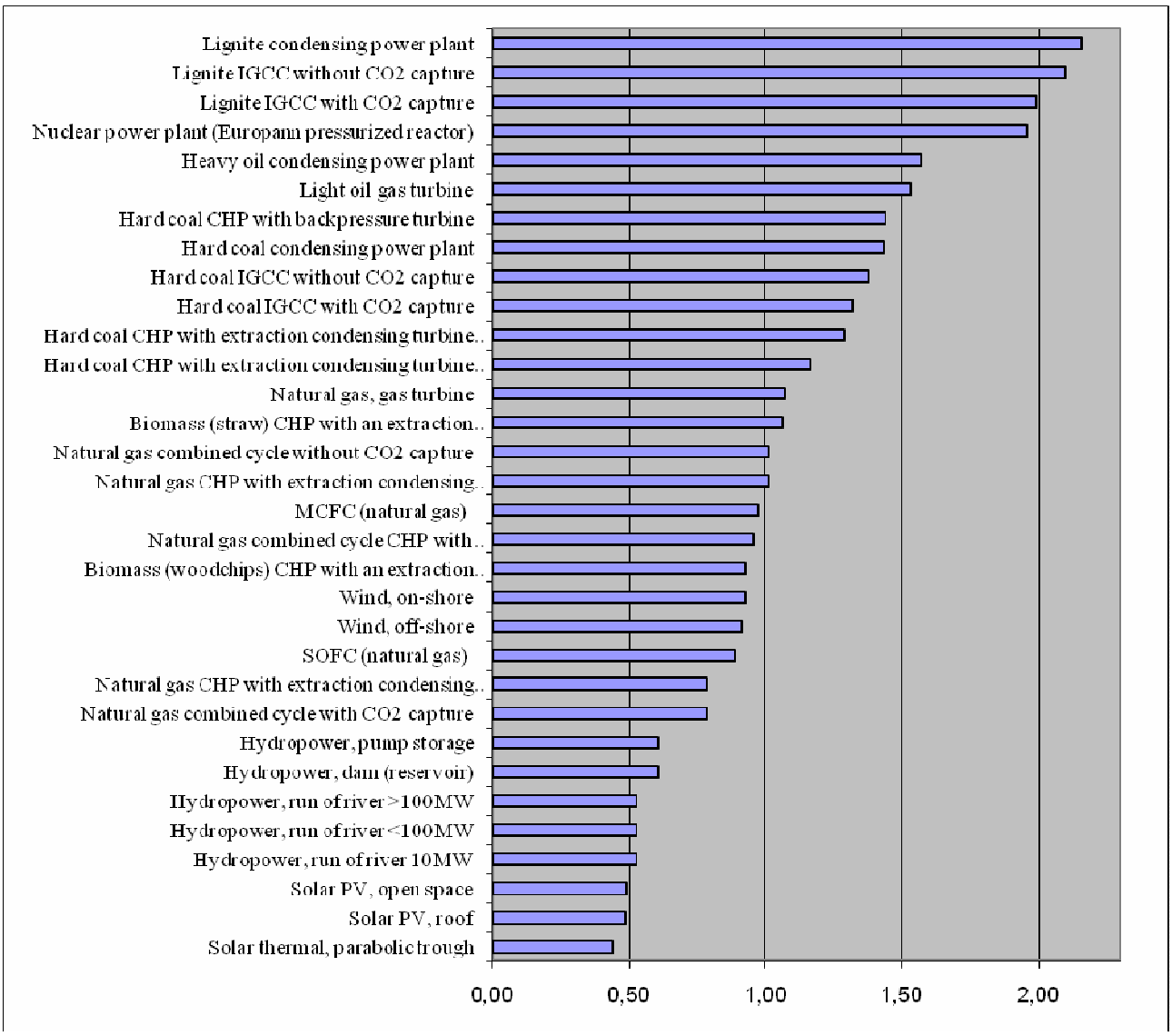

Figure 6. Ranking of electricity generation technologies according socially foccused scenario

Therefore the ranking of electricity generation technologies by providing the different weights to criteria provides the following results:

- Based on integrated sustainability index and **equally treating all** criteria the best technology (having the lowest score in assessment) is hydro, followed by wind and the worst –lignite condensing power plant, lignite ICGG without carbon capture and heavy fuel oil condensing power plant.
- **In economy focused scenario** the best technology is the natural gas combine cycle and natural gas CHP with extraction turbine and carbon capture, followed by hydro and the worst is MFSC and lignite condensing power plant followed by heavy fuel oil condensing power plant;
- In **environmentally focused** scenario the best technology is hydro, followed by wind and the worst technology is hard coal CHP with backpressure turbine, hard coal condensing power plant.

- In **socially focussed scenario** the best technology is solar, followed by wind and the worst technology is lignite condensing power plant, Lignite IGCC without carbon capture.

5.3.2 Short-term competitiveness assessment of electricity generation energy technologies

Given the variations in technical and economic parameters for the various electricity generation technologies, a synthesis of all available information allows calculating the total social cost of electricity generation for EU The total social costs of electricity generation summarise the private and external costs of a technology and therefore indicate its use of resources from an economic and environmental point of view. It can be regarded as a relative measure for sustainability and the indicative measure of competitiveness.

Summarising the calculation results for the various electricity generation technologies, regarding Average Lifetime Levelised Generation Costs and external costs for CO2 and other emissions, it can be observed that the conventional power plants are projected to have economic advantages compared to technologies using renewable energy sources like solar PV. Given the comparatively high overnight investment costs for wind and PV combined with the low utilisation rates due to wind supply and solar radiation, renewable electricity is becoming more competitive in the year 2030 but faces still higher total social costs. Table 14 and Figure 7 presents the total social costs of electricity generation for the selected conventional and renewable technologies for the years 2005, 2020 and 2030 based on EUSUSTEL and CASES project results.

Table 14. EU social costs of electricity generation in 2005, 2020, 2030 (CASES, 2007)

FULL COSTS OF ELECTRICITY GENERATION IN EU (Eurocent/kWh)						
Rank	2005-10		2020		2030	
1	biomass (woodchips) CHP with an extraction condensing turbine	1,79	biomass (woodchips) CHP with an extraction condensing turbine	1,80	biomass (woodchips) CHP with an extraction condensing turbine	1,97
2	nuclear power plant	3,32	nuclear power plant	2,76	nuclear power plant	2,40
3	hard coal CHP with backpressure turbine	3,88	lignite IGCC with CO2 capture	4,15	lignite IGCC with CO2 capture	4,28
4	hard coal CHP with extraction condensing turbine without CO2 capture	4,07	hard coal CHP with backpressure turbine	4,19	hard coal CHP with extraction condensing turbine with CO2 capture	4,48
5	hard coal CHP with extraction condensing turbine with CO2 capture	4,07	hard coal CHP with extraction condensing turbine with CO2 capture	4,26	biomass (straw) CHP with an extraction condensing turbine	4,80
6	biomass (straw) CHP with an extraction condensing turbine	4,61	hard coal CHP with extraction condensing turbine without CO2 capture	4,31	hard coal CHP with extraction condensing turbine without CO2 capture	5,21
7	lignite IGCC without CO2 capture	5,38	biomass (straw) CHP with an extraction condensing turbine	4,37	hard coal CHP with backpressure turbine	5,25
8	lignite IGCC with CO2 capture	5,38	lignite IGCC without CO2 capture	4,96	lignite IGCC without CO2 capture	5,68
9	natural gas CHP with extraction condensing turbine without CO2 capture	5,39	lignite condensing power plant	5,15	wind, off-shore	5,88
10	natural gas CHP with extraction condensing turbine with CO2 capture	5,39	hard coal IGCC with CO2 capture	5,66	hard coal IGCC with CO2 capture	5,95
11	lignite condensing power plant	5,65	natural gas CHP with extraction condensing turbine without CO2 capture	5,72	wind, on-shore	6,03
12	natural gas combined cycle CHP with backpressure turbine	5,71	natural gas combined cycle CHP with backpressure turbine	5,83	lignite condensing power plant	6,07
13	natural gas combined cycle without CO2 capture	6,20	hard coal IGCC without CO2 capture	6,03	natural gas CHP with extraction condensing turbine without CO2 capture	6,17
14	natural gas combined cycle with CO2 capture	6,20	natural gas combined cycle without CO2 capture	6,04	natural gas combined cycle CHP with backpressure turbine	6,31
15	wind, on-shore	6,21	wind, on-shore	6,09	natural gas combined cycle without CO2 capture	6,43
16	wind, off-shore	6,46	wind, off-shore	6,21	hard coal IGCC without CO2 capture	6,77
17	hard coal condensing power plant	6,47	hard coal condensing power plant	6,52	hydropower, run of river >100MW	6,86
18	hard coal IGCC without CO2 capture	6,61	hydropower, run of river >100MW	6,85	natural gas combined cycle with CO2 capture	7,03

19	hard coal IGCC with CO2 capture	6,61	natural gas combined cycle with CO2 capture	6,90	hard coal condensing power plant	7,30
20	hydropower, run of river >100MW	6,85	natural gas CHP with extraction condensing turbine with CO2 capture	7,22	natural gas CHP with extraction condensing turbine with CO2 capture	7,36
21	hydropower, run of river 10MW	7,90	hydropower, run of river 10MW	7,91	hydropower, run of river 10MW	7,92
22	hydropower, run of river <100MW	7,98	hydropower, run of river <100MW	7,99	hydropower, run of river <100MW	8,00
23	natural gas, gas turbine	8,66	natural gas, gas turbine	8,89	SOFC (natural gas)	8,25
24	heavy oil condensing power plant	8,96	heavy oil condensing power plant	10,19	natural gas, gas turbine	9,48
25	hydropower, pump storage	11,10	solar thermal, parabolic trough	10,41	solar thermal, parabolic trough	9,61
26	hydropower, dam (reservoir)	11,12	hydropower, pump storage	11,11	MCFC (natural gas)	9,91
27	light oil gas turbine	12,34	hydropower, dam (reservoir)	11,13	MCFC (biogas)	10,75
28	solar thermal, parabolic trough	12,88	SOFC (natural gas)	12,54	heavy oil condensing power plant	11,10
29	MCFC (biogas)	35,21	light oil gas turbine	13,01	hydropower, pump storage	11,13
30	MCFC (natural gas)	35,55	MCFC (natural gas)	15,77	hydropower, dam (reservoir)	11,15
31	solar PV, open space	36,80	MCFC (biogas)	17,26	light oil gas turbine	14,03
32	solar PV, roof	45,63	solar PV, open space	21,65	solar PV, open space	17,51
33	SOFC (natural gas)	47,73	Solar, PV, roof	25,94	Solar PV, roof	24,39

As one can see from information provided in Table 14 and Figure 7, at present the cheapest or most competitive electricity generation technologies after the internalization of external costs is biomass (woodchips) CHP with an extraction condensing turbine. The other cheapest energy technologies at present are: nuclear (European pressurized reactor) and hard coal CHP with backpressure turbine. Photovoltaic technologies are the most expensive technologies even if the share of external costs very small. The sets of technologies presented in Table 10 are fully comparable since back up costs, calculated for a fired CCGT plant as back up technology are added to generation costs for wind and solar which are intermittent renewable energies.

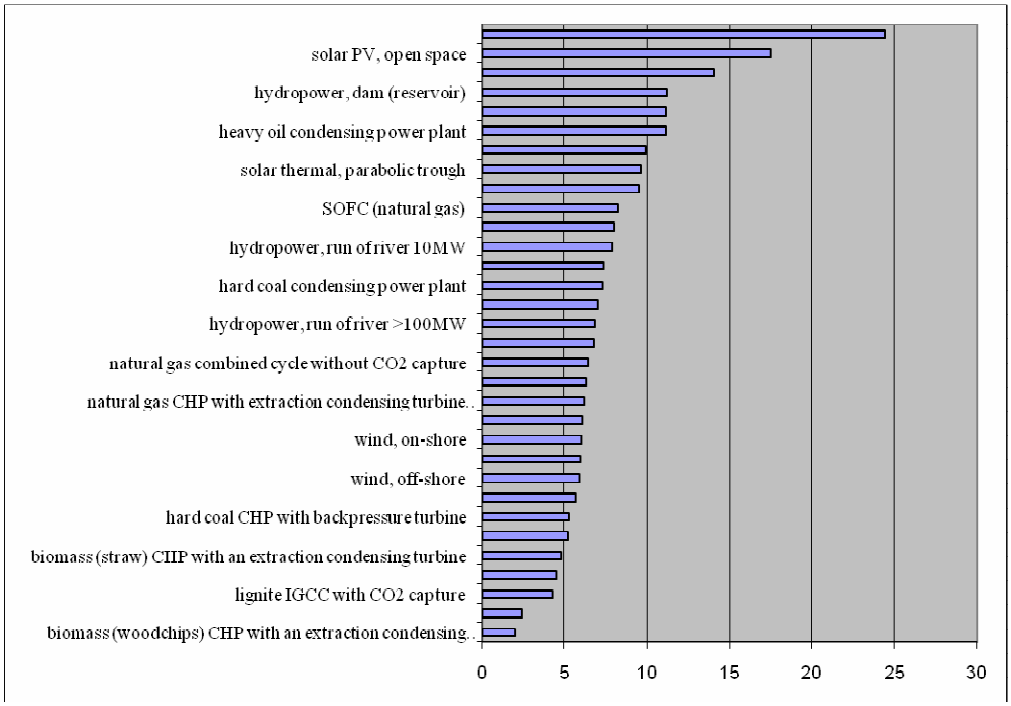

Figure 7. Ranking of electricity generation technologies according competitiveness evaluated in terms of social costs

Social costs were obtained by summing external costs due to impacts on human health, environment, crops, and materials and to climate change impacts, to private generation costs.

This exercise results in levelised and homogenous values for all EU27 countries. Data are levelised since European average values for private costs, emissions inventory and external cost of greenhouse gases and heavy metals are considered. Full costs were calculated and assessed for a wide set of technologies, which includes nuclear and fossil fired power plants, renewables and combined heat and power plants. Full costs are assessed as average values of all EU-27 countries. In the analysis performed, private and external costs are assessed for the whole life cycle of the power plant, from construction to dismantling, including cost of extraction and transportation of fuel and waste disposal. Private costs and quantity of pollutants emitted, which are plant specific, are calculated for new power plants build in 2005-2010, in 2020 and 2030, hence old power plants, still existing are excluded from the analysis. All costs are expressed in Euro 2005.

Some limits to the analysis are due to the exclusion from the assessment of probabilistic external costs, e.g. external cost of nuclear accident. These external costs may have a very high cost but are usually associated to a very low probability of occurrence. Moreover, for combined heat and power (CHP) heath credits have been subtracted to the private costs, to analyse the share of cost relative to power generation, excluding the share relative to heat generation, while all external cost are attributed into power generation costs; thus external costs for CHP are overestimated.

The same technologies will be compared by applying Competitiveness indicator (Table 15) based on the impact of new technology on the changes in the overall cost of energy production (C). This indicator is based on the quantification of the effects of the penetration of the different technologies considered in the European Strategic Energy Technology Plan. The evaluation of the effects of the additional to the baseline penetration of each technology in terms of changes in the overall production cost of the energy carrier that the technology producers (electricity, heat etc.).

Table 15 Additional cost of energy by penetrating technology in 2020 and 2030

Competitiveness of energy technologies					
Rank	**2020**	**Additional cost of energy, %**	**Rank**	**2030**	**Additional cost of energy, %**
5	biomass (woodchips) CHP with an extraction condensing turbine	0,5-1	7	biomass (woodchips) CHP with an extraction condensing turbine	1-3
1	nuclear power plant	-0,5-(-0,1)	1	nuclear power plant	-2-(-0,5)
8	lignite IGCC with CO_2 capture	0,3-2	8	lignite IGCC with CO_2 capture	2-6
7	hard coal CHP with backpressure turbine	0,5-1	7	hard coal CHP with extraction condensing turbine with CO2 capture	1-3
7	hard coal CHP with extraction condensing turbine with CO_2 capture	0,5-1	7	biomass (straw) CHP with an extraction condensing turbine	1-3
7	hard coal CHP with extraction condensing turbine without CO_2 capture	0,5-1	7	hard coal CHP with extraction condensing turbine without CO_2 capture	1-3
7	biomass (straw) CHP with an extraction condensing turbine	0,5-1	7	hard coal CHP with backpressure turbine	1-3
8	lignite IGCC without CO_2 capture	0,3-2	8	lignite IGCC without CO_2 capture	2-6

3	lignite condensing power plant	0	2	wind, off-shore	-2-0
8	hard coal IGCC with CO_2capture	0,3-2	8	hard coal IGCC with CO_2capture	2-6
7	natural gas CHP with extraction condensing turbine without CO_2capture	0,5-1	2	wind, on-shore	-2-0
7	natural gas combined cycle CHP with backpressure turbine	0,5-1	3	lignite condensing power plant	0
8	hard coal IGCC without CO_2 capture	0,3-2	7	natural gas CHP with extraction condensing turbine without CO_2 capture	1-3
5	natural gas combined cycle without CO_2 capture	0,5-1	7	natural gas combined cycle CHP with backpressure turbine	1-3
2	wind, on-shore	-0,3-0	7	natural gas combined cycle without CO_2 capture	1-3
2	wind, off-shore	-0,3-0	8	hard coal IGCC without CO_2capture	2-6
3	hard coal condensing power plant	0	4	hydropower, run of river >100MW	0,04-0,2
1	hydropower, run of river >100MW	0,05-0,2	7	natural gas combined cycle with CO_2 capture	1-3
7	natural gas combined cycle with CO_2 capture	0,5-1	3	hard coal condensing power plant	0
7	natural gas CHP with extraction condensing turbine with CO_2capture	0,5-1	7	natural gas CHP with extraction condensing turbine with CO_2capture	1-3
3	hydropower, run of river 10MW	0	3	hydropower, run of river 10MW	0
3	hydropower, run of river <100MW	0	3	hydropower, run of river <100MW	0
1	natural gas, gas turbine	-0,5-(-0,1)	6	SOFC (natural gas)	0,7-0,8
3	heavy oil condensing power plant	0	1	natural gas, gas turbine	-2-(-0,5)
5	solar thermal, parabolic trough	0,2-0,3	5	solar thermal, parabolic trough	0,3
4	hydropower, pump storage	0,05-0,2	6	MCFC (natural gas)	0,7-0,8
4	hydropower, dam (reservoir)	0,05-0,2	6	MCFC (biogas)	0,7-0,8
6	SOFC (natural gas)	0,3	1	heavy oil condensing power plant	0
1	light oil gas turbine	-0,5-(-0,1)	4	hydropower, pump storage	0,04-0,2
6	MCFC (natural gas)	0,3	4	hydropower, dam (reservoir)	0,04-0,2
6	MCFC (biogas)	0,3	1	light oil gas turbine	-2-(-0,5)
9	solar PV, open space	3-7	9	solar PV, open space	8-17
9	Solar, PV, roof	3-7	9	Solar PV, roof	8-17

As one can see from ranking of energy technologies provided in Table 15, the most competitive technologies are nuclear, natural gas turbines and other conventional electricity generation technologies. The solar PV is the most expensive and least competitive technology according both evaluation methods carried out.

The main recommendations from this partial competitiveness assessment is to use macro-economic and trade models that are able to assess competitiveness effects, e.g. via the channel of international trade on an international level and sectoral models that focus more on the detailed effects on the sectoral level. Such a comprehensive analysis has to take into

account the different national and international aspects of competitiveness, considering thus impacts of international and national policies that induce internal and external imbalances. The energy technologies competitiveness assessment based on these types of models is foreseen in EU Framework project **TRANSUST-SCAN** is going in parallel with Planets.

6. POLICY ORIENTED ASSESSMENT OF THE MAIN ENERGY TECHNOLOGIES BASED ON CARBON PRICE

The assessment of electricity generation technologies based on various economic, environmental and social criteria provided above can serve as a complementary material to results of various policy scenarios runs providing electricity generation technology ranking according priorities of EU energy and environmental policies and can serve as guidance for further policy development in EU. However as the main focus of Planets project is on the climate change mitigation issues therefore the long-term assessment of new energy technologies based on various long-run policy scenarios is necessary taking into account 2 main criteria: private costs (ALLGC) and external GHG emission costs.

