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Low carbon electricity systems

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LOW CARBON ELECTRICITY SYSTEMS

METHODOLOGY & RESULTS FOR THE EU

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SUMMARY

As background information for its new POWER SWITCH! campaign in the electricity sector WWF commissioned Ecofys to determine the possibilities for achieving carbon neutral electricity production.

This report discusses the methodology used to determine the possibilities for a low carbon electricity future (the *Power Switch scenario)* and presents the results for the European Union.

In a four-step methodology emission reduction options are determined for a broad range of saving options, both to save electricity demand and to lower the carbon content of electricity production. All emission reductions are analysed against a *Business-As-Usual (BAU-scenario).*

The following emission reduction options are described and analysed:

Demand side for emission reduction	Supply side options for emission reduction
Reduction of stand-by losses of household appliances	Increase CHP production
Increased use of efficient applicances in households	Retrofitting of existing fossil fuel power production
Efficient cooling for households	Fuel switch to low-carbon fuels
Efficient lighting, for households and services	Increase in energy efficiency of new power production plants
Recycling of aluminium	CO_2 removal[1]
Reduced electricity use in the Chlorine industry	Use of biomass for electricity production
Efficient motor technologies	Increased renewable electricity production (wind, PV, solar thermal electricity, hydro power and geothermal electricity)

The Business-As-Usual scenario for the EU already includes several emission reduction mitigation options, namely:

- Energy efficiency increases on the demand side
- Energy efficiency improvements of existing fossil fuel production capacity
- Fuel switch from coal (and oil) to gas
- Increased share of renewable electricity production

[1] While WWF does not support the full introduction of storage as a mitigation option, it believes that pilot projects and research are valid in order to address unresolved issues. CO_2 removal or storage is therefore included in this study as a back-up option.

The main additional reduction options for the *Power Switch scenario* are:

Additional demand-side reductions	Additional supply-side reductions
Best practice appliances and cooling equipment in the household sector.	Increase of the amount of CHP production
Appliances with low stand-by losses (< 1W) in the household sector.	Additional fuel switching from coal (and oil) to gas
Energy efficiency office equipment, lighting and cooling.	Co-firing of biomass in existing coal-fired plants, especially lignite plants
Increasing amount of recycled aluminium to 90%.	Increased use of wind and biomass for electricity production
Introduction of energy efficient motors in the industry.	CO_2 removal [2]

Results for the EU

Figure S1 shows the resulting CO_2 emissions from electricity production in the BAU scenario and in the Power Switch scenario. Compared to the BAU the CO_2-emissions in 2020 are approximately 60% below the levels in the BAU scenario.

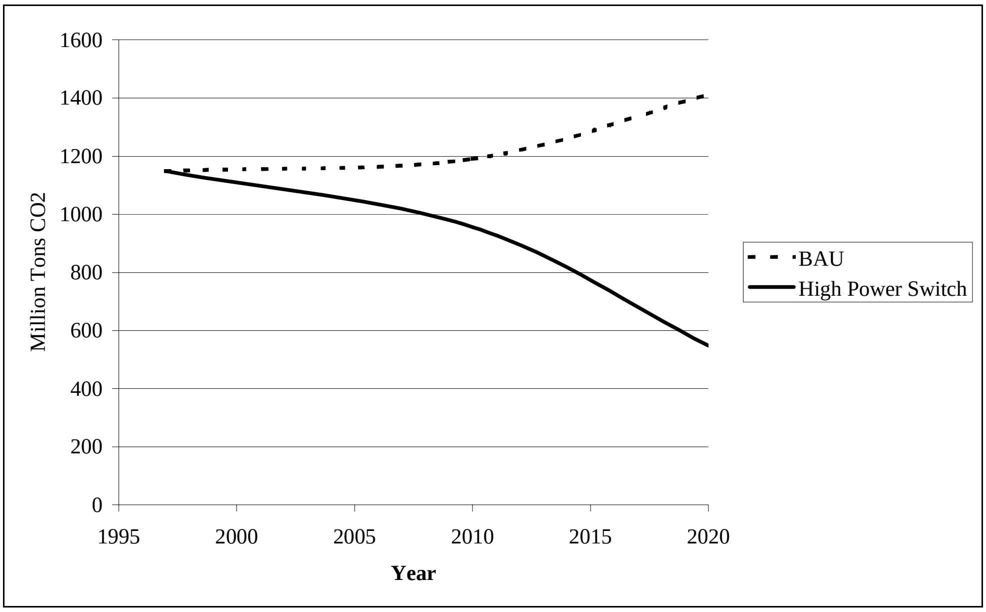


Figure S1: CO2-emissions in the BAU and in the High Power Switch scenario[3].