The aim of this chapter is to assess the main relevant energy technologies (power and transport sector) by integrating price of carbon obtained by policy scenarios run in calculating GHG emission externalities for the main future energy technologies.

6.1 The assessment of energy technologies by integrating carbon price

Seeking to assess energy technologies based on future energy and climate change mitigation policies the information on carbon price developments is crucial in terms of technologies ranking. The policy scenarios integrating various GHG emission reduction commitments and climate change mitigation targets can provide information on carbon price developments over time frame. The policy oriented assessment of the main selected power and transport technologies in this report will be provided for 2020 and 2050 and for the various regions (World, OECD, Energy Exporting EEX – Russia and mid-East, Developing Asia, DevAsia, Rest of the World, ROW) covered by models (ETSAP-TIAM, DEMETER, GEMINI and WITCH).

The results of various model runs for various policy oriented scenarios will serve as input for energy technologies assessment. 10 policy scenarios runs were performed for 4 models:

First best scenarios: FB-3p2 and FB-3p5 setting alternative targets after 2050: 3.2 W/m^2 and 3.5 W/m^2.

Second best policy scenarios:

SC1-3p2 –To reach commitments indicated in Table 16 for SC1 linearly declining from business as usual from start date (Table 16) to the indicated of 2005 emissions. The target after 2050: 3.2 W/m^2

SC1-3p5- To reach commitments indicated in Table 16 for SC1 linearly declining from business as usual from start date (Table 16) to the indicated of 2005 emissions. The target after 2050: 3.5 W/m^2

SC2-3p2- To reach commitments indicated in Table 16 for SC2 linearly declining from business as usual from start date (Table 16) to the indicated of 2005 emissions. The target after 2050: 3.2 W/m^2

SC2-3p5 - To reach commitments indicated in Table 16 for SC2 linearly declining from business as usual from start date (Table 16) to the indicated of 2005 emissions. The target after 2050: 3.5 W/m^2.

The set of 4 variant second best policy scenarios are the same as for four second best scenarios, but with a limitation on the purchasing of carbon permits between 2020 and 2050, during which period at least 80% of abatement (defined as business usual minus the allocation) has be undertaken domestically by each region, and at most 20% of the abatement can be

done with international offsets (purchase of permits). The trade restriction is levied from 2050 onwards.

Table 16. Commitments applied in policy scenarios

Regions	Starting date of commitments	Commitments SC1 in 2050 w.r.t. 2005	Commitments SC2 in 2050 w.r.t. 2005
OECD	2015	-80%	-90%
ENERGY EXPORTING (EEX)	2025	-50%	0%
DEVELOPING ASIA (Dev. Asia)	2025	+25%	0%
REST OF THE WORLD (ROW)	2025	+55%	+100%
WORLD w.r.t. 2005		-28%	-26%

The main indicators or criteria for energy technologies assessment according various policy scenarios will be private costs of energy generation and external costs of GHG emissions integrating carbon price.

The following energy technologies were selected for assessment:

In power and heat sector:

- hard coal
- natural gas
- oil
- nuclear
- biomass

In transport:

- oil
- biofuels.

In power sector just base load technologies were assessed. In transport sector some technologies such as hybrid electric vehicles and hydrogen based cars were not assessed in this report because of the lack of consistent data on GHG emissions life cycle and fuel costs. Though hydrogen could capture 10-15% of the transportation fuel market by 2050 however, important obstacles remain on the vehicle side, and in the transition to a hydrogen fuelled transportation sector which is highly uncertain. Hybrid electric vehicles (HEVs) have recently gained a lot of interest. These vehicles use a combustion engine to generate electricity. This electricity is used to drive an electric motor. The energy efficiency of this type of vehicles is up to 50% higher than for conventional vehicles.

In the following chapters of report based on recent scientific literature review and results of various EU funded projects the range of life cycle GHG emissions and private costs for the selected electricity generation and transport technologies will be derived. The average values of life cycle GHG emissions and private costs were further used for electricity generation and transport technologies policy oriented assessment and ranking. The most competitive energy technologies will be identified based on external costs of GHG emissions and total costs for the main policy scenarios. Policy oriented energy technologies assessment can provide information on the most attractive future energy technologies taking into account climate change mitigation targets and GHG emission reduction commitments for world regions.

6.2 Life cycle GHG emissions and private costs of selected electricity generation technologies

The data on life cycle GHG emissions for specific fuel cycles is necessary seeking to assess external costs of GHG emissions for different energy technologies using information about CO_2 prices over the time and space delivered by various models by running policy scenarios. Life cycle CO2 emissions from power an transport sector depend strongly upon details of supply chain, production techniques, forestry and agriculture practices, transport distance etc.

The principle factors determining the GHG emissions from a fossil fuel power plant is the type of technology (and hence choice of fuel) and its thermal efficiency. In addition, thermal efficiency increases with the load factor (although efficiency reductions can be observed towards achieving full load operation) and therefore GHG emissions from a particular fossil fuel technology will depend on the mode of its operation (e.g. peak load management, base load supply, combined heat and power supply etc.) (Weiser, 2006).

The ranges of life cycle GHG emissions for power and heat generation technologies are presented in Table 17. Life cycle GHG emission ranges (from minimal to maximal values) were presented based information provided by various sources (Elsayed et al, 2003; Ecolane Transport Consultancy, 2006; The Royal Society, 2008; Jacobson, 2009, Gross, Bauen, 2005; Lenzen, 2008, Hondo, 2005; Fritsche, Lim, 2006; Weisser, 2007, Rhodes, Keith, 2005; Mollersten, Yan, Moreira, 2003; Fritsche, Lim, 2006). The range of direct CO_2 emissions from combustion and total life cycle GHG emissions per technology were calculated in kg/MWh. Further this data will be used for external costs calculation of power generation technologies using carbon price data (EUR/tCO_2) produced by various models for various policy scenarios, regions and time frames.

Table 17. Life cycle GHG emissions of the main energy technologies in power sector

Fuel or energy type	Direct CO_2 emissions from combustion		Life cycle CO_2 emissions		Average value, of life cycle GHG emissions, kg/MWh
	kg/GJ	kg/MWh	kg/GJ	kg/MWh	
Nuclear	2.5÷30.3	9÷110	2.8÷35.9	10÷130	65
Oil	126.9÷300.7	460÷1090	137.9÷331.0	500÷1200	850
Natural gas	96.6÷179.31	350÷650	110.3÷215.2	400÷780	590
Hard coal	193.1÷262.1	700÷950	206.9÷344.8	750÷1250	1000
Hard coal IGCC with CO_2 capture	*52.4÷60.7*	*190÷220*	*38.6÷46.9*	*140÷170*	*155*
Large scale wood chips combustion	-	-	21.0÷23.0	76.0÷83.3	79.6
Large scale wood chips gasification	-	-	6.0÷8.0	21.6÷29.0	25.3
Large scale biomass IGCC with CO_2 capture	*-139.4÷-143.5*	*-505÷-520*	*-35.9÷-41.4*	*-130÷-150*	*-140*

Large scale straw combustion	-	-	62.0÷70.0	223.2÷252.0	237.6
Biomass (wood chips) CHP large scale	-	-	6÷10	21.6÷36.0	28.8
Biomass (wood chips gasification) CHP small scale	-	-	3÷6	10.8÷21.6	16.2

As one can see from information provided in Table 17 biomass wood chips gasification technologies have the lowest life cycle GHG emissions followed by wood chips CHP large scale. Hard coal technologies have the highest life cycle GHG emissions followed by oil and natural gas technologies. Hard coal IGCC with CO_2 capture technologies have quite low life cycle GHG emission comparable even with Large scale wood chips gasification technologies. Nuclear technologies have lower life cycle GHG emission than some biomass technologies for example large scale straw combustion technologies and large scale wood chips combustion technologies. Biomass technologies with CO_2 capture have negative life cycle GHG emissions. Especially high negative GHG emissions are during combustion processes of Biomass IGCC with CO_2 capture.

The range of current and long-term private costs (ALLGC) for the same power generating technologies were selected from various information sources (Gross, Bauen, 2005, Fritsche, Lim, 2006; Rhodes, Keith, 2005; Mollersten, Yan, Moreira, 2003; Elsayed at al, 2005, CASES, 2007, EUSUSTEL, 2007, NEEDS, 2008). In Table 18 the range of current private costs of the selected power generation technologies is presented.

Table 18. Current and long-term private costs of power generation technologies, EUR/MWh

Current			
Fuel or energy type	Costs, EUR/MWh		Average private costs, EUR/MWh
	Min	Max	
Nuclear	24	41	33
Oil	98	100	99
Natural gas	56	62	59
Hard coal	26	39	33
Hard coal IGCC with CO_2 capture	*40*	*43*	*42*
Large scale wood chips combustion	40	44	42
Large scale wood chips gasification	47	58	54
Large scale biomass IGCC with CO_2 capture	*59*	*62*	*61*
Large scale straw combustion	50	56	53
Biomass (wood chips) CHP large scale	40	63	52
Biomass (wood chips gasification) CHP small scale	40	63	52
Long-term (2030-2050)			
Nuclear	24	42	33
Oil	79	100	90

Natural gas	53	60	57
Hard coal	21	44	33
Hard coal IGCC with CO_2 capture	*40*	*43*	*42*
Large scale wood chips combustion	35	38	37
Large scale wood chips gasification	42	49	46
Large scale biomass IGCC with CO_2 capture	*57*	*60*	*59*
Large scale straw combustion	44	48	46
Biomass (wood chips) CHP large scale	37	60	49
Biomass (wood chips gasification) CHP small scale	37	60	49

As one see from information provided in Table 19 the cheapest technologies in long-term perspective are: nuclear and hard coal technologies followed by large scale biomass combustion and biomass CHPs. The most expensive technologies in terms of private costs are: oil and natural gas technologies. Therefore the energy technologies having the lowest life cycle GHG emissions are not the most expensive but not the cheapest one in terms of private costs. Therefore the ranking of technologies in terms of competitiveness would highly depend on the carbon price implied by various policy scenarios integrating specific GHG emission reduction commitments taken by countries and set climate change mitigation targets.

6.3 Life cycle GHG emissions and private costs of selected electricity transport technologies

The range of life cycle GHG emissions of transport technologies in g/vehicle km were obtained by gathering data on GHG emissions from transport sector from various sources (The Royal Society, 2008; Elsayed et al, 2003; Cramer Commission, 2006; Edwards et al., 2007; Hofstedt, 2007, Woods, Bauen, 2003) and evaluating direct CO_2 emissions from combustion and total life cycle GHG emissions for specific transport technologies (Table 19).

Fuel GHG intensity is the key factor which represents the net lifecycle emissions impact associated with the consumption of a unit of fuel. Sometimes termed a fuel's "carbon footprint," it can be expressed in units of grams of carbon dioxide-equivalent per megajoule (gCO_2 eq/MJ) of energy delivered to vehicles or other transportation equipment. Fuel GHG intensity is but one factor among many that contribute to transportation emissions. For our assessment of transport technologies GHG life cycle and direct GHG emissions from combustion will be evaluated in g CO_2 per vehicle km. Conversion of GHG emission data from g CO_2 /l to g CO_2/vehicle km for various fuels is presented in Table 19 as well.

Table 19. Life cycle GHG emissions of transport technologies

Fuel	CO_2 **emissions on combustion**				**Life cycle GHG emissions,** CO_2 **eq**					Average life cycle GHG emissions g/vehicle km
	g/litre	kg/gal	g/MJ	g/mile at 4.5 MJ/mile	g/litre	kg/gal	g/MJ	g/mile at 4.5 MJ/mile[1]	g/vehicle km[2]	
Petrol	2328	10.6	72.8	328	2600	11.8	81-110	366-495	227.4-307.6	268
Diesel	2614	11.9	72.6	327	3128	14.2	87-90	391-405	243.0-251.7	247
Bioethanol from sugar beet	1503	6.8	71.6	322	724	3.3	37-43	166.5-193.5	103.5-120.2	112
Bioethanol from wheat	1503	6.8	71.6	322	511	2.3	27-31	121.5-139.5	75.5-86.7	81
Biodiesel from rapeseed	2486	11.3	75.3	338	1334	6.1	39-43	175.5-193.5	109.1-120.2	115
Biodiesel from waste vegetable oil	2486	11.3	75.3	338	437	2.0	11-15	49.5-67.5	30.8-41.9	36

As one can see from information provided in Table 19 biodiesel from waste vegetable oil has the lowest life cycle GHG emission followed by bioethanol from wheat. Petrol based transport technologies have s the highest life cycle GHG emissions followed by diesel based transport technologies.

The range of current and long-term private costs of transport technologies were evaluated in EURcnt/vehicle km based on information about costs of fuels provided by various data sources (Woods and Bauen, 2003; Gross, Bauen, 2005; The Royal Society, 2008; Elsayed et al., 2003, Farrell et al, 2008; Pimental, Patzek, 2005) are presented in Table 20. The price of gasoline and diesel is based on cost of crude oil c.$50/barrel (FOB Gulf cost). These costs for biofuels vary widely depending on location for existing bioethanol and biodiesel technologies.

[1] 4.5 MJ/mile is equivalent to 32.5 mpg for a petrol car or 36.4 mpg for a diesel car. However, this makes no allowance for differences in combustion efficiency between different engine designs. For example, diesel engines run at higher compression ratio than petrol engines and therefore are typically more efficient (fewer MJ per mile).

[2] To convert miles per gallon of a particular fuel to grammes of CO_2 per km divide the figure for g/litre of CO_2 (either directly from combustion or lifecycle) by the mpg (miles per gallon) figure multiplied by 0.354 (to convert to km/litre):
g/km = (g/l)/(mpg x 0.354) = (g/l x 2.825)/mpg

Table 20. Current private and long costs of transport fuel technologies, EURcnt/vehicle km

Fuel	Private costs					Average private costs, EURcnt/ vehicle km
	EURcnt/ litre	Energy density MJ/litre	EURcnt/MJ	EURcnt/mile at 4.5 MJ/vehicle mile	EURcnt/ vehicle km	
Current						
Petrol	27.6-47.3	32	0.86-1.08	3.87-4.86	2.41-3.02	2.72
Diesel	27.6-47.3	36	0.77-1.31	3.47-5.90	2.16-3.67	2.92
Bioethanol from sugar beet	47.3-63.0	21	2.25-3.0	10.13-13.50	6.30-8.39	7.35
Bioethanol from wheat	55.1-74.8	21	2.62-3.56	11.79-16.02	7.33-9.96	8.65
Biodiesel from rapeseed	31.5-43.3	33	0.95-1.31	4.28-5.90	2.66-3.67	3.17
Biodiesel from waste vegetable oil	55.1-78.8	33	1.67-2.39	7.52-10.80	4.67-6.71	5.69
Long term (2030-2050)						
Petrol	27.6-47.3	32	0.86-1.08	3.87-4.86	2.41-3.02	2.72
Diesel	27.6-47.3	36	0.77-1.31	3.47-5.90	2.16-3.67	2.92
Bioethanol from sugar beet	31.5-47.3	21	1.50-2.25	6.75-10.13	4.20-6.30	5.25
Bioethanol from wheat	53.4-61.2	21	2.54-2.9	11.43-13.05	7.10-8.12	7.11
Biodiesel from rapeseed	31.5-59.4	33	0.95-1.80	4.28-8.10	2.70-5.00	3.85
Biodiesel from waste vegetable oil	51.5-59.1	33	1.56-1.79	7.02-8.06	4.30-5.00	4.65

As one can see from information provided in Table 20 the most expensive in terms of fuel costs are bioethanol technologies and the cheapest are transport technologies based on petrol and diesel. Therefore the transport technologies having lowest life cycle GHG emission are among the most expensive terms of fuel costs.

Seeking to conduct policy oriented assessment of energy technologies external costs of GHG emissions will be evaluated for electricity generation and transport technologies based on carbon price developments provided by range policy scenarios runs.

It is important to stress that the ranking of energy technologies based on costs (private, external and total) points to a general problem in having costs as the main parameter for comparison of different technologies since these energy technologies do not compete on the same markets. For example, biomass technologies show a large span in costs and efficiencies and different processes yield different installed capacities therefore it is problematic to compare such processes if comparison is only made on cost basis since the different processes are suitable for different markets however comparison of different energy technologies based on total costs and carbon price enables to develop some important policy recommendations even

taking into account high uncertainties in private and external costs if appropriate interpretation of results is provided.

6.4 External costs of GHG emissions of selected electricity and transport technologies

Further the policy oriented power and transport technologies assessment will be performed for various policy scenarios (10 scenarios) for 2020 and 2050 time frame and for various regions by calculating external costs of GHG emission using data on carbon price development over time and space obtained by various models (Table 21). Energy technologies in policy oriented assessment will be ranked for various scenarios based on external costs of GHG emissions and also based on the total costs (the sum of external costs of GHG emissions calculated by using carbon price data obtained by various models and private costs).

Carbon price developments obtained by 10 policy scenario runs for ETSAP-TIAM, DEMETER, GEMINI and WITCH models are presented in Table 21.

Table 21. GHG price in 2020 and 2050 EUR (2005)/metric tonne of CO_2 eq,

Fuel or energy type	2020					2050				
	Global	OECD	EEX	DEV Asia	ROW	Global	OECD	EEX	DEV Asia	ROW
REF	0	0	0	0	0	0	0	0	0	0
FB-3p2 scenario	21-89	21-48	21-48	21-48	21-48	176-573	195-573	195-573	195-573	195-573
FB-3p5 scenario	13-52	13-48	13-48	13-48	13-48	89-297	195-297	195-297	195-297	195-297
SC1-3p2 scenario	3-21	3-21	3-21	3-21	3-21	107-248	107-248	107-248	107-248	3-107
SC1-3p5 scenario	3-44	3-13	3-13	3-13	3-13	110-289	110-289	110-289	110-289	110-289
SC2-3p2 scenario	3-14	3-14	3-14	3-14	3-14	110-229	110-229	110-229	110-229	110-229
SC2-3p5 scenario	3-13	3-13	3-13	3-13	3-13	110-268	110-268	110-268	110-268	110-268
VAR1-3p2scenario	0-14	0-14	0-17	0-12	0-12	111-192	113-192	125-192	103-192	103-192
VAR1-3p5 scenario	3-13	3-14	3-15	3-11	3-11	110-238	114-238	120-238	103-238	103-238
VAR2-3p2 scenario	0-13	0-15	0-12	0-12	0-12	105-164	115-164	101-164	101-164	101-164
VAR2-3p5 scenario	3-11	3-15	3-10	3-10	3-10	105-203	114-203	101-203	101-203	101-203

In Table 22 external costs of GHG emissions for selected power technologies were evaluated for year 2020 and 2050 for various regions (World, OECD, EEX, DEVAsia and ROW) by integrating carbon price obtained various policy scenarios runs provided by various models.

In Table 23 external costs of GHG emissions for selected transport technologies were evaluated for years 2020 and 2050 for various regions (World, OECD, EEX, DEVAsia and ROW) by integrating carbon price obtained various policy scenarios runs provided by various models.

Table 22. The average life cycle external GHG emission costs of electricity generation technologies in 2020 and 2050 for various policy scenarios, EUR/MWh

FB-3p2 scenario										
	2020					2050				
	Global	**OECD**	**EEX**	**DEV Asia**	**ROW**	**Global**	**OECD**	**EEX**	**DEV Asia**	**ROW**
Nuclear	**3.6**	2.3	2.3	2.3	2.3	**24.4**	25	25	25	25
Oil	**46.8**	29.2	29.2	29.2	29.2	**318.4**	326.5	326.5	326.5	326.5
Natural gas	**32.5**	20.4	20.4	20.4	20.4	**173.05**	226.6	226.6	226.6	226.6
Hard coal	**55**	34.5	34.5	34.5	34.5	**374.5**	384	384	384	384
Hard coal IGCC with CO_2 capture	**8.5**	5.4	5.4	5.4	5.4	**58.1**	59.5	59.5	59.5	59.5
Large scale wood chips combustion	**4.4**	2.75	2.75	2.75	2.75	**29.95**	30.7	30.7	30.7	30.7
Large scale wood chips gasification	**1.38**	0.86	0.86	0.86	0.86	**9.35**	9.6	9.6	9.6	9.6
Large scale biomass IGCC with CO_2 capture	**-7.7**	-4.8	-4.8	-4.8	-4.8	**-52.4**	-53.8	-53.8	-53.8	-53.8
Large scale straw combustion	**13.1**	8.2	8.2	8.2	8.2	**89.15**	91.4	91.4	91.4	91.4
Biomass (wood chips) CHP large scale	**1.59**	1	1	1	1	**10.85**	11.15	11.15	11.15	11.15
Biomass (wood chips gasification) CHP small scale	**0.88**	0.55	0.55	0.55	0.55	**6**	6.15	6.15	6.15	6.15
FB-3p5 scenario										
	2020					2050				
	Global	**OECD**	**EEX**	**DEV Asia**	**ROW**	**Global**	**OECD**	**EEX**	**DEV Asia**	**ROW**
Nuclear	2.12	1.97	1.97	1.97	1.97	12.3	16	16	16	16
Oil	27.65	25.95	25.95	25.95	25.95	164.1	209.15	209.15	209.15	209.15
Natural gas	19.2	18	18	18	18	113.85	145.15	145.15	145.15	145.15
Hard coal	32.5	30.5	30.5	30.5	30.5	193	246	246	246	246
Hard coal IGCC with CO_2 capture	5.0	4.7	4.7	4.7	4.7	29.9	38.1	38.1	38.1	38.1
Large scale wood chips combustion	2.6	2.4	2.4	2.4	2.4	15.45	19.7	19.7	19.7	19.7
Large scale wood chips gasification	0.8	0.75	0.75	0.75	0.75	4.8	6.1	6.1	6.1	6.1
Large scale biomass IGCC with CO_2 capture	-4.6	-4.3	-4.3	-4.3	-4.3	-27.0	-37.4	-34.4	-34.4	-34.4
Large scale straw combustion	7.75	7.25	7.25	7.25	7.25	45.95	58.55	58.55	58.55	58.55
Biomass (wood chips) CHP large scale	0.94	0.89	0.89	0.89	0.89	5.6	7.15	7.15	7.15	7.15
Biomass (wood chips gasification) CHP small scale	0.5	0.5	0.5	0.5	0.5	3.1	3.95	3.95	3.95	3.95

SC1-3p2 scenario										
	2020					2050				
	Global	**OECD**	**EEX**	**DEV Asia**	**ROW**	**Global**	**OECD**	**EEX**	**DEV Asia**	**ROW**
Nuclear	0.8	0.8	0.8	0.8	0.8	11.55	11.55	11.55	11.55	3.6
Oil	10.25	10.25	10.25	10.25	10.25	150.9	150.9	150.9	150.9	46.8
Natural gas	7.1	7.1	7.1	7.1	7.1	104.7	104.7	104.7	104.7	32.45
Hard coal	12	12	12	12	12	177.5	177.5	177.5	177.5	55
Hard coal IGCC with CO_2 capture	1.9	1.9	1.9	1.9	1.9	27.5	27.5	27.5	27.5	8.5
Large scale wood chips combustion	0.97	0.97	0.97	0.97	0.97	14.2	14.2	14.2	14.2	4.42
Large scale wood chips gasification	0.31	0.31	0.31	0.31	0.31	4.45	4.45	4.45	4.45	1.39
Large scale biomass IGCC with CO_2 capture	-1.7	-1.7	-1.7	-1.7	-1.7	-24.9	-24.9	-24.9	-24.9	-7.7
Large scale straw combustion	2.85	2.85	2.85	2.85	2.85	42.25	42.25	42.25	42.25	13.1
Biomass (wood chips) CHP large scale	0.34	0.34	0.34	0.34	0.34	5.15	5.15	5.15	5.15	1.59
Biomass (wood chips gasification) CHP small scale	0.19	0.19	0.19	0.19	0.19	2.05	2.05	2.05	2.05	0.9
SC1-3p5 scenario										
	2020					2050				
	Global	OECD	EEX	DEV Asia	ROW	Global	OECD	EEX	DEV Asia	ROW
Nuclear	1.55	0.55	0.55	0.55	0.55	13	13	13	13	13
Oil	20	6.85	6.85	6.85	6.85	169.6	169.6	169.6	169.6	169.6
Natural gas	13.9	4.75	4.75	4.75	4.75	117.7	117.7	117.7	117.7	117.7
Hard coal	23.5	8	8	8	8	199.5	199.5	199.5	199.5	199.5
Hard coal IGCC with CO_2 capture	3.6	1.2	1.2	1.2	1.2	30.9	30.9	30.9	30.9	30.9
Large scale wood chips combustion	1.87	1.64	0.64	0.64	0.64	15.95	15.95	15.95	15.95	15.95
Large scale wood chips gasification	0.59	0.21	0.21	0.21	0.21	5	5	5	5	5
Large scale biomass IGCC with CO_2 capture	-3.3	-1.1	-1.1	-1.1	-1.1	-27.9	-27.9	-27.9	-27.9	-27.9
Large scale straw combustion	5.6	1.9	1.9	1.9	1.9	47.5	47.5	47.5	47.5	47.5
Biomass (wood chips) CHP large scale	0.69	0.23	0.23	0.23	0.23	5.8	5.8	5.8	5.8	5.8
Biomass (wood chips gasification) CHP small scale	0.37	0.13	0.13	0.13	0.13	3.2	3.2	3.2	3.2	3.2
SC2-3p2 scenario										
	2020					2050				
	Global	OECD	EEX	DEV Asia	ROW	Global	OECD	EEX	DEV Asia	ROW
Nuclear	0.55	0.55	0.55	0.55	0.55	11.05	11.05	11.05	11.05	11.05
Oil	7.3	7.3	7.3	7.3	7.3	144.25	144.25	144.25	144.25	144.25
Natural gas	5.05	5.05	5.05	5.05	5.05	100	100	100	100	100
Hard coal	8.5	8.5	8.5	8.5	8.5	169.5	169.5	169.5	169.5	169.5
Hard coal IGCC with CO_2 capture	1.3	1.3	1.3	1.3	1.3	26.3	26.3	26.3	26.3	26.3
Large scale wood chips combustion	0.67	0.67	0.67	0.67	0.67	13.4	13.4	13.4	13.4	13.4
Large scale wood chips gasification	0.21	0.21	0.21	0.21	0.21	4.25	4.25	4.25	4.25	4.25
Large scale biomass IGCC	-1.2	-1.2	-1.2	-1.2	-1.2	-23.7	-23.7	-23.7	-23.7	-23.7

with CO_2 capture										
Large scale straw combustion	2	2	2	2	2	40.35	40.35	40.35	40.35	40.35
Biomass (wood chips) CHP large scale	0.25	0.25	0.25	0.25	0.25	4.9	4.9	4.9	4.9	4.9
Biomass (wood chips gasification) CHP small scale	0.13	0.13	0.13	0.13	0.13	2.75	2.75	2.75	2.75	2.75
SC2-3p5 scenario										
	2020					2050				
	Global	OECD	EEX	DEV Asia	ROW	Global	OECD	EEX	DEV Asia	ROW
Nuclear	0.55	0.55	0.55	0.55	0.55	12.3	12.3	12.3	12.3	12.3
Oil	6.85	6.85	6.85	6.85	6.85	160.65	160.65	160.65	160.65	160.65
Natural gas	4.75	4.75	4.75	4.75	4.75	111.5	111.5	111.5	111.5	111.5
Hard coal	8	8	8	8	8	189	189	189	189	189
Hard coal IGCC with CO_2 capture	1.2	1.2	1.2	1.2	1.2	29.3	29.3	29.3	29.3	29.3
Large scale wood chips combustion	0.64	0.64	0.64	0.64	0.64	15.1	15.1	15.1	15.1	15.1
Large scale wood chips gasification	0.19	0.19	0.19	0.19	0.19	4.75	4.75	4.75	4.75	4.75
Large scale biomass IGCC with CO_2 capture	-1.1	-1.1	-1.1	-1.1	-1.1	-26.4	-26.4	-26.4	-26.4	-26.4
Large scale straw combustion	1.9	1.9	1.9	1.9	1.9	45	45	45	45	45
Biomass (wood chips) CHP large scale	0.24	0.24	0.24	0.24	0.24	5.45	5.45	5.45	5.45	5.45
Biomass (wood chips gasification) CHP small scale	0.12	0.12	0.12	0.12	0.12	3.05	3.05	3.05	3.05	3.05
VAR1-3p2 scenario										
	2020					2050				
	Global	OECD	EEX	DEV Asia	ROW	Global	OECD	EEX	DEV Asia	ROW
Nuclear	0.45	0.45	0.55	0.39	0.39	9.85	9.9	10.3	9.6	9.6
Oil	5.95	5.95	7.25	5.1	5.1	128.8	129.65	134.75	125.4	125.4
Natural gas	4.15	4.15	5	3.55	3.55	89.4	90	93.55	87.05	87.05
Hard coal	7	7	8.5	6	6	151.5	152.5	158.5	147.5	147.5
Hard coal IGCC with CO_2 capture	1.1	1.1	1.3	0.93	0.93	23.5	23.6	24.6	22.9	22.9
Large scale wood chips combustion	0.55	0.55	0.7	0.48	0.48	12.15	12.2	12.7	9.1	9.1
Large scale biomass IGCC with CO_2 capture	-0.98	-0.98	-1.2	-0.84	-0.84	-21.2	-21.4	-22.2	-20.7	-20.7
Large scale wood chips gasification	0.2	0.2	0.2	0.15	0.15	3.8	3.8	3.95	3.7	3.7
Large scale straw combustion	1.65	1.65	2.05	1.45	1.45	36.05	36.05	37.75	35.1	35.1
Biomass (wood chips) CHP large scale	0.2	0.2	0.25	0.2	0.2	4.4	4.4	4.6	4.3	4.3
Biomass (wood chips gasification) CHP small scale	0.1	0.1	0.15	0.1	0.1	2.45	2.45	2.55	2.4	2.4
VAR1-3p5 scenario										
	2020					2050				
	Global	OECD	EEX	DEV Asia	ROW	Global	OECD	EEX	DEV Asia	ROW
Nuclear	0.52	0.55	0.59	0.46	0.46	11.35	11.45	11.65	11.1	11.1
Oil	6.85	7.25	7.7	6	6	147.9	149.6	152.15	144.95	144.95
Natural gas	4.75	5.05	5.35	4.15	4.15	102.65	103.85	105.6	100.6	100.6
Hard coal	8	8.5	9	7	7	174	176	179	170.5	170.5

Hard coal IGCC with CO_2 capture	1.2	1.3	1.4	1.1	1.1	27.0	36.1	27.7	26.5	26.5
Large scale wood chips combustion	0.64	0.68	0.72	0.57	0.57	13.9	14.05	14.3	13.6	13.6
Large scale wood chips gasification	0.21	0.21	0.24	0.19	0.19	4.4	4.45	4.5	4.3	4.3
Large scale biomass IGCC with CO_2 capture	-1.1	-1.2	-1.3	-0.98	-0.98	-24.4	-32.6	-25.1	-23.9	-23.9
Large scale straw combustion	1.9	2	2.15	1.65	1.65	41.4	41.85	42.6	40.55	40.55
Biomass (wood chips) CHP large scale	0.23	0.25	0.26	0.21	0.21	5.05	5.1	5.2	4.95	4.95
Biomass (wood chips gasification) CHP small scale	0.13	0.13	0.14	0.11	0.11	2.8	2.8	2.85	2.75	2.75
VAR2-3p2 scenario										
	2020					2050				
	Global	OECD	EEX	DEV Asia	ROW	Global	OECD	EEX	DEV Asia	ROW
Nuclear	0.42	0.49	0.39	0.39	0.39	8.75	9.05	8.65	8.65	8.65
Oil	5.55	6.4	5.1	5.1	5.1	114.35	118.6	112.65	112.65	112.65
Natural gas	3.85	4.45	3.55	3.55	3.55	65.9	82.35	112.65	112.65	112.65
Hard coal	6.5	7.5	6	6	6	134.5	139.5	132.5	132.5	132.5
Hard coal IGCC with CO_2 capture	0.98	1.1	0.93	0.93	0.93	20.9	21.6	20.5	20.5	20.5
Large scale wood chips combustion	0.5	0.6	0.5	0.5	0.5	10.75	11.15	10.6	10.6	10.6
Large scale wood chips gasification	0.16	0.19	0.15	0.15	0.15	3.35	3.5	3.3	3.3	3.3
Large scale biomass IGCC with CO_2 capture	-0.91	-1.05	-0.84	-0.84	-0.84	-18.8	-19.5	-18.6	-18.6	-18.6
Large scale straw combustion	1.55	1.8	1.45	1.45	1.45	32	33.2	31.5	31.5	31.5
Biomass (wood chips) CHP large scale	0.19	0.22	0.17	0.17	0.17	3.91	4.05	3.85	3.85	3.85
Biomass (wood chips gasification) CHP small scale	0.11	0.12	0.09	0.09	0.09	2.15	2.2	2.1	2.1	2.1
VAR2-3p5 scenario										
	2020					2050				
	Global	OECD	EEX	DEV Asia	ROW	Global	OECD	EEX	DEV Asia	ROW
Nuclear	0.46	0.59	0.42	0.42	0.42	10	10.3	9.9	9.9	9.9
Oil	6	7.7	5.55	5.55	5.55	130.95	134.75	129.25	129.25	129.25
Natural gas	4.15	5.35	3.85	3.85	3.85	90.9	93.55	89.7	89.7	89.7
Hard coal	7	9	6.5	6.5	6.5	154	158.5	152	152	152
Hard coal IGCC with CO_2 capture	1.05	1.4	1.01	1.01	1.01	23.9	24.6	23.6	23.6	23.6
Large scale wood chips combustion	0.56	0.72	0.52	0.52	0.52	12.3	12.65	12.15	12.15	12.15
Large scale wood chips gasification	0.18	0.23	0.16	0.16	0.16	3.85	4	3.8	3.8	3.8
Large scale biomass IGCC with CO_2 capture	-0.98	-1.26	-0.91	-0.91	-0.91	-21.6	-22.2	-21.3	-21.3	-21.3
Large scale straw combustion	1.65	2.15	1.55	1.55	1.55	36.65	37.7	36.15	36.15	36.15
Biomass (wood chips) CHP large scale	0.21	0.26	0.19	0.19	0.19	4.47	4.6	4.45	4.45	4.45
Biomass (wood chips gasification) CHP small scale	0.11	0.14	0.1	0.1	0.1	2.46	2.52	2.42	2.42	2.42

Table 23. The average life cycle external GHG emission costs of transport technologies in 2020 and 2050 for various policy scenarios, EURcnt/vehicle km

FB-3p2 scenario										
	2020					2050				
	Global	**OECD**	**EEX**	**DEV Asia**	**ROW**	**Global**	**OECD**	**EEX**	**DEV Asia**	**ROW**
Petrol	1.47	1.122	1.122	1.122	1.122	10.037	10.291	10.291	10.291	10.291
Diesel	1.358	0.852	0.852	0.852	0.852	92.5	0.9485	0.9485	0.9485	0.9485
Bioethanol from sugar beet	0.616	0.386	0.386	0.386	0.386	41.94	0.43	0.43	0.43	0.43
Bioethanol from wheat	0.445	0.279	0.279	0.279	0.279	30.33	0.311	0.311	0.311	0.311
Biodiesel from rapeseed	0.632	0.397	0.397	0.397	0.397	43.07	0.4416	0.4416	0.4416	0.4416
Biodiesel from waste vegetable oil	0.198	0.124	0.124	0.124	0.124	13.48	0.1382	0.1382	0.1382	0.1382
FB-3p5scenario										
	2020					2050				
	Global	**OECD**	**EEX**	**DEV Asia**	**ROW**	**Global**	**OECD**	**EEX**	**DEV Asia**	**ROW**
Petrol	0.871	0.817	0.817	0.817	0.817	5.172	6.593	6.593	6.593	6.593
Diesel	0.803	0.753	0.753	0.753	0.753	4.767	6.076	6.076	6.076	6.076
Bioethanol from sugar beet	0.364	0.342	0.342	0.342	0.342	2.162	2.755	2.755	2.755	2.755
Bioethanol from wheat	0.263	0.247	0.247	0.247	0.247	1.563	1.993	1.993	1.993	1.993
Biodiesel from rapeseed	0.373	0.351	0.351	0.351	0.351	2.219	2.829	2.829	2.829	2.829
Biodiesel from waste vegetable oil	0.117	0.11	0.11	0.11	0.11	0.695	0.886	0.886	0.886	0.886
SC1-3p2 scenario										
	2020					2050				
	Global	**OECD**	**EEX**	**DEV Asia**	**ROW**	**Global**	**OECD**	**EEX**	**DEV Asia**	**ROW**
Petrol	0.322	0.322	0.322	0.322	0.322	4.757	4.757	4.757	4.757	1.474
Diesel	0.296	0.296	0.296	0.296	0.296	4.384	4.384	4.384	4.384	1.358
Bioethanol from sugar beet	0.134	0.134	0.134	0.134	0.134	1.988	1.988	1.988	1.988	0.616
Bioethanol from wheat	0.097	0.097	0.097	0.097	0.097	1.438	1.438	1.438	1.438	0.445
Biodiesel from rapeseed	0.138	0.138	0.138	0.138	0.138	2.041	2.041	2.041	2.041	0.632
Biodiesel from waste vegetable oil	0.043	0.043	0.043	0.043	0.043	0.639	0.639	0.639	0.639	0.198
SC1-3p5 scenario										
	2020					2050				
	Global	**OECD**	**EEX**	**DEV Asia**	**ROW**	**Global**	**OECD**	**EEX**	**DEV Asia**	**ROW**
Petrol	0.63	0.214	0.214	0.214	0.214	5.347	5.347	5.347	5.347	5.347
Diesel	0.58	0.198	0.198	0.198	0.198	4.928	4.928	4.928	4.928	4.928
Bioethanol from sugar beet	0.263	0.09	0.09	0.09	0.09	2.234	2.234	2.234	2.234	2.234