[2] While WWF does not support the full introduction of storage as a mitigation option, it believes that pilot projects and research are valid in order to address unresolved issues. CO_2 removal or storage is therefore included in this study as a back-up option.
[3] The BAU was adapted with regard to the phase out of nuclear energy. It was assumed that Germany, Belgium and Sweden will phase out large parts of their nuclear energy production capacity before 2020 and that no additional nuclear capacity will be installed as of 2003.

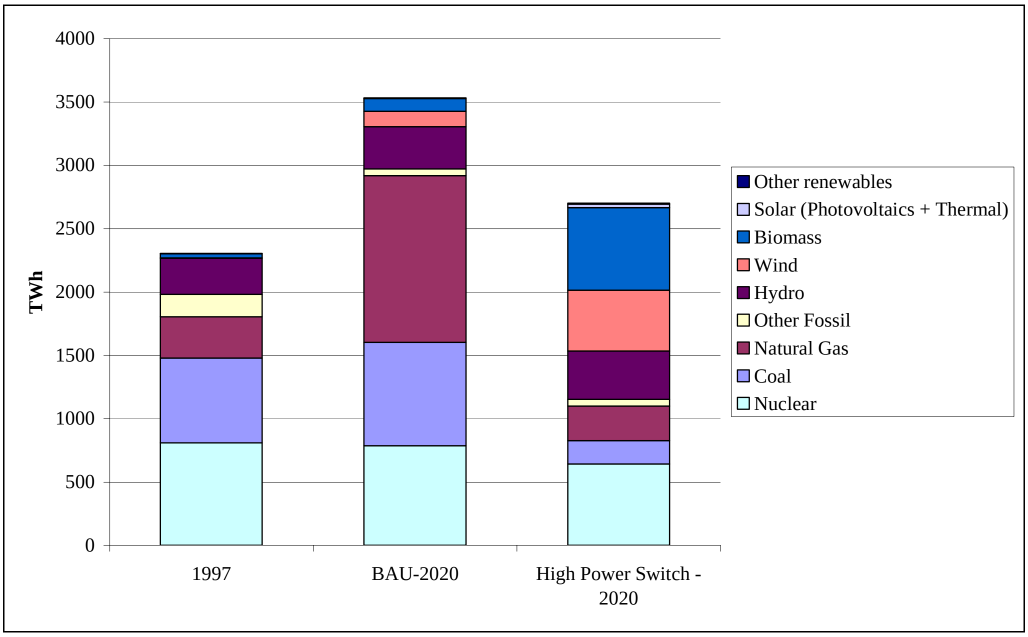
The ‘Power Switch!’ scenario:

- Under the ‘High Power Switch!’ Scenario, i.e. assuming high levels of electricity demand reduction through energy efficiency measures, carbon neutrality can be achieved for new and retrofitted electricity production capacity installed in the period 2010-2020. Additional electricity with biomass is the key option to make new and retrofitted production capacity fully carbon neutral.
- Under the high levels of energy efficiency and main renewable measures assumed, CO_2 emissions fall from 1190 Mtonne CO_2 in 2010 under BAU to 956 Mtonne, and then 548 Mtonne in 2020. This is a 20% fall in CO_2 emissions by 2010 and 61% by 2020 compared to the BAU scenario. Bringing in substantial additional biomass capacity and possible carbon storage (where energy efficiency is less effective) then achieves full carbon neutrality in 2020.
- Demand reduction is the key difference with the BAU scenario. In the “high” demand reduction assumption scenario this brings demand down by 9% in 2010 and a further 27% in 2020
- Where demand reductions are lower (Low Power Switch scenario), and assumed to be only one-third of the potential, additional measures such as carbon storage would be needed to achieve carbon neutrality[4]
- On the supply side, renewable energy options such as wind power, hydro, fuel switching from coal to natural gas, CHP and especially co-firing of biomass are the big CO_2 reduction options
- European wind capacity reaches 60 GWe in 2010, and 150 GWe in 2020. This is equivalent to the total UK generating capacity in 2010 and that for the UK, Germany and Belgium combined in 2020.
- The share of renewable energy in the fuel mix increases to between 50-60% of the total electricity production.