Bioethanol from wheat	0.19	0.065	0.065	0.065	0.065	1.616	1.616	1.616	1.616	1.616
Biodiesel from rapeseed	0.27	0.092	0.092	0.092	0.092	2.294	2.294	2.294	2.294	2.294
Biodiesel from waste vegetable oil	0.085	0.029	0.029	0.029	0.029	0.718	0.718	0.718	0.718	0.718
SC2-3p2 scenario										
	2020					2050				
	Global	**OECD**	**EEX**	**DEV Asia**	**ROW**	**Global**	**OECD**	**EEX**	**DEV Asia**	**ROW**
Petrol	0.228	0.228	0.228	0.228	0.228	4.543	4.543	4.543	4.543	4.543
Diesel	0.21	0.21	0.21	0.21	0.21	4.187	4.187	4.187	4.187	4.187
Bioethanol from sugar beet	0.095	0.095	0.095	0.095	0.095	1.898	1.898	1.898	1.898	1.898
Bioethanol from wheat	0.069	0.069	0.069	0.069	0.069	1.373	1.373	1.373	1.373	1.373
Biodiesel from rapeseed	0.098	0.098	0.098	0.098	0.098	1.949	1.949	1.949	1.949	1.949
Biodiesel from waste vegetable oil	0.031	0.031	0.031	0.031	0.031	0.61	0.61	0.61	0.61	0.61
SC2-3p5 scenario										
	2020					2050				
	Global	**OECD**	**EEX**	**DEV Asia**	**ROW**	**Global**	**OECD**	**EEX**	**DEV Asia**	**ROW**
Petrol	0.214	0.214	0.214	0.214	0.214	5.065	5.065	5.065	5.065	5.065
Diesel	0.198	0.198	0.198	0.198	0.198	4.668	4.668	4.668	4.668	4.668
Bioethanol from sugar beet	0.09	0.09	0.09	0.09	0.09	2.117	2.117	2.117	2.117	2.117
Bioethanol from wheat	0.065	0.065	0.065	0.065	0.065	1.531	1.531	1.531	1.531	1.531
Biodiesel from rapeseed	0.092	0.092	0.092	0.092	0.092	2.173	2.173	2.173	2.173	2.173
Biodiesel from waste vegetable oil	0.029	0.029	0.029	0.029	0.029	0.68	0.68	0.68	0.68	0.68
VAR1-3p2 scenario										
	2020					2050				
	Global	**OECD**	**EEX**	**DEV Asia**	**ROW**	**Global**	**OECD**	**EEX**	**DEV Asia**	**ROW**
Petrol	0.188	0.188	0.228	0.161	0.161	4.05	4.09	4.248	3.95	3.95
Diesel	0.173	0.173	0.209	0.148	0.148	3.742	3.767	3.915	3.643	3.643
Bioethanol from sugar beet	0.0784	0.0784	0.0952	0.0672	0.0672	1.697	1.708	1.775	1.652	1.652
Bioethanol from wheat	0.0567	0.0567	0.0688	0.0486	0.0486	1.227	1.235	1.284	1.195	1.195
Biodiesel from rapeseed	0.0805	0.0805	0.0978	0.069	0.069	1.742	1.754	1.823	1.696	1.696
Biodiesel from waste vegetable oil	0.0252	0.0252	0.0306	0.0216	0.0216	0.545	0.549	0.571	0.531	0.531
VAR1-3p5										
	2020					2050				
	Global	**OECD**	**EEX**	**DEV Asia**	**ROW**	**Global**	**OECD**	**EEX**	**DEV Asia**	**ROW**
Petrol	0.214	0.228	0.241	0.188	0.188	4.663	4.717	4.798	4.569	4.569

Diesel	0.198	0.209	0.222	0.173	0.173	4.298	4.347	4.421	4.211	4.211
Bioethanol from sugar beet	0.0896	0.0952	0.1008	0.0784	0.0784	1.949	1.971	2.005	1.9096	1.9096
Bioethanol from wheat	0.0648	0.06885	0.0729	0.0567	0.0567	1.409	1.4256	1.449	1.381	1.381
Biodiesel from rapeseed	0.092	0.09775	0.1035	0.0805	0.0805	2.001	2.024	2.058	1.961	1.961
Biodiesel from waste vegetable oil	0.0288	0.0306	0.0324	0.0252	0.0252	0.626	0.6336	0.6444	0.6138	0.6138
VAR2-3p2 scenario										
	2020					2050				
	Global	**OECD**	**EEX**	**DEV Asia**	**ROW**	**Global**	**OECD**	**EEX**	**DEV Asia**	**ROW**
Petrol	0.0174	0.201	0.1608	0.1608	0.1608	3.604	3.739	3.551	3.551	3.551
Diesel	0.1605	0.1852	0.148	0.148	0.148	3.322	3.446	3.273	3.273	3.273
Bioethanol from sugar beet	0.0728	0.084	0.0672	0.0672	0.0672	1.506	1.562	1.484	1.484	1.484
Bioethanol from wheat	0.0526	0.0607	0.0486	0.0486	0.0486	1.089	1.129	1.073	1.073	1.073
Biodiesel from rapeseed	0.0747	0.0862	0.069	0.069	0.069	1.547	1.604	1.524	1.524	1.524
Biodiesel from waste vegetable oil	0.0234	0.027	0.0216	0.0216	0.0216	0.484	0.5022	0.477	0.477	0.477
VAR2-3p5 scenario										
	2020					2050				
	Global	**OECD**	**EEX**	**DEV Asia**	**ROW**	**Global**	**OECD**	**EEX**	**DEV Asia**	**ROW**
Petrol	0.0187	0.241	0.174	0.174	0.174	4.127	4.248	4.073	4.073	4.073
Diesel	0.1729	0.222	0.161	0.161	0.161	3.804	3.915	3.754	3.754	3.754
Bioethanol from sugar beet	0.0784	0.1008	0.0728	0.0728	0.0728	1.725	1.7752	1.702	1.702	1.702
Bioethanol from wheat	0.0567	0.0729	0.0526	0.0526	0.0526	1.247	1.284	1.231	1.231	1.231
Biodiesel from rapeseed	0.0805	0.1035	0.0747	0.0747	0.0747	1.771	1.8227	1.748	1.748	1.748
Biodiesel from waste vegetable oil	0.0252	0.0324	0.0234	0.0234	0.0234	0.5544	0.5706	0.547	0.547	0.547

Further the ranking of power and transport technologies is performed based on life cycle external GHG emission costs and on the sum of private and external GHG emission costs for the first best and second best policy scenarios for the global region (average over 4 regions: OECD, EEX, DEVAsia and ROW) for years 2020 and 2050.

6.5 Ranking of electricity generation technologies based on carbon price

Seeking to compare electricity generation technologies based on carbon price developments several most reliable scenarios were selected: first best and second best scenarios. The average data for global region (the average over four regions: OECD, EEX, DevAsia, ROW) on carbon price was applied in analysis. The first best scenarios (FB-3p2 and FB-3p5) include specific targets: 3.2 W/m^2 and 3.5 W/m^2. The second best scenarios (SC) also include 3.5 W/m^2 and 3.2 W/m^2 targets and 2 options for GHG emission reduction

commitments for world regions: (SC2) include GHG emission reduction commitments just for OECD – GHG emission reduction in 2050 by 90% from 2005 levels and (SC1) include different commitments for OECD (80% reduction in 2050 from 2005 level); energy exporting countries (50% reduction in 2050 from 2005 level); Developing Asia countries (25% increase in 2050 from 2005 level) and for the rest of the world (55% increase in 2050 from 2005 level).

The ranking of 11 main future electricity generation technologies for 2020 and 2050 based on external costs of GHG emissions is the same as the same life cycle GHG emissions were applied for technologies assessment in all time frames. The most attractive technologies according external costs of GHG emissions in 2020 are: biomass IGCC with CO_2 capture, small scale biomass CHP (wood chips gasification), large scale wood chips gasification, large scale biomass CHP (wood chips combustion), nuclear, large scale wood chips combustion, hard coal IGCC with CO_2 capture. Less attractive technologies are: large scale straw combustion, natural gas, oil and hard coal. The ranking of electricity generation technologies based on external and private costs for the first best scenario in 2020 and 2050

In Figure 8 and 9 the range and average values of total (private and external costs of GHG emissions) costs of electricity generation technologies are presented in 2020 and 2050 respectively according the more strict first best policy scenario FB-3p2.

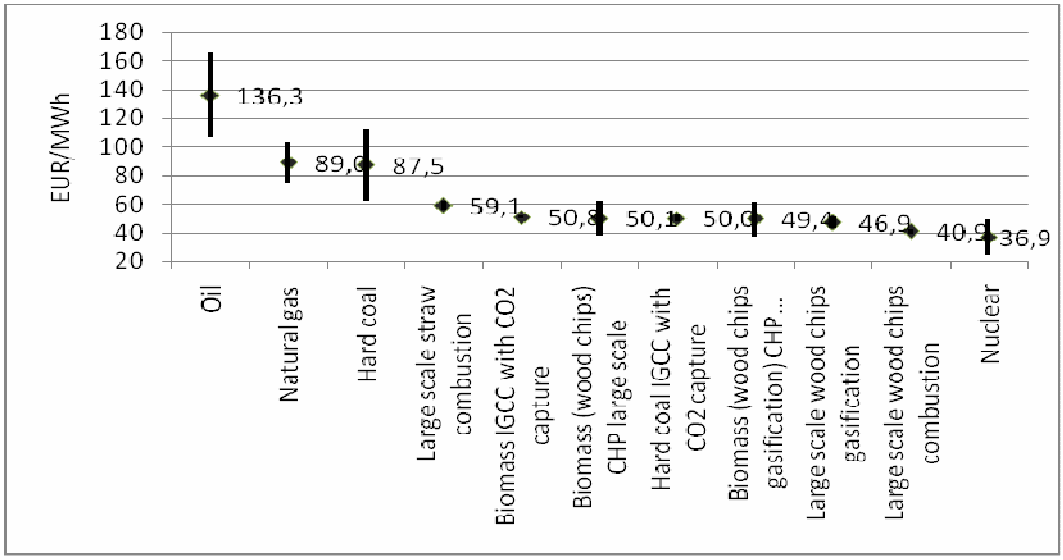

Figure 8. The range of total (private and external costs of GHG emissions) costs of electricity generation technologies in 2020 according the more strict first best policy scenario FB-3p2.

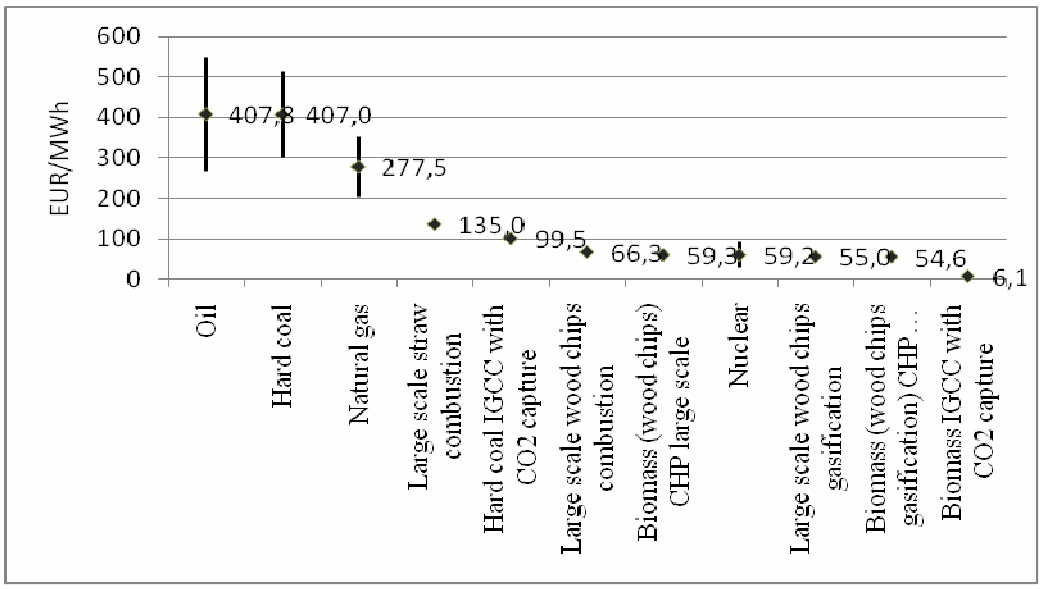

Figure 9. The range of total (private and external costs of GHG emissions) costs of electricity generation technologies in 2050 according the more strict first best policy scenario FB-3p2

As one see from Figure 8 because of large uncertainties related with life cycle GHG emission and private costs of power generation technologies the ranking of electricity generation technologies is quite complicated however from Figure 8 is obvious that the best electricity generation option in 2020 is nuclear following by large scale wood chips combustion and other biomass technologies. Oil based technologies are the least attractive following natural gas and coal technologies. The most expensive biomass based technology in 2020 is large scale straw combustion technology. Hard coal with CO_2 capture technology is ranked in the same order like most biomass based technologies including biomass with CO_2 capture.

In 2050 the ranking of electricity generation technologies according the same scenario even taking into account big uncertianties and wide range of total costs for electricity generation technologies provides completeley different results. The most competetive technology in 2050 is biomass ICGG with CO_2 capture, following by other large scale biomass technologies and nuclear. Oil, hard coal and natural gas based technologies are the least competetive technologies in 2050. Hard coal with CO_2 capture is less attractive technology comparing with variety of biomass based technologies except large scale straw combustion.

Therefore the ranking of 11 future electricity generation technologies based on total costs in 2020 and 2050 is quite different. This is related with the fact that the high carbon prices in 2050 have significant impact on technologies ranking as external costs of GHG emissions overweigh private costs of electricity generation technologies. The most competitive technologies according total costs (private and external costs of GHG emissions) in 2020 are: nuclear, large scale wood chips combustion, large scale wood chips gasification, biomass (wood chips gasification) CHP small scale, hard coal IGCC with CO_2 capture, biomass (wood chips) CHP large scale and biomass IGCC with CO_2 capture. Total costs of these first ranked technologies are quite similar except nuclear. The less attractive technologies are: large scale straw combustion, hard coal, natural gas and oil. In 2050 the following ranking of the same electricity generation technologies based on total costs is provided: biomass IGCC with CO_2 capture, biomass (wood chips gasification) CHP small scale, large scale wood chips gasification, nuclear, biomass wood chips CHP large scale, large scale wood chips combustion, hard coal IGCC with CO_2 capture, large scale straw combustion, natural gas, hard coal and oil.

Seeking to compare the impact of private costs on electricity generation technologies ranking in different time frames in Figure 10 and Figure 11 the ranking of electricity generation technologies (world) in 2020 and 2050 accordingly is provided based on external costs of GHG emissions and total costs according the first best policy scenario FB-3p2.

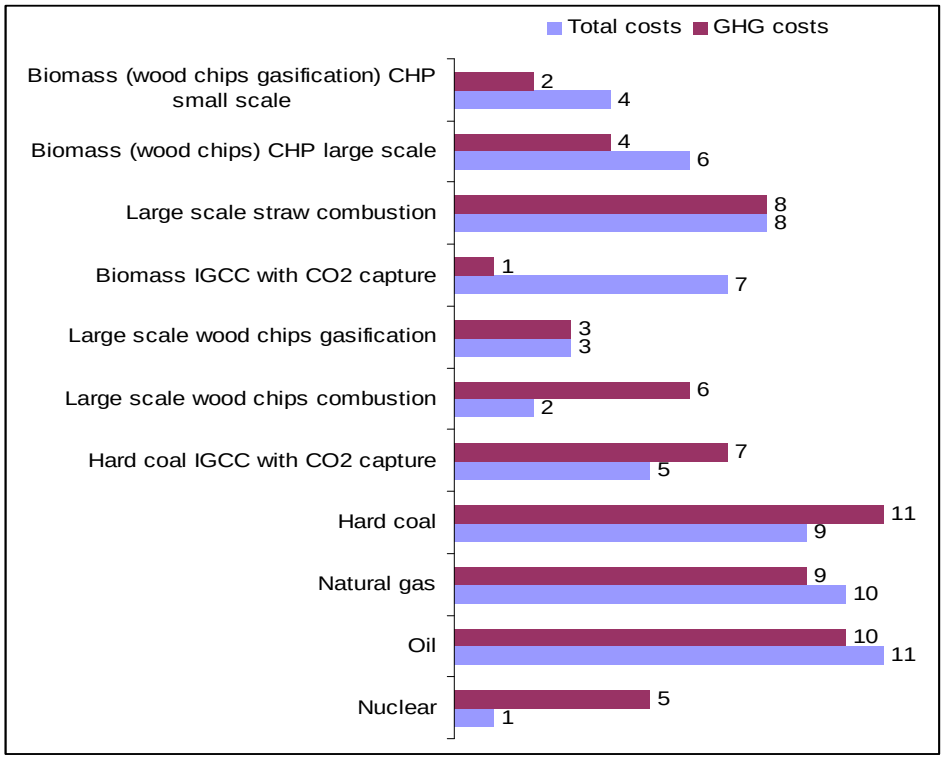

Figure 10. Ranking of electricity generation technologies (world) in 2020 based on external costs of GHG emissions and total costs for the first best policy scenario FB-3p2

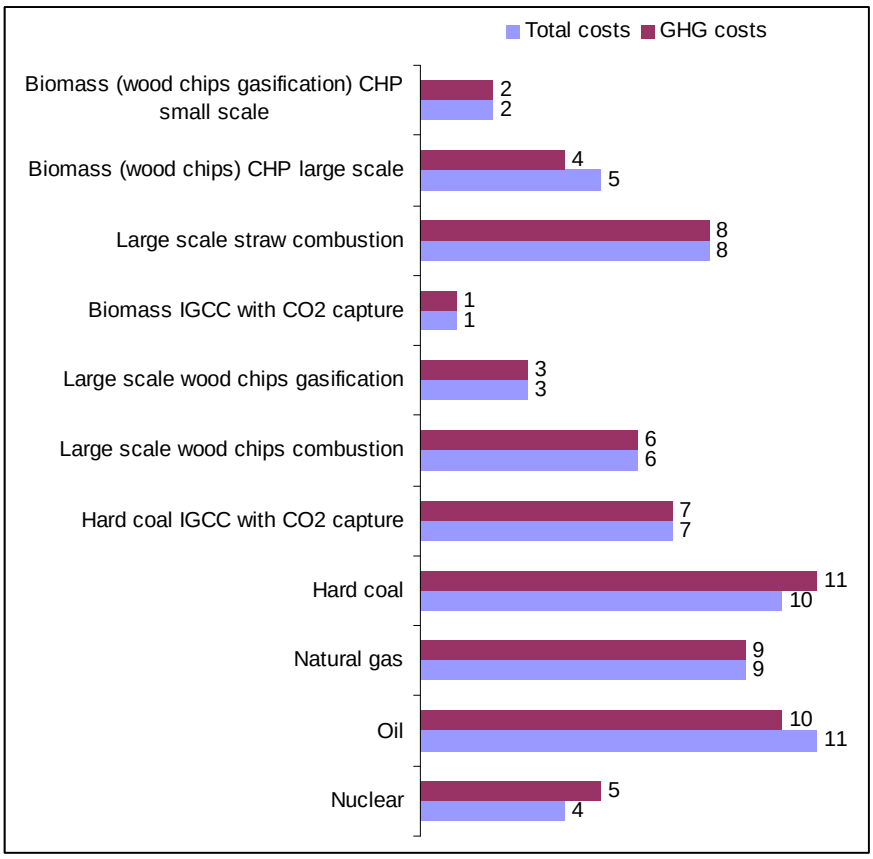

Figure 11. Ranking of electricity generation technologies (world) in 2050 based on external costs of GHG emissions and total costs for the first best scenario FB-3p2.

As one see from Figure 10 the ranking of 11 future electricity generation technologies in 2020 according external costs of GHG emissions and total costs provides for quite different results as carbon price is not high enough in 2020 to overweight the impact of external costs of GHG emissions on technologies ranking. The following ranking of electricity generation technologies in 2020 based on total costs is achieved: nuclear, large scale wood chips combustion, large scale wood chips gasification, biomass (wood chips gasification) CHP small scale, hard coal IGCC with CO_2 capture, biomass (wood chips) CHP large scale and biomass IGCC with CO_2 capture, large scale straw combustion, hard coal, natural gas and oil. The ranking of electricity generation technologies according GHG external costs provides the following ranking: biomass IGCC with CO_2 capture, biomass (wood chips gasification) CHP small scale, large scale wood chips gasification, biomass wood chips large scale CHP, nuclear, large scale wood chips combustion, hard coal IGCC with CO_2 capture, large scale straw combustion, natural gas, oil and hard coal.

As one see from Figure 11 the ranking of electricity generation technologies according external costs of GHG emissions and total costs in 2050 is quite similar for the presented scenario FB-3p.2 just ranking order of oil and hard coal technologies has changed then private costs were added to external costs of GHG emissions. External GHG emission costs as it was already mentioned are the highest for hard coal technologies, followed by oil and natural gas technologies however taking into account private costs hard coal technologies is cheaper than oil. The significant impact of external costs of GHG emissions in 2050 because of the high carbon price is crucial for technologies ranking in 2050.

The ranking of electricity generation technologies according external costs of GHG emissions and total costs (private and external) costs is similar for less strict first best policy scenario where 3.5 W/m^2 target is imposed instead of 3.2 W/m^2.

For all policy scenarios electricity generation technologies ranking in 2020 and 2050 based on external GHG costs provides the same results because of the same life cycle GHG emission data of electricity generation technologies. In Figure 12 and Figure 13 the range of total costs and average costs of electricity generation technologies in 2020 and 2050 respectively according the second best policy scenario SC1-3p2 is presented.

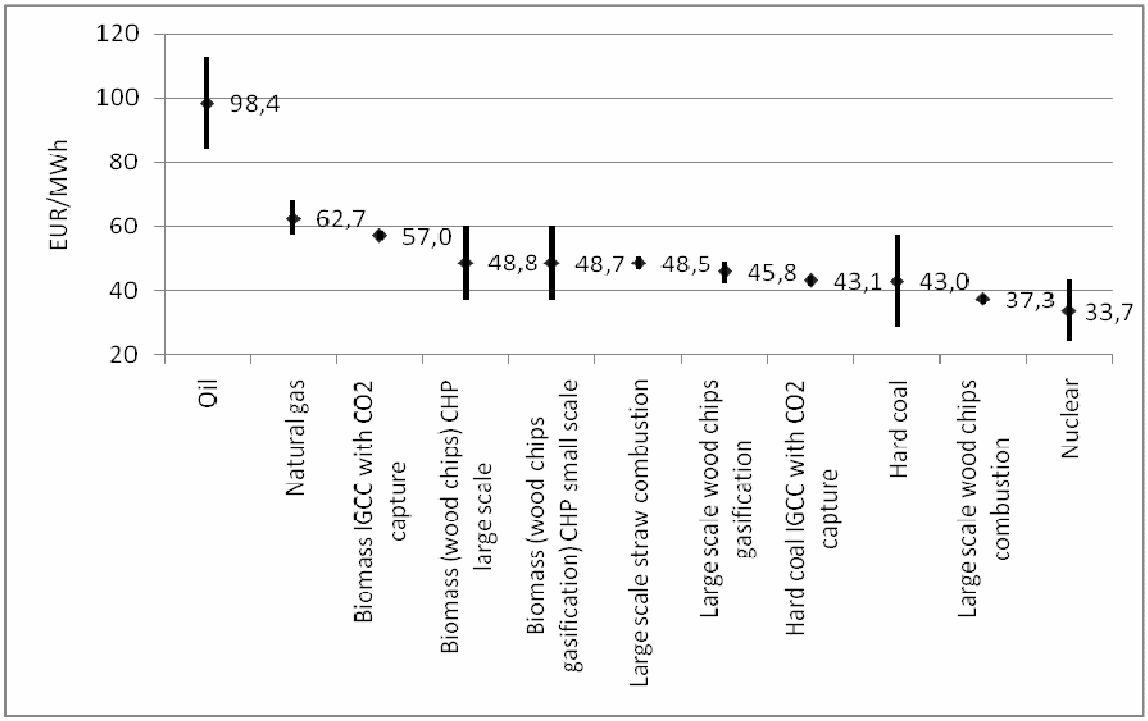

Figure 12. The range and average total costs of electricity generation technologies (world) in 2020 according the second best scenario SC1-3p2

As one can see from Figure 12 the most competetive technology according the second best scenario SC1-3p2 in 2020 like in the case the first best policy scenario is nuclear folowed by large scale wood chips combustion technologies however the hard coal based technologies are ranked in the same order. This is because of low carbon price in 2020 according this scenario as private costs of hard coal based technologies overweight impacts of external GHG emission costs. Biomass IGCC with CO_2 capture technologies because of quite high private costs are less competetive in 2020 according this scenario. The most expensive technologies like in the case of first best scenario are oil, hard coal and natural gas based technologies.

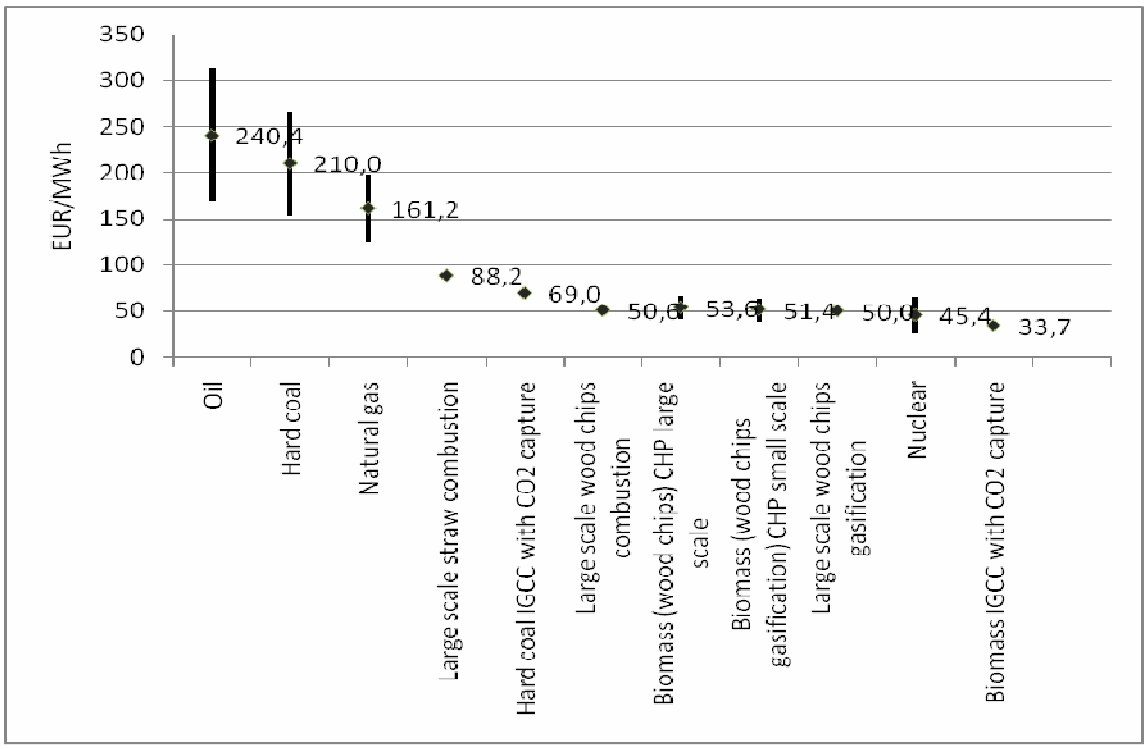

Figure 13. The range and average total costs of electricity generation technologies (world) in 2050 according the second best scenario SC1-3p2

The most competitive electricity generation technology in 2050 according the second best policy scenario like in the case of the first best policy scenario is biomass IGCC with CO2 capture however the nuclear is ranked as second best technology. The lower carbon price of second best scenario has impact on the competitiveness of electricity generation technologies as external costs of GHG emissions according this scenario do not overweight private costs of some technologies like in the case of first best scenario therefore provides for different ranking in first bets and second best policy scenarios.

The ranking of electricity generation technologies based on total costs according the second best scenario SC1-3p2 in 2020 and 2050 is compared in Figure 14.

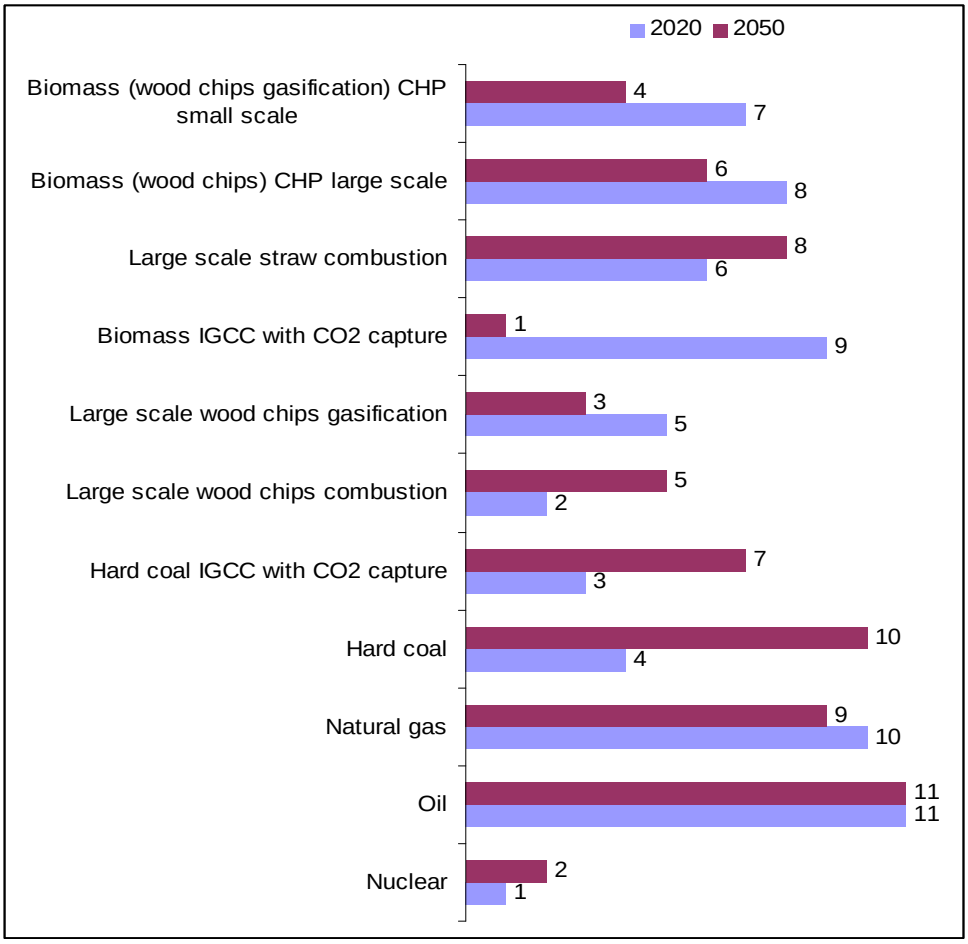

Figure 14. Ranking of electricity generation technologies (world) in 2020 and 2050 based on total costs for the second best scenario SC1-3p2

As one can see from Figure 14 the ranking of electricity generation technologies according SC1-3p2 scenario based on total costs provides completely different results in 2020 and 2050. Just oil technologies according total costs are the least attractive technologies for all scenarios and all time frames. The nuclear is the most competitive technology in 2020 based on total costs for all scenarios however in 2050 the most competitive technology is biomass IGCC with CO2 capture. As the ranking of electricity generation technologies based on total costs provides different results for different scenarios and specific dates in the following figures electricity generation technologies ranking is presented for the main policy scenarios in specific year.

In Figure 15 and Figure 16 the ranking of electricity generation technologies (world) in 2020 and 2050 accordingly based on total costs and external costs of GHG emissions for the first best FB-3p2 and second best scenarios SC1-3p2 SC2-3p2 is presented.

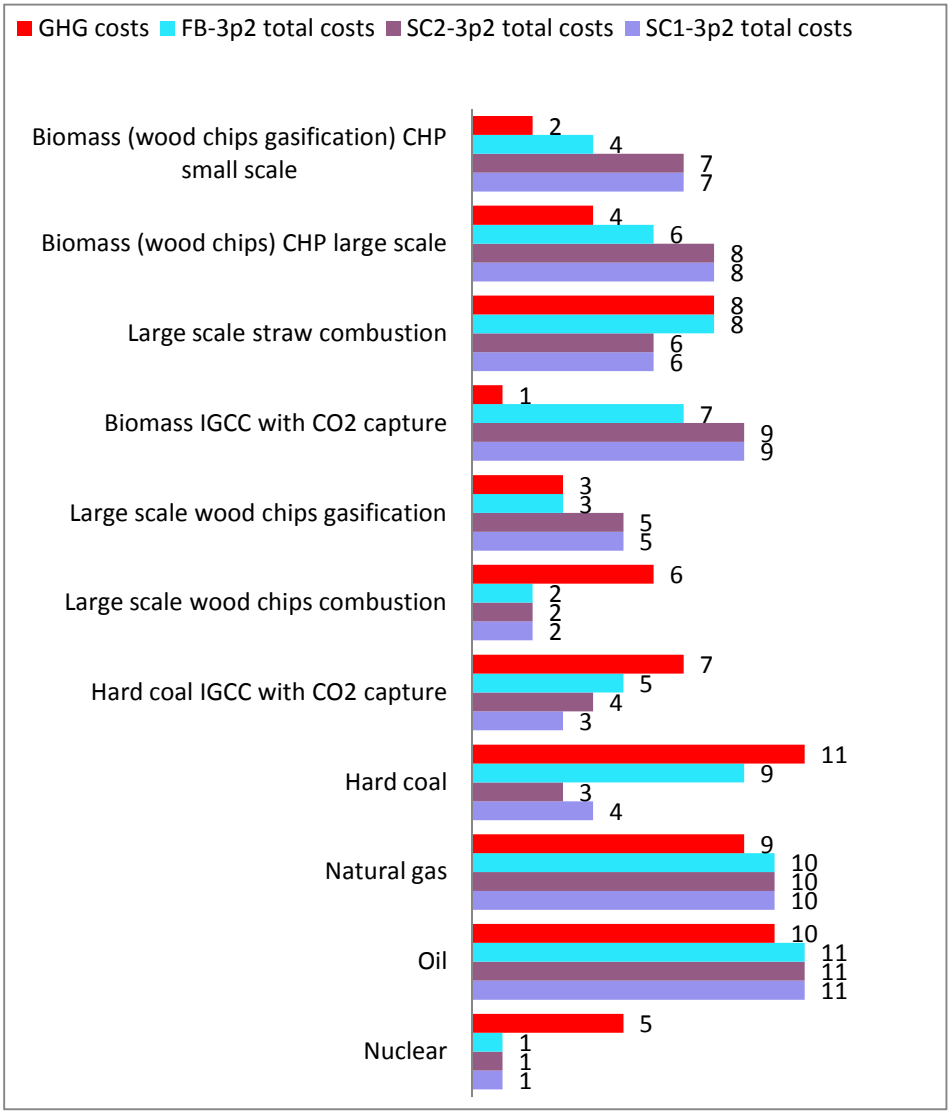

Figure 15. Ranking of electricity generation technologies (world) in 2020 based on GHG costs and total costs for the first best FB-3p2 and second best scenarios SC1-3p2 SC2-3p2

As one can see from Figure 15 the comparsion of electricity generation technologies ranking based on total costs and external costs of GHG in 2020 for the main three policy scenarios provides quite different results. The most competteive technology based on total costs in 2020 according all scenarios is nuclear, followed by large scale wood chips combustion, hard coal (for second best policy scenarios and biomass wood chips gasification small CHP (for first best scenario). In the first best scenario the average carbon price in 2020 is significantly higher (55 EUR/tCO2eq) comparing with carbon price in other policy scenarios investigated (12 EUR/tCO2 in SC1-3p2 scenario and 9 EUR/tCO2 in SC2-3p2 scenario) therefore the high price of carbon in first best scenario makes hard coal technologies less competetive in 2020. The most expensive technologies for all scenarios are oil and natural gas. The ranking of other biomass technologies slightly differs between scenarios. This is related with high carbon price in FB-3p2 scenario and differences in GHG life cycle emissions.

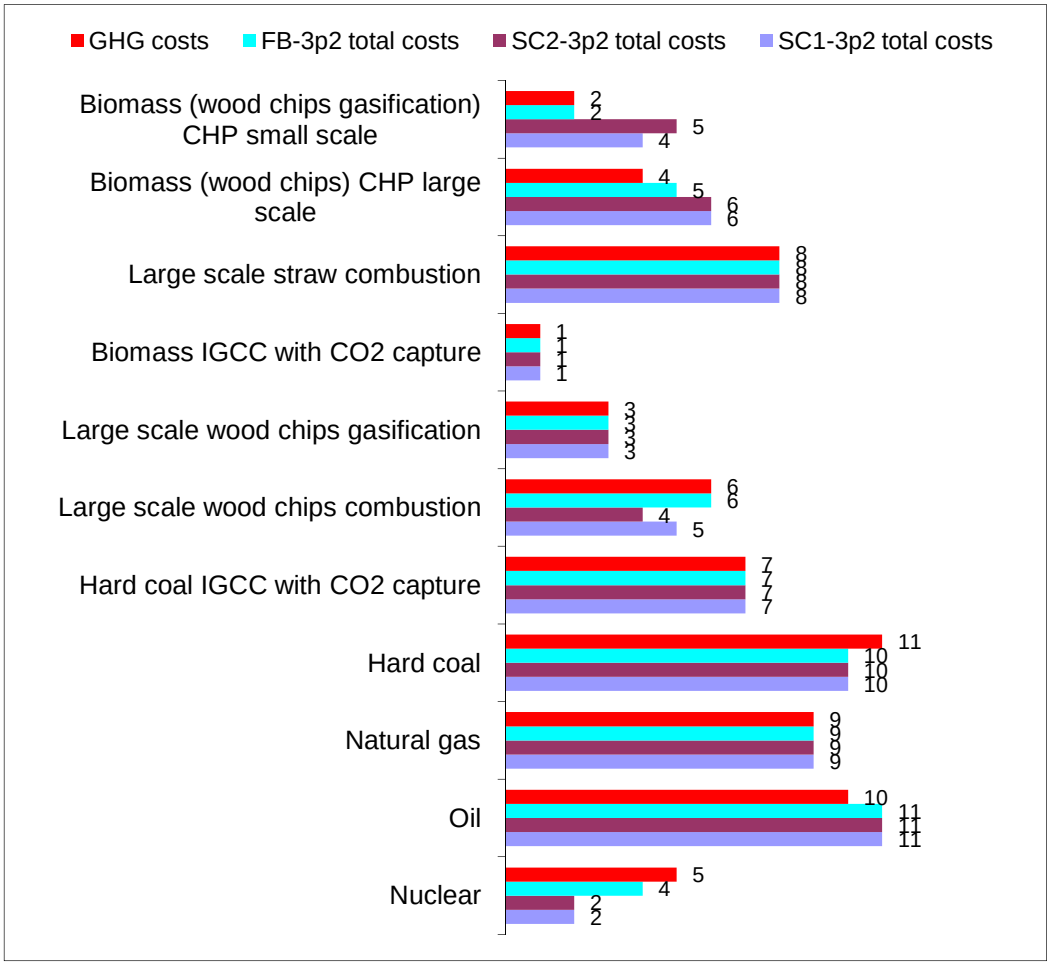

Figure 16. Ranking of electricity generation technologies (world) in 2050 based on GHG costs and total costs for the first best FB-3p2 and second best scenarios SC1-3p2 SC2-3p2

As one see from Figure 16 the different ranking of electricity generation technologies in 2050 for different policy scenarios is also related with high differences in carbon prices obtained for FB-3p2 and second best policy scenarios. For all scenarios in 2050 the most competetive electricity generation technology is biomass IGCC with CO_2 capture. For the second best policy scenarios the most competetive technologies are: IGCC with CO_2 capture followed nuclear and biomass technologies and the most expensive technologies are: oil, hard coal, natural gas, large scale straw combustion and hard coal IGCC with CO2 capture technologies.

In first best policy scenario, as it was mentioned above the most competetive technology in terms of total costs is biomass IGCC with CO2 capture followed by biomass (wood chips gasification) small scale CHP and other biomass technologies. The nuclear is higly ranked in second best policy scenarios however in the first best scenarios biomass technologies (biomass (wood chips gasification) CHP small scale, large scale wood chips gasification) are more competetive than nuclear. The most expensive technologies in 2050 for all policy scenarios are oil, hard coal and natural gas.

The ranking of electricity generation technologies based on GHG emission costs and total costs for the main policy scenarios (first best and second best with 3.2 W/m2 target in 2020 and 2050 is povided in Figure 17.