Figure S2 shows the electricity production in 1997 and in 2020 for the BAU scenario and for the Power Switch scenario is shown. The figures illustrate that it is possible to achieve carbon neutrality for new and/or retrofitted electricity production capacity in the year 2020 in the case of high savings in energy demand. It furthermore shows that biomass is the crucial options to reach this carbon neutrality for new and retrofitted power plants.

[4] While WWF does not, at this point, fully support the use of carbon storage due to a number of uncertainties that still exist, it does support pilot projects and research into the issue. For this reason, storage is included as an option in this analysis, but only one to show the future reductions that could be possible if the issues surrounding carbon storage are resolved and if meaningful deep targets are undertaken by industrialised countries.

Figure S2: Electricity production in the 1997 and in 2020 for the BAU scenario and the Power Switch scenario



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1 Introduction

1.1 Background

WWF's Climate Change Programme is planning to launch the POWER SWITCH! initiative aimed at the electricity sector. This sector - also called power sector - includes both electricity demand and electricity supply. With this initiative WWF aims to set out a strategy to achieve a carbon-neutral electricity sector in the longer term (2040/2050).

WWF commissioned Ecofys to determine a realistic implementation potential for greenhouse gas emission reductions for the electricity sector in the European Union (EU). The results of this analysis are input for WWF in setting realistic targets for all major actors in the electricity sector.

1.2 Aim of the study

The aim of the overall study is to determine a realistic implementation potential for CO_2 emission reductions for the electricity sector for Europe. Other studies are being commissioned around the world to assess the situation in other countries. The study aims to identify the required electricity production, as well as electricity demand savings.

This report presents the results of the first phase, which aims to describe the methodology used and the results for the European Union. Calculations are made for the years 2010 and 2020.

1.3 Contents of the report

This report discusses the methodology used to determine the possibilities for a carbon neutral electricity sector in the longer term in the European Union. First (chapter 2) it discusses the approach and methodological issues. Next, chapter 3 provides a description of the CO_2 reduction options included in the analysis. In this, a distinction is made between demand side options and supply side options. For each option a short description is provided as well as the basic assumptions and resulting reduction potential.

Chapter 4 discusses the results of the analysis for the European Union. Reduction potentials for the years 2010 and 2020 are indicated as well as the possibility to achieve carbon neutral electricity production.

2 Approach and methodological issues

2.1 Introduction

This chapter includes a description of the approach and scope of the project, followed by some methodological issues.

2.2 Approach and scope of the project

Figure 1 shows the steps taken in this study to identify the CO_2 reduction potential of electricity production and consumption. Each step is carried out for the years 2010 and 2020.