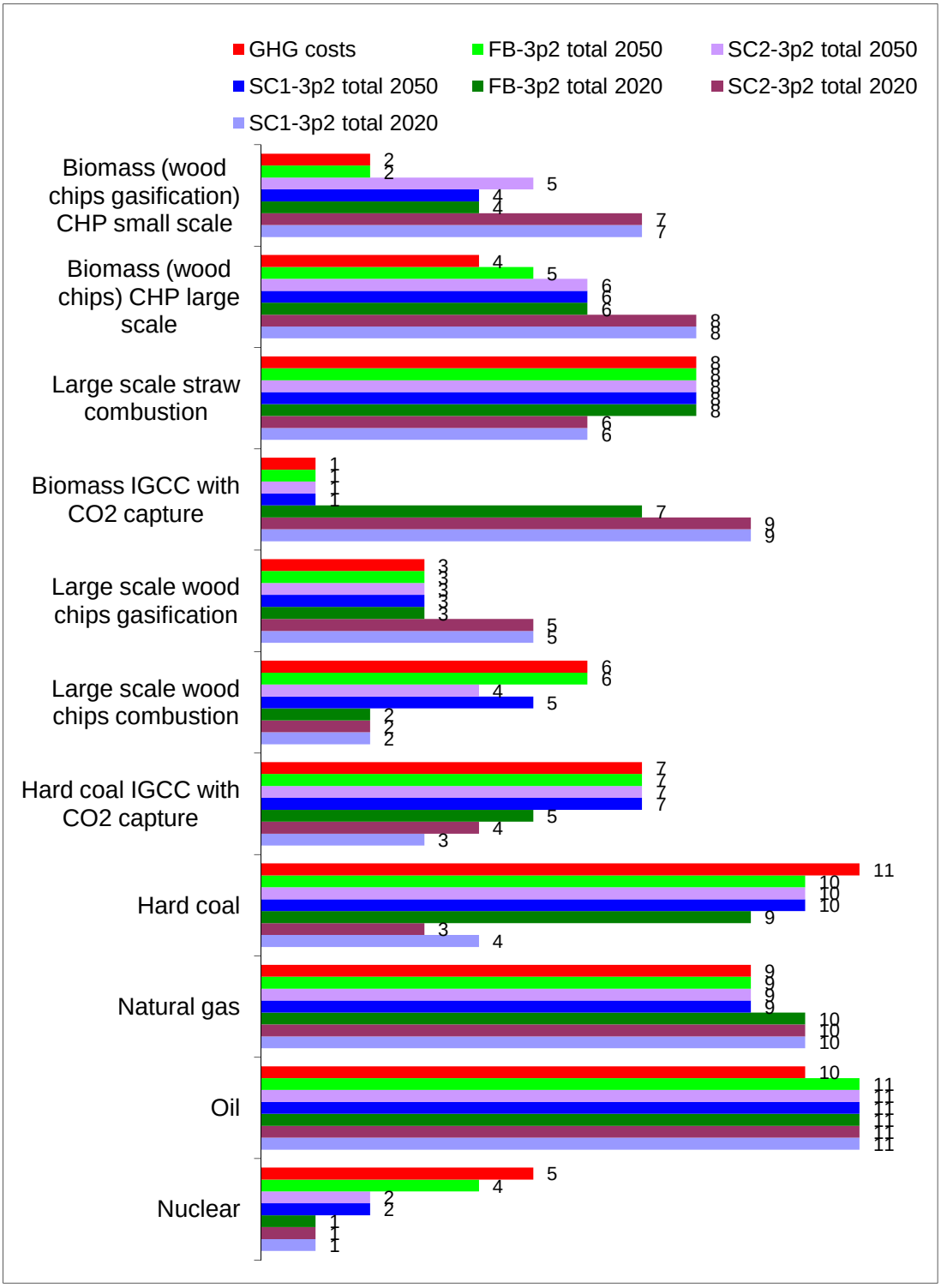

Figure 17. Ranking of electricity generation technologies (world) in 2020 and 2050 based on GHG costs and total costs for the first best FB-3p2 and second best scenarios SC1-3p2 SC2-3p2

As one can see from Figure 17 though quite different ranking of electricity generation technologies is obtained for various scenarios and time frame the results obtained in technologies ranking based on external GHG emission costs and total costs are similar just for

FB-3p2 scenario in 2050 because of very high carbon price (375 EUR/tCO_2 eq). External costs of GHG emissions in FB-3p2 scenario in 2050 overweight impact on private costs in technologies ranking. For all other policy scenarios electricity generation technologies ranking based on total costs and GHG emission costs provides for different results in technologies ranking. The most expensive technology in terms of total costs for all main policy scenarios in 2020 and 2050 is oil. The most competitive technology for all scenarios in 2020 is nuclear and in 2050 – biomass IGCC with CO_2 capture. Biomass IGCC with CO_2 capture is the most competitive in technologies assessment based on total GHG emission costs. The hard coal, oil and natural gas technologies are among the most expensive for all policy scenarios and all time frames. In 2050 because of the high carbon prices in all scenarios natural gas technologies are more competitive and in 2020 coal technologies are more competitive than natural gas technologies as private costs overweight external costs of GHG emissions in comparative assessment of technologies. In the ranking of technologies based on external costs of GHG emissions the coal technologies are the last attractive one. The ranking of biomass technologies based on total costs is different for specific scenarios and time frame and depends on carbon price obtained by specific scenarios. Very high carbon prices make more competitive technologies having low life cycle GHG emission such as biomass IGCC with CO_2 capture, biomass wood chips gasification and biomass CHPs technologies though these technologies in terms of private costs are more expensive than other biomass technologies external costs of GHG emissions in high carbon price scenarios overweight the private costs in technologies ranking. Hard coal with CO_2 capture technologies are ranked in the middle and in 2050 have similar total costs as large scale straw combustion technologies.

6.6 Ranking of transport technologies based on carbon price

Seeking to compare transport technologies based on carbon price developments several most reliable scenarios were selected as in the case of policy oriented electricity generation technologies ranking: first best and second best scenarios. The average data for global region (the average over four regions: OECD, EEX, DevAsia, ROW) on carbon price was applied in analysis. As the first best scenarios and second best scenarios include specific targets: 3.2 W/m^2 and 3.5 W/m^2 the scenarios with stricter target as in the case of electricity generation technologies were used in transport technologies assessment.

Transport technologies were compared based on external costs and total costs in 2020 and 2050. The same ranking of transport technologies based on external costs of GHG emissions was achieved for all policy scenarios considered and for both time framewoks: 2020 and 2050 as the same life cycle GHG emissions costs were applied. The most competetive transport technologies based on external GHG costs are technologies having the lowest life cycle GHG emissions, i. e. biodiesel from waste vegetable oil based technologies followed by bioethanol from wheat and from sugar beet based technologies.

In Figure 18 and Figure 19 the range of total costs and average total costs of transport technologies is provided in 2020 and 2050 respectively according the first best scenario FB-3p2.

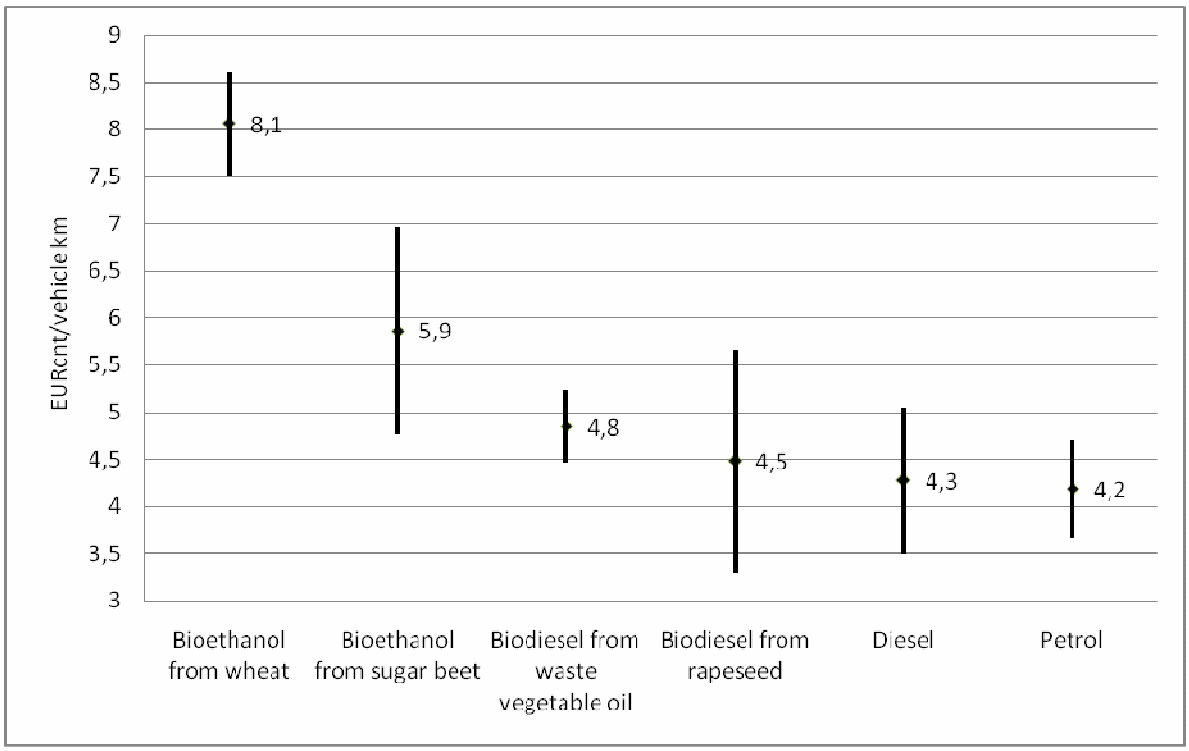

Figure 18. The average and range of total costs of transport technologies in 2020 according FB-3p2 scenario (world region)

As one can see from Figure 18 the high uncertainties are relevant to total costs assessment of transport technolgies however even taking into account wide range of total costs of transport technologies in 2020 it is obviuos that petrol and diesel fuel based technologies are the most competetive in 2020 as carbon price and external costst of GHG emissions do not overweight fuel price differences in transport technologies assessment. Therefore even taking quite big uncertainties biomass based technologies are more expensive comparing with conventional transport technologies in 2020.

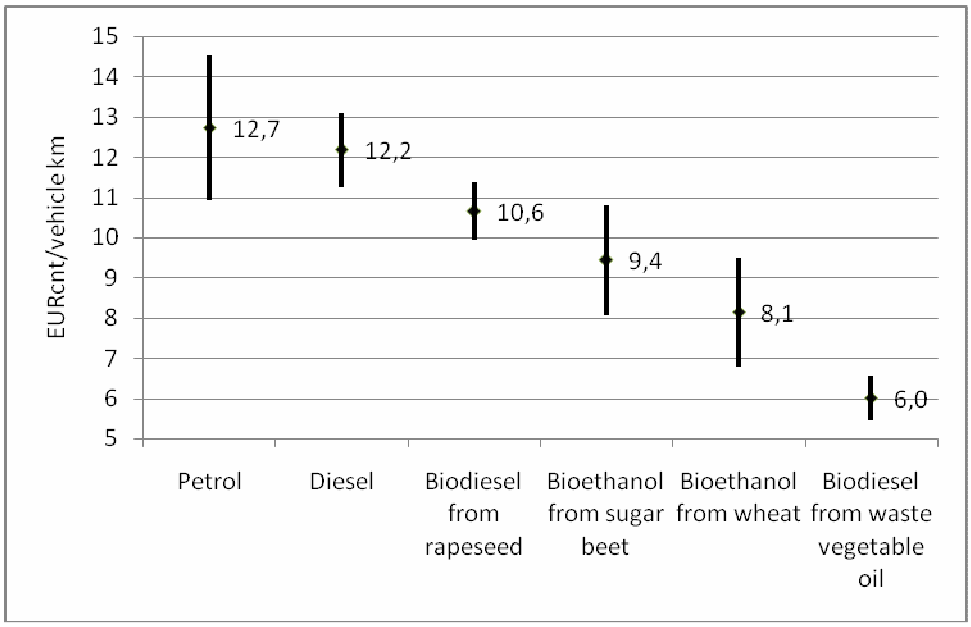

Figure 19. The average and range of total costs of transport technologies in 2050 according FB-3p2 scenario (world region)

However as one can see from Figure 19 the high carbon price in 2050 accoring first best policy scenario makes transport technologies based on biofuels more competetive than those fossil fuel based. In Figure 20 the ranking of transport technologies in 2020 and 2050 based on total costs is compared for the first best policy scenario FB-3p2.

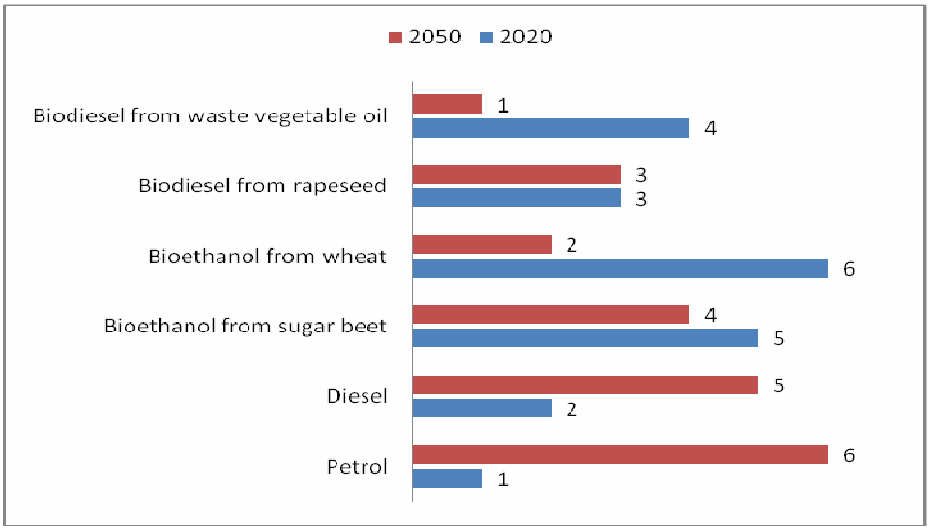

Figure 20. Ranking of transport technologies based on total costs (private and external costts of GHG emissions) in 2050 and 2020 according the first best policy scenario FB-3p2 (world region)

As one can see from Figure 20 the ranking of transport technologies based on total costs according the first best scenario in 2020 and 2050 provides oposite results. Because of the high carbon price in 2050 the petrol and diesel based transport technologies are ranked as the least atractive in this year though in 2020 these transport technologies are ranked as the most competetive. At the same time biodiesel from waste wegetable and bioethanol from wheat based transport technologies are the most competetve in 2050 though these technologies in 2020 were ranked as the least attractive because of the high fuel costs.

For the comparison of carbon price impact over the time frame on transport technologies ranking in first best policy scenario the ranking of transport technologies based on total costs in 2020 and 2050 and on external GHG emission costs were compared according the first best policy scenario FB-3p2 in Figure 21.

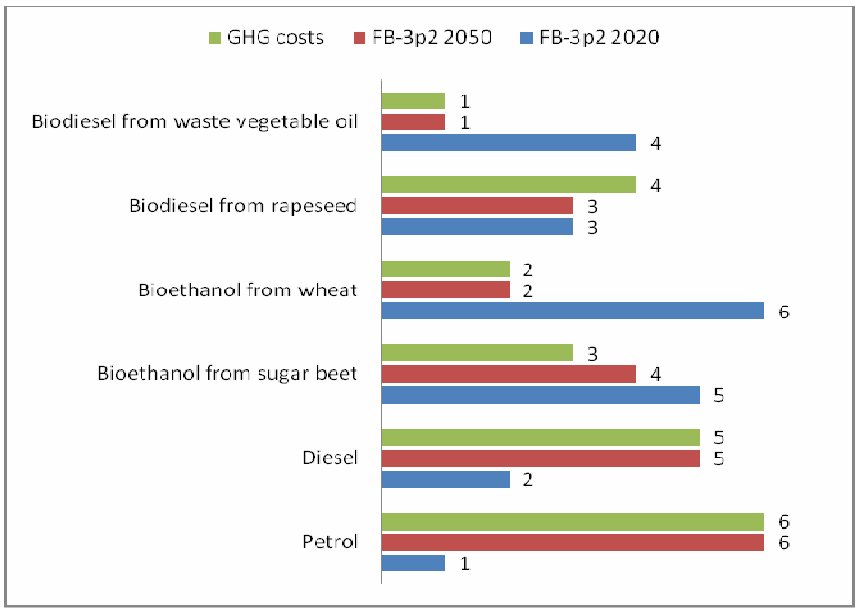

Figure 21. Ranking of transport technologies based on external costs of GHG emissions and total costs in 2020 and 2050 according first best policy scenario FB-3p2

As one can see from Figure 21 the high carbon price in the first best policy scenario in 2050 overweights private fuel cost and provides for very similar results in technologies ranking based on total costs and external GHG emission costs.

Further transport technologies ranking based on total costs will be provided for the second best policy scenarios. In Figure 22 and Figure 23 the range of total costs and average total costs of transport technologies is provided in 2020 and 2050 respectively according the second best policy scenario SC1-3p2.

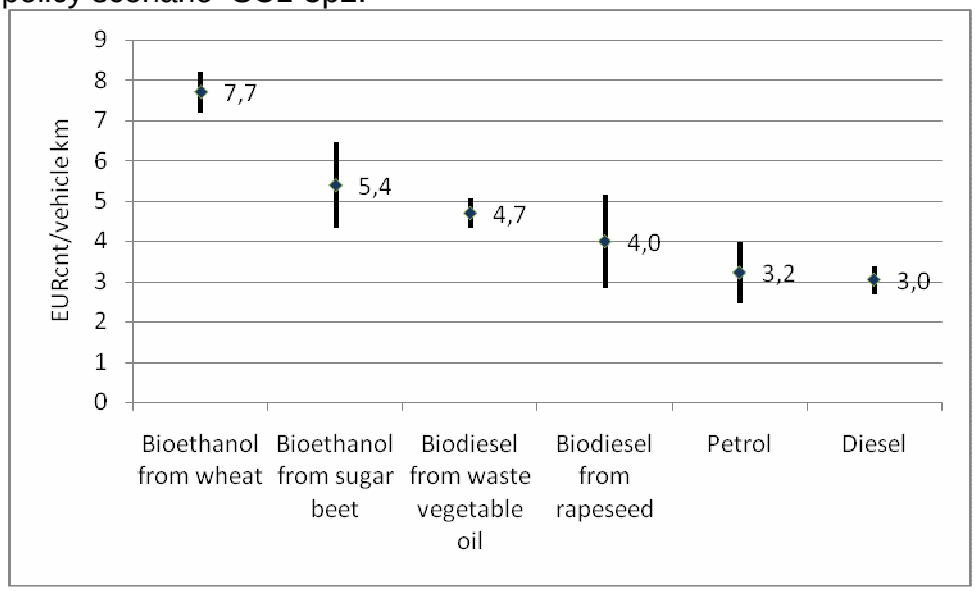

Figure 22. The average and range of total costs of transport technologies in 2020 according the SC1-3p2 scenario (world region)

As one can see from Figure 22 the most expensive technologies according the second best scenario like in the case of the first best scenario in 2020 are transport technologies based on biofuels.

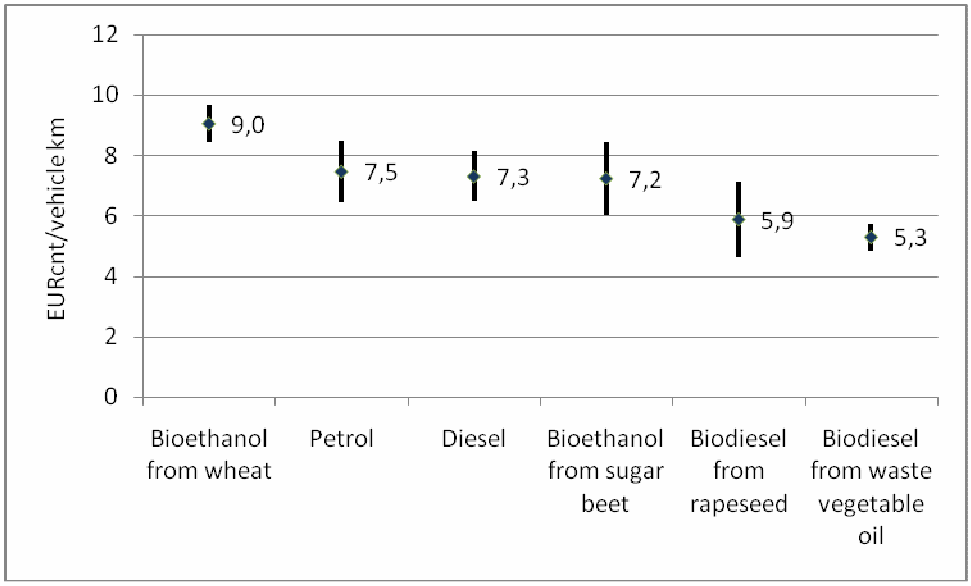

Figure 23. The average and range of total costs of transport technologies in 2050 according the SC1-3p2 scenario (world region)

As one can see from Figure 23 even taking into account big uncertainties according the second best scenario like in the case of the first best scenario the most expensive technologies in 2050 are based on conventional fuels and the most competetive technologies are based on biofuels however in the case of second best scenario as lower carbon prices were obtained for this scenario the most expenive technology is bioethanol from wheat as carbon price is not high enough to overwight the high costs of fuel in technologies assessment.

In Figure 24 the ranking of transport technologies based on total costs for second best policy scenarios SC1-3p2 and SC2-3p2 in 2020 and 2050 is presented.

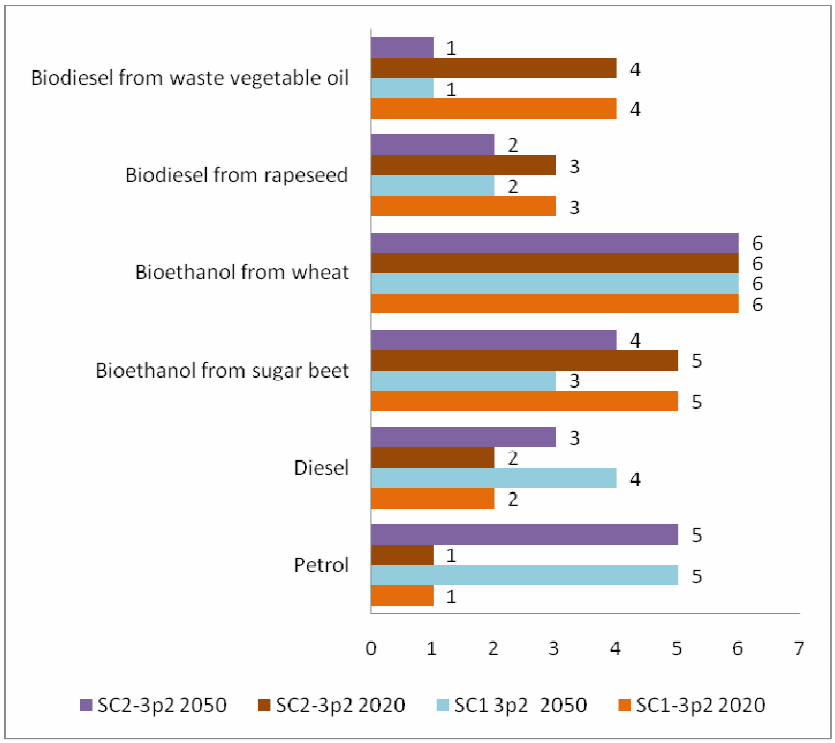

Figure 24. Ranking of transport technologies based on total costs (private and external costs of GHG emissions) in 2050 and 2020 according second best policy scenarios SC1-3p2 and SC2-3p2 (world region)

As the seond best policy scenarios have almost twice lower carbon prices (178 EUR/tCO2 eq and 170 EUR/tCO2eq) in 2050 comparing with first best scenario (375 EUR/tCO2 eq) it provides very different ranking of transport technologies comparing with the first best scenario. Though in 2020 the most competetive transport technologies are those based on petrol and diesel like in the case of first best scenario however the least attractive transport technololgies according these scenarios are based on bioethanol from wheat. This is related with the fact that carbon prices obtainaed during the second best policy scenarios runs in all time frame are too low to overweight the high costs of bioethanol from wheat.

Though in year 2020 carbon prices in first best scenario are significantly higher (55 EUR/tCO2) than in second best scenarios (12 EUR/tCO2 eq in SC1-3p2 and 9 EUR/tCO2eq in SC2-3p2) the ranking of transport technologies in 2020 obtained by applying carbon prices provides very similar ranking of transport technologies for all scenarios as high carbon price in first best policy scenario is not able to overweight the mpact of private fuel costs in technologies ranking (Figure 25).

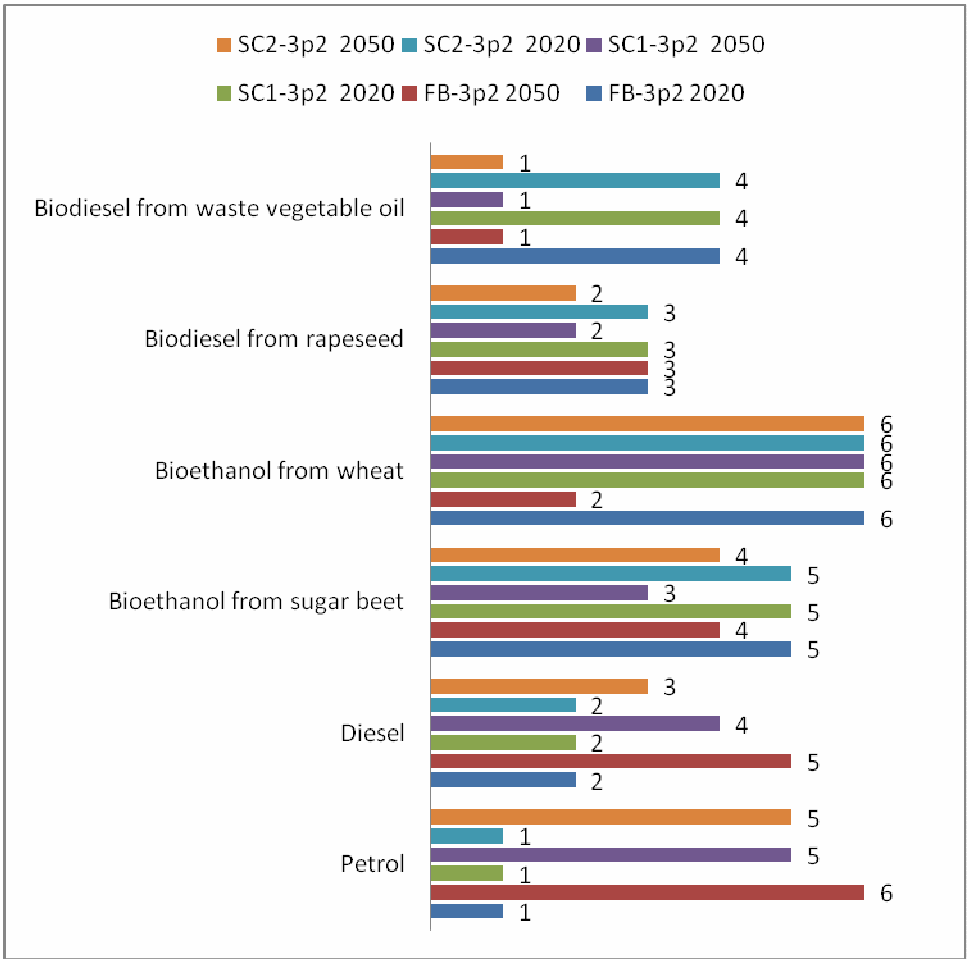

Figure 25. Ranking of transport technologies based on total costs (private and external costts of GHG emissions) in 2050 and 2020 according main policy scenarios FB-3p2, SC1-3p2 and SC2-3p2 (world region)

As one see from Figure 25 the most competteive transport technologies in 2020 for all policy scenarios are based on petrol. The least comptetive technologies in 2020 are based on bioetanol from wheat. In 2050 the most competetive transport technologies for all scenarios are based on bioethanol from waste vegetbale oil and the least competetive transport technologies are based on bioethanol from wheat excpet FB-3p2. In the case of this scenario the bioethanol form wheat is ranked among the most transport technologies because of high carbon price in 2050 overweighting high fuel cost of bioethanol.

The ranking of transport technologies based on GHG emission costs and total costs for all the main policy scenarios (first best and second best with 3.2 W/m2 target in 2020 and 2050 is povided in Figure 26.

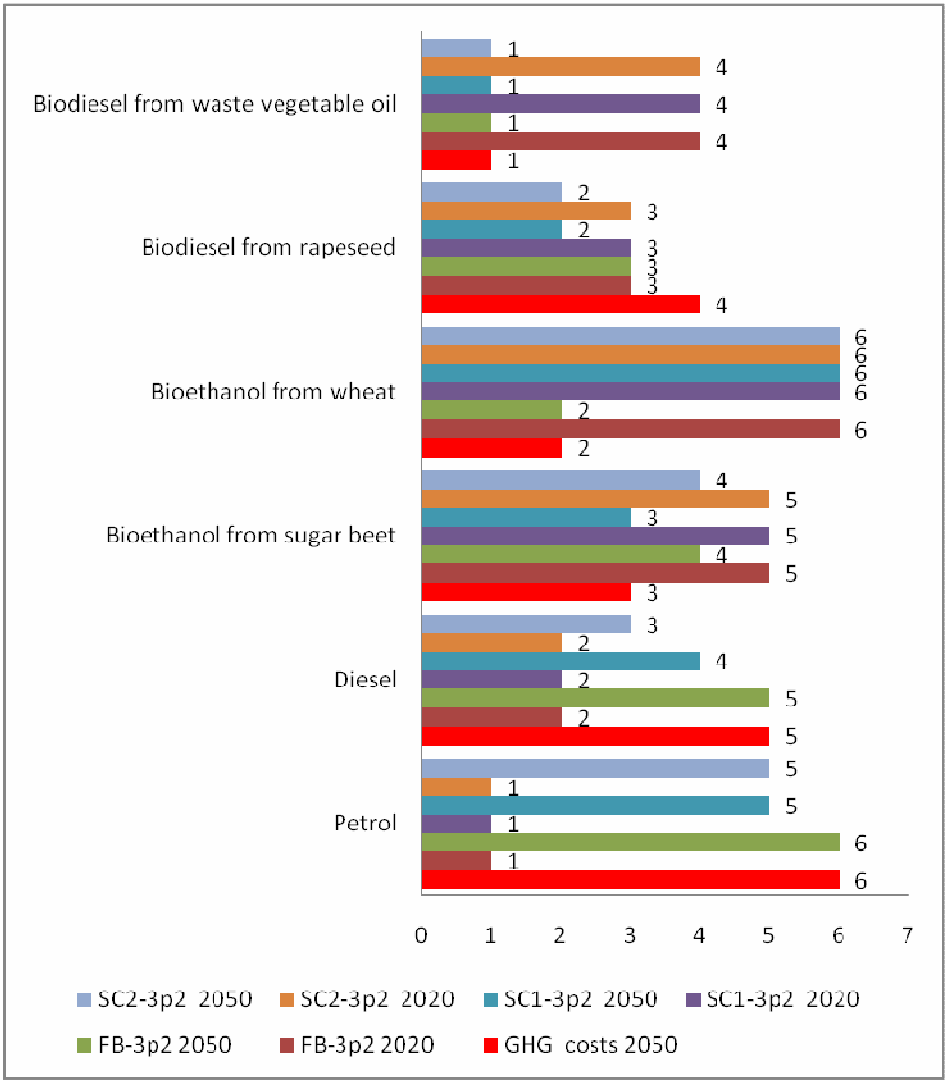

Figure 26. Ranking of transport technologies (world region) in 2020 and 2050 based on GHG emission costs and total costs for the first best FB-3p2 and second best scenarios SC1-3p2 SC2-3p2

As one see from Figure 26 because of very high carbon prices in 2050 in FB-3p2 scenario the ranking of transport technologies based on total costs and GHG emission costs are very similar for this scenario but very different for all other policy scenarios especially in year 2020 where fuel costs are dominating in transport technologies ranking because of comparatively low

carbon prices. However in 2050 the carbon price is the main determinant in transport technologies ranking. Especially first best policy scenario provides the competitive advantage for low carbon transport technologies such as biodiesel and bioethanol.

7. CONCLUSIONS

EU policy analysis performed and the main quantitative targets are presented in the framework of indicators. Analysis of methods and tools for sustainability assessment and studies dealing with assessment of technologies was performed. Based on these analyses indicators for technologies assessment were selected and integrated sustainability indicators integrating these indicators were developed. Electricity generation technologies were assessed applying integrated sustainability indicators and information provided by recent studies performed in this field: NEEDS, CASES. EUSUSTEL, GaBE, Global energy and climate project and other relevant information sources. Electricity and heat generation technologies were assessed in terms of sustainability and competitiveness.

Based on integrated sustainability index and equally treating all criteria the best technology (having the lowest score in assessment) is hydro, followed by wind and the worst – lignite condensing power plant, lignite ICGG without carbon capture and heavy fuel oil condensing power plant.

In economy focused scenario the best technology is the natural gas combine cycle and natural gas CHP with extraction turbine and carbon capture, followed by hydro and the worst is MFSC and lignite condensing power plant followed by heavy fuel oil condensing power plant;

In environmentally focused scenario the best technology is hydro, followed by wind and the worst technology is hard coal CHP with backpressure turbine, hard coal condensing power plant.

In socially focussed scenario the best technology is solar, followed by wind and the worst technology is lignite condensing power plant, Lignite IGCC without carbon capture.

Based on the total social cost assess the most competitive electricity generation technologies after the internalization of external costs is biomass (woodchips) CHP with an extraction condensing turbine. The other cheapest energy technologies are: nuclear (European pressurized reactor) and hard coal CHP with backpressure turbine. Photovoltaic technologies are the most expensive technologies even if the share of external costs very small.

Based on the comparativeness indicator assessment the most competitive technologies are nuclear, natural gas turbines and other conventional electricity generation technologies. The solar PV is the most expensive and least competitive technology according both evaluation methods carried out.

The assessment of electricity generation technologies based on various economic, environmental and social criteria provided in this report can serve as a complementary material to results of various policy scenarios runs providing electricity generation technology ranking according priorities of EU energy and environmental policies and can serve as guidance for further policy development in EU. However taking into account the main focus of project - climate change mitigation issues the long-term assessment of new energy technologies was performed for various long-run policy scenarios taking into account 2 main criteria: private costs (ALLGC) and external GHG emission costs. Such policy oriented energy technologies assessment based on carbon price and private costs of technologies can provide information on the most attractive future energy technologies taking into account climate change mitigation targets and GHG emission reduction commitments for world regions.

The ranking of energy technologies based on costs (private, external and total) points to a general problem in having costs as the main parameter for comparison of different technologies

since these energy technologies do not compete on the same markets. Energy technologies show a large span in costs and efficiencies and different processes yield different installed capacities therefore it is problematic to compare such processes if comparison is only made on cost basis since the different processes are suitable for different markets however comparison of different energy technologies based on total costs and carbon price enables to develop some important policy recommendations even taking into account high uncertainties in private and external costs.

Analysis of life cycle GHG emissions and private costs of the main future electricity generation technologies performed in report indicated that biomass technologies except large scale straw combustion technologies followed by nuclear have the lowest life cycle GHG emission. The cheapest future electricity generation technologies in terms of private costs in long-term perspective are: nuclear and hard coal technologies followed by large scale biomass combustion and biomass CHPs. The most expensive technologies in terms of private costs are: oil and natural gas technologies. As the electricity generation technologies having the lowest life cycle GHG emissions are not the most expensive but not the cheapest one in terms of private costs the ranking of technologies in terms of competitiveness highly depend on the carbon price implied by various policy scenarios integrating specific GHG emission reduction commitments taken by countries and set climate change mitigation targets.

Analysis of life cycle GHG emissions and private costs of the main future transport technologies performed in report derived that transport technologies based on biodiesel from waste vegetable oil have the lowest life cycle GHG emission followed by technologies using bioethanol from wheat. Petrol based transport technologies have the highest life cycle GHG emissions followed by diesel technologies. The most expensive in terms of fuel costs are bioethanol transport technologies and the cheapest are transport technologies based on petrol and diesel. Therefore the transport technologies having lowest life cycle GHG emission are among the most expensive in terms of fuel costs. Therefore as in the case of electricity generation technologies the policy oriented ranking of transport technologies highly depends on carbon price developments caused by foreseen future specific policy scenarios.

The assessment of the main selected power and transport technologies based on external costs of GHG emissions and total costs was performed in 2020 and 2050 for the first best (FB-3p2) and second best scenarios (SC1-3p2; SC2-3p2). Scenarios with more strict targets (3.2 M/m2) were selected for technologies assessment.

11 main future electricity generation technologies were selected: nuclear, oil, natural gas, hard coal including hard coal technologies with CO_2 capture and various biomass technologies (wood chips combustion, gasification, CHP, straw combustion, biomass IGCC with CO_2 capture). For all policy scenarios electricity generation technologies ranking in 2020 and 2050 based on external GHG costs provides the same results as the same data on life cycle GHG emissions were applied for technologies ranking. The most competetive technology according all policy scenarios based on external GHG costs in 2020 and 2050 is biomass IGCC with CO_2 capture biomass followed by other biomass technologies. Nuclear is ranked in the middle.

Though quite different ranking of electricity generation technologies is obtained for various scenarios and time frames the results obtained in technologies ranking based on external GHG emission costs and total costs are similar just for FB-3p2 scenario in 2050 because of very high carbon price (375 EUR/tCO_2 eq). External costs of GHG emissions in FB-3p2 scenario in 2050 overweight impact on private costs in technologies ranking. For all other policy scenarios electricity generation technologies ranking based on total costs and GHG emission costs provides for different results in technologies ranking. The most expensive technology in terms of total costs for all main policy scenarios in 2020 and 2050 is oil. The most competitive technology for all scenarios in 2020 is nuclear followed by large scale wood chips combustion

technologies and in 2050 biomass IGCC with CO_2 capture followed by biomass wood chips gasification CHP small scale having the lowest life cycle GHG emissions among analyzed technologies except biomass with CO_2 capture. This technology is the most competitive in technologies assessment based on total GHG emission costs as well. The hard coal and natural gas technologies are among the most expensive for all policy scenarios.

In 2050 because of the high carbon prices in all policy scenarios natural gas technologies are more competitive than coal and in 2020 coal technologies are more competitive than natural gas technologies as private costs overweight external costs of GHG emissions in comparative assessment of technologies. In the ranking of technologies based on external costs of GHG emissions the coal technologies are the least attractive one. The ranking of biomass technologies based on total costs is different for specific scenarios and time frames and depends on carbon price obtained by specific scenarios. Very high carbon prices make more competitive technologies having low life cycle GHG emission such as biomass IGCC with CO_2 capture and biomass wood chips gasification technologies though these technologies in terms of private costs are more expensive than other biomass technologies nevertheless the external costs of GHG emissions in high carbon price scenarios overweight the private costs in technologies ranking.

Policy oriented comparative assessment of transport technologies based on carbon prices performed in reprt indicated that the most competetive transport technologies based on external GHG costs are technologies having the lowest life cycle GHG emissions, i. e. biodiesel from waste vegetable oil based technologies followed by bioethanol from wheat and from sugar beet based technologies. The same ranking of transport technologies is achived for all policy scenarios considered and for both time framewoks: 2020 and 2050.

The ranking of transport technologies based on total costs for the first best scenario in 2020 and 2050 provides oposite results. Because of high carbon price in 2050 the petrol and diesel based transport technologies are ranked as the last atractive in this year though in 2020 these transport technologies are ranked as the most competetive. At the same time biodiesel from waste wegetable oil and bioethanol from wheat based transport technologies are the most competetive in 2050 though these technologies in 2020 were ranked as the least attractive because of the high fuel costs.