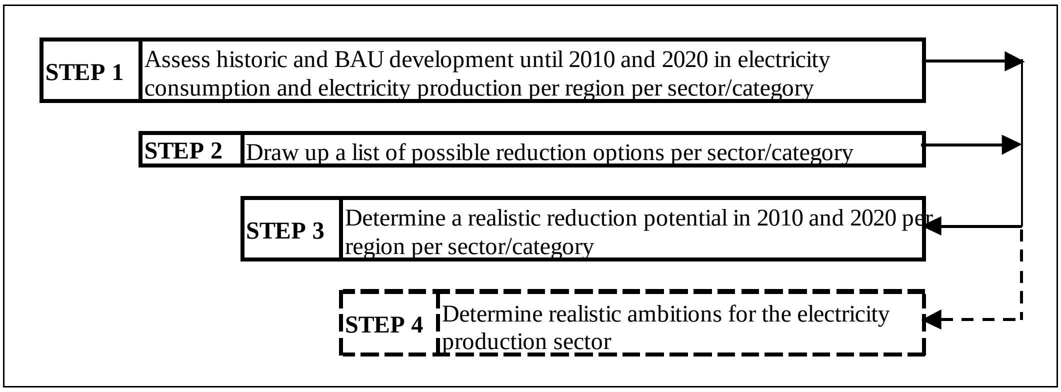

Figure 1 Steps taken within the project

In the first step an overview is provided of the electricity consumption and production of each sector or category. The historical development as well as the development in a Business-As-Usual scenario (BAU) is assessed.

In the second step an overview is made of possible reduction options per sector or category, which:

- Can be implemented to reduce consumption of electricity,
- Can be implemented to reduce the carbon intensity of the electricity systems,
- Potentially have a substantial impact on the level of CO_2 emissions of the electricity sector in 2010 and 2020.

Table 1 shows the reduction options analysed. The list of options is derived from a project previously executed by Ecofys [Ecofys, 2001][5]. In this project an inventory was made of the emission reduction options for greenhouse gases for each EU Member State. From the total list of more than 250 options those options were selected, which:

1. Affect the electricity consumption,
2. Can be implemented to reduce the carbon intensity of electricity production, and
3. May result in a substantial CO_2 reduction for 2010 and 2020.

Because of their limited impact on the level of CO_2 emissions the following options were not assessed:

- Stationary fuel cells for electricity production. Most research is currently aimed at fuels cells in the transport sector and less at stationary fuel cells. The use of fuel cells requires the shift towards another energy infrastructure, and such a shift is generally not expected to take place on a large scale before 2020. Therefore this option is excluded from this study. However, WWF is investigating these options further in other studies, assessing whether even further reductions are possible than are included in this analysis.
- Wave and tidal energy. The World Energy Council (WEC, 2000)[6] estimates the global potential for energy from wave and tidal at 2 million TWhe. Capturing this potential is however very difficult. Some small-scale research and demonstration projects are currently conducted (Portugal, Scotland, and Denmark). It his however not expected that wave and tidal energy will contribute substantially to the overall electricity production before 2020.

Increased use of nuclear electricity is also not included in this study as a means for further reduction of CO_2 emissions from electricity production because of the other environmental concerns attached to it.

Table 1 Overview of categories of reduction options assessed in the study

Electricity consumption	
Households	Efficient cooling equipment
Households	Efficient lighting
Households	Reduce stand-by losses
Services	Efficient electric appliances
Services	Efficient lighting
Services	Efficient cooling
Industry	Increase secondary aluminium production

[5] Ecofys, 2001. Data on greenhouse gas emission reduction options for 2010 for the Member States of the European Union. Data reported in: C.A. Hendriks, D. de Jager, K. Blok et al. Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change: Bottom-up Analysis of Emission Reduction Potentials and Costs for Greenhouse Gases in the EU, Ecofys Energy and Environment and AEA Technology, Utrecht, The Netherlands, January 2001.
[6] WEC (2000). World Energy Assessment: Energy and the challenge of sustainability. World Energy Council. Chapter 5. Energy Resources.

Industry	Efficient electricity use in the Chlorine industry
Industry	Efficient motor technologies
Households & Services	District heating and small-scale CHP
Coal fired power plants	Implement more efficient new power plants
Coal fired power plants	Fuel Switch: from coal to low carbon fuels
Coal fired power plants	Co-firing of biomass in existing coal plants
Coal fired power plants	CO -removal
Oil fired power plants	Retrofit existing oil fired power plants
Oil fired power plants	Implement more efficient new power plants
Oil fired power plants	Fuel Switch: from oil to low carbon fuels
Oil fired power plants	CO2-removal
Natural gas fired power plants	Implement more efficient new power plants
Natural gas fired power plants	CO -removal
Wind power	Increase installed capacity
Photovoltaic	Increase installed capacity
Solar Thermal Electricity	Increase installed capacity
Biomass	More biomass for electricity production
Small hydro (< 10 MWe)	Increase installed capacity
Large hydro (< 10 MWe)	Retrofit existing large hydro plants
Geothermal	Increase installed capacity