Because of very high carbon prices in 2050 in first best policy scenario FB-3p2 the ranking of transport technologies based on total costs and GHG emission costs are very similar for this scenario but very different for all other policy scenarios especially in year 2020 where fuel costs are dominating in transport technologies ranking because of comparatively low carbon prices. However in 2050 the carbon price is the main determinant in transport technologies ranking and there are no big differences in transport technologies ranking in this year for all policy scenarios. Transport technologies having low life cycle GHG emissions are the most competitive in 2050. Especially first best scenario provides the competitive advantage for low carbon transport technologies such as biodiesel and bioethanol.

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ANNEX I

Description of electricity generation technologies

The main technologies for electricity and heat generation are described including the expected future development of these technologies, the potential share of the new energy technologies to the future European energy system, short-term competitiveness and the main barriers to penetration in the European energy market.

Technology and its potential	**Description**	Short-term competitiveness	**Barriers**	**Future development**
Nuclear: 2020: 127÷150 GWe ; 2030: 127÷200 GWe; 2050: about 300 GWe	Approximately 35% of the electricity in the European Union is produced by nuclear power plants (NPP's), in 13 countries. Nuclear fission energy is a competitive and mature low-carbon technology, operating to high levels of safety within the EU. Most of the current designs are Light Water Reactors (LWR), capable of providing base-load electricity with availability factors of over 90%. Nuclear Generation III (Gen-III) LWR plants, has an investment of 150G€. However, the further expected global expansion of the LWR fleet has problems regarding availability of uranium resources. Current estimated exploitable reserves are in the range of 15Mt. In 2050, the current known uranium resources would be completely earmarked for the LWR.	The economic competitiveness for electricity production can be considered as rather high. The penetration of nuclear fission to its maximum potential could bring about a decrease of the overall production cost of electricity by 0.5% in 2020 and a more significant 2% in 2030, with respect to the baseline. Competitiveness would be even more enhanced in the event of an increase in carbon taxes. The Sustainable Nuclear Energy Technology Platform (SNE-TP), launched in 2007, will foster competitive operation of existing nuclear power plants.	The fusion development faces 2 major challenges: decrease of capital cost and decrease of construction time to 6 to 8. The reactor's *availability* has to be over 80% to let the reactor pay back itself by producing electricity. Lack of overall EU nuclear strategy. Lack of harmonised regulations and standards. Lack of public and political acceptance. Lack of suitable qualified scientists and engineers. Insufficient public R&D funding for Gen-IV.	New generation (Gen-IV) of fast reactors better able to exploit the resources (typically multiplying the energy production by more than 50 for the same quantity of uranium). Nuclear Fusion has a great potential to become a successful energy source but will be available just after 2030.

Zero emission fossil fuel fired power plants with CO2 capture: 2020: 5÷30 GWe 2030: 90÷190 GWe 2050: about 510 GWe	CO2 sequestration or CCS (carbon capture and storage) technology implies adding infrastructure to a fossil power plant: either by pre-combustion or post combustion measures or by using oxygen instead of air to separating (sequestering) CO2 from the process. The additionally needed infrastructure has in any case an impact on the cost and efficiency of fossil power generation, i.e. it increases the investment expenses and reduces the efficiency. To reduce the anthropogenic CO2-emissions, Carbon Capture Storage (CCS) seems to be one of the best options. From the three aspects included in CCS (i.e. capture, transport and storage), long term and reliable storage is the most difficult challenge	Once commercially available, CCS will play an important role in future electricity production. The cost of CO2 capture can be about €25-30/t in 2020. The development of zero emission plant technology in the EU will make Europe a world leader in the energy technology markets, increasing the potential for exports and hence benefit the competitiveness of the European industry and will create business opportunities.	Oxyfuel combustion is promising technology, but a lot of research is requested. Although some options are already used in commercial applications, questions remain open on the long term behaviour of the stored CO2. And this issue needs to be tackled before storage can be implemented on a large scale. Technology is not demonstrated at large scale. High cost of first-of-a-kind plants. Unfavourable market and regulatory conditions. Lack of supportive fiscal measures. Lack of CO2 transmission and storage infrastructure. Low public and political acceptance.	Concerning CO2 capture, post-combustion capture is not expected to be a long term solution as the costs and the efficiency penalisation are high. Pre-combustion capture looks promising, but an R&D-effort is needed before commercialisation is possible By 2030, it is anticipated that technological developments will have reduced the efficiency gap between zero emission plants and similar plants without capture to about 8%. Similar developments will have ensured that the capital cost of zero emission plants will be decreased by 10% to 25% compared to the first generation units.

Coal and lignite	The main fossil fuel based electricity generation technology in the EU is pulverized coal. A typical state-of-the-art supercritical pulverised coal plant has 45% efficiency, while few, more advanced coal power plants demonstrate efficiencies up to 48%. Fuel costs represent approximately 40% of the total electricity production cost. The main coal fired technologies are: The Pulverised Coal Combustion (PCC) technology; The Advanced Pulverised Coal Combustion (APCC); The Advanced Pulverised Coal Combustion (APCC); Subcritical or moderately Supercritical Pulverised Coal Combustion, Advanced Ultra Supercritical Pulverised Coal Combustion, IGGC. IGCC is an emerging advanced generating technology for fossil fuels such as hard coal and lignite. Its large-scale commercial availability is expected from 2010 onwards. Due to the specifics of the gasification and combustion processes, hard coal and lignite IGCC plants offer different efficiency and emission profiles.	The specific capital investment of the technology is currently of the order of 1300/kW. The contractor prices have recently increased by about 25% over the past few years as a result of the increase of material costs, mainly steel. It is expected that, in 2020, pulverised coal plants will have efficiencies around 50%. The first generation of commercialised pulverised coal, combined cycle gas turbine and IGCC plants with CO2 capture are expected to have efficiencies of 33%, 48% and 35% respectively, with corresponding specific capital investments of the order of €1800/kW, €1300/kW and €1700/kW.	The main challenges are related with the temperature resistance. As higher steam temperatures lead to higher efficiency, materials are needed which can resist to temperatures above 700°C. Another challenge is the corrosion resistance. Ameliorated material parameters will lead to a better durability and so to higher power plant availability. The major drawback of the post-combustion capture is the large reduction on the power plant's efficiency. E.g., for a modern lignite power plant with an overall efficiency of 43% (without CCS), the installation of a capture unit leads to a decrease in efficiency of 10 to 12% points.	New materials will play a crucial role in the further development of new coal-fired technologies. Nickel-based alloys look very promising and are expected to be commercially available in the next decade. Integrated Gasification Combined Cycle (IGCC), in which coal is converted into syngas, which is used as the primary fuel for the gas turbine. This can become an environmental friendly option in combination with CO2-sequestration, prior to the combustion process.

Natural gas	The basis of a gas fired plant is a gas turbine (GT). This turbine can be used in a simple configuration (SCGT) or in a combined cycle (CCGT). The Simple Cycle Gas Turbine (SCGT) makes use of the thermodynamic Brayton cycle for the production of electricity. They are very flexible in operation with (cold) start-up times from 15 to 30 minutes and with their quick load change capabilities. As a rule of thumb, SCGT's have a power output of 40 MWth, 40 MW_e and an electric efficiency of 40 to 42%. The Combined Cycle Gas Turbine (CCGT) is based on the SCGT, but a second turbine, i.e. a steam turbine is added. The residual heat from the flue gasses from the SCGT-cycle is recuperated in a Heat Recovery Steam Generator (HRSG) for the formation of steam; steam which is fed to a Rankine cycle. Different configurations and optimisations are possible (single/double shaft, superheaters, economisers, etc.), but the basic principle remains the same. The partial load efficiency is rather good, but once below 50% partial load the efficiency drops quickly. The gas cycle has an efficiency of approximately 38%. This is less than in a SCGT, because a maximised GT efficiency does not automatically results in a maximised CC efficiency. In practice, overall efficiency of the CC reaches 54 to 60%. Fuel costs represent approximately 80% of the total electricity production cost.	Gas turbines and CCGT's are rather mature technologies and no real technical breakthroughs are foreseen. Also costs are not expected to decrease a lot, indicated by a so-called progress ratio of 90% (i.e. doubling in capacity, 10% reduction in costs).	The main challenge as for the coal technologies is possibilities to increase the turbine inlet temperature (TIT) of the GT (up to 1450°C) and secondly to increase the steam parameters up to supercritical circumstances	By 2030, with the combination of the new materials and cooling options, an overall CCGT efficiency of 65% is projected. As CCGT units come more and more into cycling operation, it is important to work out efficient options (both from a technical and economical point of view) for a higher flexibility towards the partial load behaviour. More efficient gas fired power plants are envisaged and other options which make use of the gas turbine technology are under development. Combined Cycle PP, in combination with CO2-sequestration, prior to the combustion process is environmentally friendly promising option.

Hydropower: 2020: 101÷108 GW refurbishment from 2005 park: 25÷50% 2030: 104÷112 GW refurbishment achieved from 2005 park: 55÷85% 2050: about 120 GW	Hydro power units are in range from a few kW's up to 800 MW. The distinction between large- and small-scale units is defined by the European Commission at 10 MW. Large-scale installations are most of the time *reservoirs installations*, with the storage of large amounts of water behind a dam of sites where rivers haves variable flows. *Run-of-river installations* are mostly of a smaller scale and are ideal for rivers with a stable flow throughout the year. From a technical and operational point of view, hydro power stations have a high efficiency, well above 80% and up to 95%, which is nearly flat for a wide range of flows. *Pumped hydro power plants* are the most effective of all large scale storage methods and are used for more than 70 years. The hydro power plants have quick response times (only a minute from a complete standstill), and have round trip efficiencies of 70 to 80%. As a drawback, hydro plants require geologically special sites, which are very often only found at remote locations and although there is no environmental impact while operating the plant, the construction of the plant does have an impact.	The operational costs of hydropower plants are low, but the investment costs are high. Depending on the site, they vary between $1000 and $3000 per kW. Some increase in the hydro power capacity is expected in Europe, but most of the investments are expected to happen in Asia.	The main challenge is the refurbishment of out-dated plants. All over Europe, a lot of small plants are out of service, due to lack of maintenance, even though they require only a little investment for an update.	Hydro power technology is mature and the currently reached efficiencies are already high. Small ameliorations could be made on the hydraulic losses, the electrical system and the turbine efficiency itself. Currently, several types of emerging technologies are being tested to extract energy from freely floating water, like currents and tides. Those systems are wind power like installations under water, but are still in a stage of development and commercial breakthrough is rather speculative.
Wind: 2020: 120÷180 GWe; 2030: 168÷300 GWe 2050: 540 GWe	Currently the average turbine size in the EU is around 1.3 MW onshore and 2.1 MW offshore. By 2030, average turbine sizes of 2 MW and 10 MW are expected for on- and off- shore respectively, with GW- size wind farms likely for offshore. In recent years, 3 major trends could be seen. First of all, the turbines have become larger and taller. A second important trend is the steadily increase of the efficiency. Over the last 15 years, overall efficiency annually increased by 2 to 3%-pts. Modern wind turbines have an efficiency of 45 to	There is trend of decreasing investment cost per kW. The two main parameters in wind power economics are the investment costs, which are dominated by the cost of the turbine itself as this represents 82% of the total costs, and the electricity production rate of the turbine. Choosing the right turbine site with good wind	Inflexible grid infrastructure. Lack of large-scale testing facilities. Under-developed storage mechanisms. Disparate level of financial support. Lack of social acceptance. Lack of skilled professionals. Fewer suitable onshore sites are available	The recent push in scaling-up of turbine size is driven by offshore technology, as higher wind speeds and wind energy generation can be reached here.. The further upscaling of wind turbines leads to new challenges in the field of load control and wind turbine construction materials. Moving offshore has also meant increased technological focus on materials In the

	50%. The theoretical maximum of the utilisation of the kinetic energy passing through its swept rotor area is 16/27 ≈ 59%. This is known as the 'Betz limit'.	conditions is crucial to achieve economic viability, knowing that the power density is proportional to the wind velocity cubed. The technology evolves continuously towards higher efficiencies and larger power output, and the installed capacity is ever increasing.	due to land constraints. As the wind conditions are of primordial importance for the economic viability of a wind turbine, offshore sites is the most challenging.	near term, continued wind deployment will need to be accompanied by developments in storage technologies and increased grid flexibility, to be able to accommodate increasing levels of wind energy penetration in the electricity network.
Solar PV: 2020: 65÷125 GWp 2030: 300÷665 GWp 2050: about 2000 GWp	Photovoltaic (PV) systems are currently based predominantly on crystalline silicon technology and are mature for a wide range of applications. Today the average turn-key price of a small to medium size (3 to 20 kWp) PV system is €5/Wp and for large systems in the multi MWp range about 3 - 4 €/Wp. The efficiency of commercial flat-plate modules and of commercial concentrator modules is up to 15% and 25%, respectively. The typical system energy pay-back time depends on the location of the installation. In southern Europe this is approximately 1 to 2 years and increases at higher latitudes. Finally, the average generation cost of electricity today is about 30€c/kWh, ranging between 20 and 45 €c/kWh depending on the location of the system. Crystalline silicon PV cells are the most commonly used types at the moment. The cell conversion efficiencies amount up to 17% and at laboratory scale even to 25%. The module efficiencies are in the typical range of 10 to 15%. The total system costs are 3 to 8 €/W. During the production process, a lot of energy and material is required. A second technology is the thin film PV cell. As this cell only uses a micrometer thick layer of photosensitive material it	Based on existing learning curves, system costs would decrease by 20% for every doubling in capacity. With the current growth rates, this would result in a halving of the costs by 2015. Building integrated PV's show already a clear trend for cost reductions. The price is one of the major obstacles in the commercial breakthrough of PV cells. The cost of a typical turn-key system is expected to reach €1/Wp in 2030 and €0.5/Wp in the longer term. Simultaneously, module efficiencies will also increase. Flat-panel module efficiencies will reach up to 40% in the long term, while concentrator module efficiencies will reach 60% respectively. In addition, PV systems have a direct impact on local wealth development as a	High cost of electricity. Techno-economic issues. Building integration. Lack of skilled professionals. Access to grid. Regulations and administration	PV technology development will have to focus on two major topics. Firstly, attention has to be paid on the *cost reduction*, by using less material, less energy and less labour during the construction process. A second pillar is the *efficiency increase*. Current technologies are still far apart from the thermodynamic limit of sunlight conversion (i.e. 87%). Nowadays, multi junction, third generation PV cells have efficiencies of above 35%. In order to reach high efficiencies, third generation PV's will focus on the heat losses and the structural properties of the semiconductors. Organic PV cells are a potential future technology. Though it can be manufactured inexpensively. The main drawbacks are its low efficiency (less than 3%) and some stability issues. In the long term, new and emerging technologies will come to the market, such as

	consumes far less material than the crystalline silicon PV's. This gives a great potential for cost reductions on the long term. Nowadays, the total system costs are 2 to 7 €/W. The major drawbacks are the lower cell efficiencies (10% on a commercial level, 20% at a laboratory scale; 5 - 10% is a typical range for the module efficiency) and a lack of experience in lifetime performance. However, it is expected that before 2030 thin film technology will pass crystalline silicon PV's in market share.	significant number of jobs are created locally, associated with sales, installation and maintenance of the systems. On average, 50 specialised jobs are created for each new MW of production capacity.		high concentration devices that are better suited for large grid-connected multi-MW systems, and, compact concentrating PV systems for integration in buildings. It is expected that crystalline silicon, thin films and other technologies will have equal shares in the installed PV capacity in 2030.
Solar thermal: 2020: 1.8 GWe in EU27 → 1.8 GWe with 55 TWhe imports 2030: 4.6 GWe in EU27 → 4.6 GWe with 216 TWhe Imports 2050: about 10 GWeE	Concentrated Solar Power Plant (CSP) consists, schematically, of a solar concentrator system made of a receiver and collector to produce heat and a power block (in most cases a Rankine cycle). Three main CSP technologies are under development: Trough, Tower/Central and Dish. Today CSP technologies are in the stage of a first commercial deployment for power production in Europe. In Europe, a parabolic trough power plant of 50 MWe power capacity with 7.5 hours of storage (Andasol 1) is under construction in Granada in Spain, expected to be in operation in 2008. Two more plants of 50 MWe each are scheduled to be built on this site. The solar only average load factor without thermal storage of a CSP plant is about 1800 to 2500 full-load hours per year.	Capital investment for solar-only reference systems of 50 MWe are currently of the order of 3 300 to 4 500 €/kWe. The upper limit accounts for systems with thermal storage to achieve capacity factor of between 5000 to 6000 hours. Depending on the Direct Normal Insolation (DNI), the cost of electricity production is currently in the order of 20 c€/kWh. For a given DNI, cost reduction of the order of 25% to 35% is achievable due to technological innovations and process scaling up to 50 MWe. Facility scaling up to 400 MWe will result in cost reduction of the order of 14%.	High cost of electricity. Lack of feed-in support in most EU country. Equity shortage for demonstrating first of a kind project. Investments in grid infrastructure.	Parabolic Dish engines or turbines (e.g. using a Stirling or a small gas turbine) are promising modular systems of relatively small size (between 5 to 50 kWe), in the development phase, and are primarily designed for decentralised power supply.
CHP: 2020: 165÷185 GWe; 2030: 195÷235 GWe; 2050: about 335	Various technologies are used for power generation in existing cogeneration systems (Combined Heat and Power - CHP) and co-produced heat is	Specific investment for typical state-of-the-art CHP is in the range of 650÷950€/kWe for	Lack of coherent policies in some MS. Market liberalisation	More recently, attention has also given to the development of small-scale CHP systems because of the large

GWe	used in different forms and on different temperature levels. Therefore, energy conversion efficiency considerably varies among different systems. The average overall efficiency in EU CHP industry is around 70%, while average electrical efficiency is less than 25%. However, overall efficiency of newly installed CHP systems varies from 60 to 90% while electrical efficiency is about 30÷55%. Besides the mature technologies like gas turbines, steam turbines, reciprocating engines and combined cycle units, which are all commonly used for cogeneration applications, more prospective technologies are under development as well. Firstly, there is the Stirling engine, which is based upon a thermodynamic cycle which has a theoretical efficiency equal to the Carnot efficiency. More recently, attention has also given to the development of small-scale CHP systems because of the large potential market in the residential and commercial sectors. Small CHP units of 100 kWe and above, represent a steadily growing market with features rather similar to large units. Micro-CHP units, particularly below 20 kWe, are still in the R&D and demonstration phase (Stirling engines, organic Rankine cycle, micro-turbine), while only internal combustion engines of that size are already on the EU market. Electrical efficiency of such units is still low and improvements are expected (e.g. up to 30% for micro-turbines).	large size units and about 900÷1500€/kWe for medium size. For biomass systems specific investment is about 900÷3000€/kWe. Investments for small scale and micro-CHP are in the range 1500÷2500€/kWe and for fuel cell based CHP from 8000 up to 20000€/kWe. Since the later is the price for early field test, a significant price decrease is expected for the deployment phase. Stationary fuel cells has high electrical efficiency compared to other options (i.e. 34÷50% electrical and up to 90% overall efficiency) and they have some operational advantages (noise, size, etc).	exposes short term profitability projects. Market uncertainties about fuel and electricity prices. Many (older) installations now operate with lower efficiency and uncompetitive costs level. Correlation of heat and electricity demand. Slow progress on micro-CHP.	potential market in the residential and commercial sectors. Small CHP units of 100 kWe and above, represent a steadily growing market with features rather similar to large units. Micro-CHP units, particularly below 20 kWe, are still in the R&D and demonstration phase (Stirling engines, organic Rankine cycle, micro-turbine), while only internal combustion engines of that size are already on the EU market. Electrical efficiency of such units is still low and improvements are expected (e.g. up to 30% for micro-turbines). Particular interest for CHP is development of stationary fuel cells, as their electrical efficiency is high compared to other options (i.e. 34÷50% electrical and up to 90% overall efficiency) and they have some operational advantages (noise, size, etc.). Significant progress is expected with MCFC and SOFC for industry and public applications, and PEMFC for households (micro-CHP).