In the third step a 'realistic' emission reduction potential is determined for the years 2010 and 2020 compared to a Business-As-Usual (BAU) scenario. This realistic reduction potential lies between the technical reduction potential and the economic reduction potential. The technical reduction potential can be defined as the achievable savings resulting from the most effective combinations of the energy efficiency improvement options (and/or greenhouse gas emissions reduction options) available in the period under investigation. The economic reduction potential can be defined as the potential energy savings or emissions reduction that can be achieved at a net positive economic effect, i.e. the benefits of the measure are larger than the costs (Worrel, 1994)[7]. This is elaborated in section 4.6

A clear definition for a 'realistic' emission reduction potential is less straightforward. In this study the 'realistic' potential is obtained through:

- Assuming that progressive energy and greenhouse gas reduction policies are in place but accounting for policies in the field of liberalisation of the energy market and competitiveness.

[7] Worrell E (1994)/ Potential for Improved Use of Industrial Energy and Materials. PhD Thesis University of Utrecht, The Netherlands.

- Assuming that the electricity production capacity (including renewables), appliances and electrical engines will be replaced when reaching the end of their economic lifetime.
- Taking into account technical limits (like maximum share of secondary aluminium or contribution of wind to total electricity supply), supply limits, environmental constraints and when applicable cost constraints.

In the fourth step possible overall reduction targets are determined for the electricity production sector, reflecting realistic market ambitions and reduction potentials.

2.3 Definitions and Methodological issues

2.3.1 Business-As-Usual scenario

The Business-As-Usual (BAU) scenario is defined as the development in energy use and emissions up to 2020, assuming:

1. No large changes take place in the production and consumption structure of the current economy
2. All currently adopted energy and climate change policies are implemented.

The reduction potential of the emission reduction options is determined by assessing the additional implementation potential for each option compared to the BAU scenario, i.e. determining the difference between the 'realistic' implementation of the options and the penetration in the BAU scenario. The resulting CO_2 reduction of a certain option is thus additional to reductions resulting from the BAU scenario. For the European Union the European Energy Outlook (EC, 1999)[8] is used for the BAU scenario.

2.3.2 Determination of a realistic reduction potential

The third step of the methodology deals with determining a realistic reduction potential for each reduction option in the years 2010 and 2020, compared to the Business-As-Usual scenario. In this phase all reduction options are considered separately, without taking into account interactions between options and possible mutual exclusion of options. The total reduction potentials can thus NOT be based on a simple adding-up of individual reductions.

Reduction options for the demand side are defined in such a way that there is no (or limited) overlap between the options. This means that the total savings on electricity demand

[8] EC (1999). Energy in Europe. European Union Energy Outlook to 2020. Special Issue November 1999. The Shared Analysis Report

(in terms of TWhe of electricity consumed) can be determined by adding the reduction potential of the separate options.

Total reduction potential on the supply side cannot be determined by adding-up reduction potentials of individual options. On the one hand there is overlap with saving on the demand side (due to a decrease in the demand for electricity, less new capacity needs to be installed or old capacity can be taken out of operation earlier). On the other hand there is an overlap between options on the supply side (a fuel switch from coal to natural gas cannot be combined with a switch of the same plant to biomass).

The methodology thus requires a fourth step in which a rough estimate is made of the total reduction potential, taking into account the interaction between (demand and supply side) options.

2.3.3 Avoided CO_2 emissions

Figure 2 provides a schematic outline of the electricity systems. The electricity consumption in a region determines the amount of electricity that needs to be produced (corrected for import and export). The electricity can either be produced by means of fossil fuel fired power systems (coal, natural gas or oil), nuclear power plants or by means of renewable energy sources.

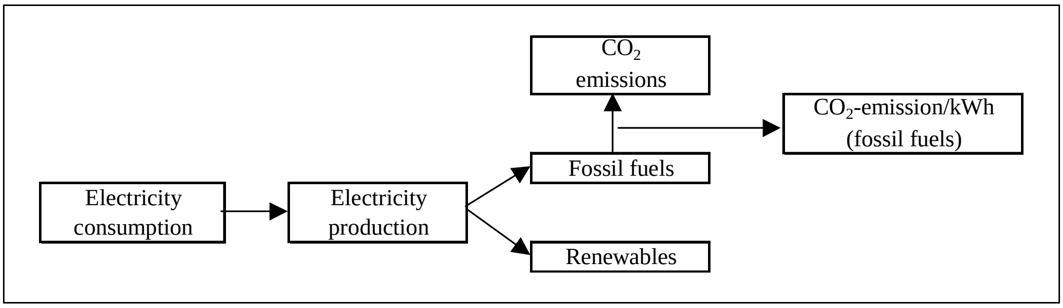

Figure 2 Outline of the electricity system

To calculate the avoided indirect CO_2 emissions of electricity savings on the demand side it is assumed that the marginal production capacity is avoided. This means that the avoided indirect CO_2 emission is equal to the CO_2 emission per kWh of the marginal production capacity in the BAU scenario multiplied by the electricity savings resulting from additional policies. [9]

[9] Of course the methodology of calculated avoided CO_2 emissions on the basis of avoided marginal production capacity only holds to the extent to which new (i.e. additional to existing) production capacity is avoided. When larger amounts of savings are implemented or large amounts of renewables are installed, existing fossil fuel production capacity will be replaced. Consequently, avoided emissions are then calculated on the basis of the average fuel mix of existing capacity.

To calculate the avoided amount of CO_2 resulting from the implementation of additional capacity of renewable energy sources, it is assumed that the marginal production capacity is avoided. The avoided CO_2 emissions due to retrofit, efficiency improvements with electricity production technologies, or co-firing of biomass that apply to specific fossil fuel electricity production technologies, is calculated by taking the CO_2 emission factor of this technology in the BAU scenario.

2.3.4 Uncertainties in results

To make an estimate of the emission reduction potential per option we used many different sources, and had to make a number of assumptions. This means that the results are surrounded by considerable uncertainties. We therefore present the reduction potential in ranges instead of one single number. The following emission reduction ranges are distinguished: < 1 Mtonne, 1-5 Mtonne, 5-10 Mtonne, 10-25 Mtonne, 25-50 Mtonne, and > 50 Mtonne.

3 Description of the reduction options

3.1 Introduction

This chapter contains a general description of the reduction options considered within this project. The description includes the general assumptions made to determine the possible saving potential. More detailed assumptions per region are included in the following chapter on the results for the European Union.

3.2 Supply side reduction options

The following supply side reduction options are described in detail below:

- Increased use of combined heat and power production
- Retrofitting of existing power production plants
- Fuel switch to low-carbon fuels
- Increase in energy efficiency of new power production plants
- CO_2 removal [10]
- Use of biomass for electricity production
- Increased wind power production
- Increase of other renewable electricity production (PV, solar thermal electricity, hydro power and geothermal electricity production)

3.2.1 Combined heat and power

Combined production of heat/steam and electric power - CHP - can result in energy savings when compared to the situation where heat/steam and electricity are generated separately (under the precondition that the heat/steam is usefully applied). To calculate the reduction potential for an increase in the installed amount of CHP several assumption per region are made with regard to:

1. Maximum share of heat and steam demand in the industry sector that can be covered with CHP. For all regions we assumed a maximum share CHP in the coverage of heat and steam for the industry of 80%.
2. Maximum share of heat and steam demand in the households and service sector that can be covered with CHP. For these sectors region specific assumptions were made

[10] While WWF does not support the full introduction of storage as a mitigation option, it believes that pilot projects and research are valid in order to address unresolved issues. CO_2 removal or storage is therefore included in this study as a back-up option.

with regard to the amount of heat that will be covered with CHP. The maximum share depends on the climate circumstances, as a substantial demand for heat is required in order to make district heating a profitable option.

3. Efficiency of the reference system. As a reference for the heat and steam production in the industry, a boiler efficiency of 80-90% is taken (depending on the region and the type of fuel used). The same assumptions were taken for the household and service sector. As a reference for the electricity production the marginal production capacity per region is taken, as this is the technology that will be replaced by the CHP plant (i.e. for the EU and the USA a natural gas fired power plant and for China and India a coal fired power plant).
4. Efficiency of the CHP systems. Regional specific assumptions are made with regards to type of fuel used and the power and heat efficiencies. E.g. for the EU it is most realistic to assume that most new CHP plants in industry will be natural gas fired with a power efficiency of 43% and a heat efficiency of 33%.

3.2.2 Retrofit of existing power plants

The BAU scenarios utilised are in most cases not very clear on its assumptions with regard to the retirement and retrofit rates of electricity production plants. The share of existing capacity (already there in 1995/1997) and new capacity in a future year is therefore difficult to determine from the BAU scenario. Coal-fired power plants have an average lifetime of 30 year, after which they are either put out of operation or undergo a full refurbishment. For natural gas and oil-fired power plants this term is somewhat shorter. We therefore assumed that each large-scale coal fired plant will either be retired or will be fully retrofitted after 30 years. For natural gas and oil fired power plants an average lifetime of 25 years is used. In this project we treat a fully refurbished as new capacity, because we assume that in a full refurbishment operation all options are in principle open, i.e. choice of the fuels, level of efficiency etc.

There is a whole range of retrofit options that can be applied to existing power stations for increasing their efficiency. These range from (small) plant modifications to major plant upgrades like conversion of a gas turbine to a combined cycle. The option “retrofit of existing power plants” only includes small plant modifications requiring relatively low capital costs (the large plant modifications are considered a part of a full refurbishment operation). According to IEA (1999)[11] improvement and refurbishment of a steam turbine results in an emission reduction of up to 2.3%. In analysing several detailed projects it is clear that increases in electricity output due to small refurbishment operations range from 2%-10% (Power Industry, 2002)[12]. We therefore assumed an average increase of 5% of the output of a coal and gas fired power plant due to the implementation of a mix of ‘small’ retrofit options.

[11] IEA (1999). Retrofit of Power Stations for Green House Gas Abatement: case studies. IEA Greenhouse Gas Programme. Report number PH3/18, October 1999.
[12] Power Industry (2002) http://www.power-technology.com/projects

3.2.3 Fuel switch to low carbon fuels

One option to reduce CO_2 emission from coal-fired power plants is to switch from high to low (or no) carbon fuels. Switching to no carbon fuels means the move towards biomass wind and other renewable energy (this option is discussed in section 3.2.5). The switch towards lower carbon fuels means that more natural gas is used for electricity production instead of coal and oil.

The easiest switch from coal to natural gas seems to be an increase in the amount of running hours of natural gas fired power plants, and a decrease in the amount of running of coal fired power plants. Natural gas fired power plants are currently mostly used at peak load plants, because they can be easily switched on and off. Natural gas fired plants therefore have a low number of yearly running hours compared to a coal fired power plant. Coal fired power plants are mostly used at base load capacity with a high number of running hours per year. Coal fired plants cannot easily be used as peak load capacity because it needs a substantial amount of time to switch it on and off. This is therefore not considered a realistic option.

Another option is to switch from coal to natural gas in existing coal fired power plants. This requires additional investments; according to Interlaboratory Working Group (Int, 2000)[13] the economics are in most cases not favourable with the current price levels of coal and natural gas. The additional investments do not level out the extra cost for natural gas compared to the cheap coal, and furthermore the sunk costs in the coal-fired power plant can make the switch very uneconomical. We however assumed that such a switch could take place if e.g. a high carbon tax is introduced. Switching to natural gas is of course restricted by the availability of natural gas and transmission capacity per region.

A third option is to implement new natural gas fired plants instead of new coal or oil fired power plants. Specific assumptions are made per region, in which it is checked if a further growth of natural gas consumption can be accommodated and if enough resources are available.

3.2.4 More efficient new power plants

During the last decades considerable improvement has been made in the energy efficiency performance of power plants. Nowadays new coal-fired power plants can obtain (fuel to power) efficiencies of over 45%. After the large-scale introduction of gas turbines and combined cycles in the eighties, the efficiency of natural gas-fired power plant improved considerably. New combined cycles may reach efficiencies up to 60%. When

[13] Int (2000). Scenarios for a Clean Energy Future. Oak Ridge, TN: Oak Ridge National Laboratory and Berkeley, CA: Lawrence Berkeley National Laboratory, USA.

new technologies are combined - for instance the integration of coal gasification and combined cycles (IGCC) - efficiencies of coal-fired power plants can be close to 50%[14].

We assumed that for the period 2004-2010 new gas-fired power plant could reach efficiencies of 58%, and for the period 2010-2020 an efficiency of 60%. For coal fired power plants we assumed that for the period 2001-2010 new coal fired power plants can reach efficiencies up to 45%, and that for the period 2010-2020 only IGCC will be introduced with an efficiency of 50%.

3.2.5 Biomass

The present global energy consumption of biomass is estimated at about 14% of the total energy consumption. In developing countries this share is significantly larger than in industrialised countries: 35% and 3% respectively (van den Broek, 2000)[15]. The larger part of the biomass used in developing countries is used for cooking and heating purposes. In 1999, worldwide about 3% of the fuel input for electricity production comes from biomass (EC, 2002)[16]. It must be noted that electricity is just one of the potential energy carriers and that biomass use for electricity production will have to *compete* with the use for heat production and (transport) fuel production.

The most important routes for the conversion of biomass into electricity are:

- Direct combustion. The biomass is directly burned in a boiler for the production of electricity or combined heat and electricity production.
- Gasification. Biomass is first converted into a gas by heating the biomass uder low oxygen conditions. Before burning the gas in an engine, turbine or boiler for electricity and/or heat generation the gas is cleaned up.
- Pyrolysis. Biomass is converted into a liquid fuel that can be stored for later use. Like with gasification the fuel can be used in an engine, turbine or boiler for the generation of electricity and/or heat.
- Anaerobic digestion. Through a biological process solid or liquid biomass is converted into a gas that can be used for electricity generation (this also includes the collection of landfill gas).

The most promising option for electricity generation at least up to 2010 is the *direct combustion* of biomass. The technique is commercially available, has relatively high conversion efficiency and has relatively low investment compared to the other conversion routes.

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[14] Chris Hendriks, David de Jager, Jeroen de Beer, Margreet van Brummelen, Kornelis Blok and Manon Kerssemeeckers (2001) Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change: Economic Evaluation of Reduction of Greenhouse Gases in the Energy Supply Sector in the EU. Ecofys, The Netherlands.

[15] Van den Broek, R (2000). Sustainability of Biomass Electricity systems. Ph D Thesis (page 141)

[16] EC (2002). 2001- Annual Energy Review. European Commission.

A promising option for the medium to short term for the direct combustion of biomass is *co-firing of biomass in existing power plants*. According to Eurelectric (1997)[17] co-firing has the advantage that (1) higher conversions efficiencies can be achieved compared to (the current) stand alone plants, (2) continuous supply of biomass is not necessary which provides a larger flexibility and (3) use can be made of the existing infrastructure. Biomass can either be co-fired directly or indirectly in power plants:

- *Direct* co-firing means that the biomass (sometimes after preliminary treatment) is mixed with the fuel and directly fired in the boiler. Direct co-firing can be implemented with existing *coal-fired* power plants, and is currently already widely applied. Direct co-firing is currently the most profitable option, because it only requires limited investments. In the current applications biomass is co-fired up to a maximum of 20% by mass (approximately 10% by energy input). Due to the direct co-firing of biomass the capacity of the plant is lower by ~5%-10%.
- *Indirect* co-firing means that biomass is first converted into either a gas or fluid by means of e.g. gasification or pyrolysis. In this case higher shares of biomass can be co-fired. Indirect co-firing can be implemented with coal-fired power plants and when a gas is produced it can also be implemented with gas-fired power plants. Due to the direct co-firing of biomass the capacity of the plant is lower by ~10%-20%. A Dutch utility company is currently making preparations to perform experiments with the gasification of biomass and burning the gas in a STEG. Indirect co-firing of biomass requires higher investment than direct co-firing. Besides, most techniques are not yet commercially available.

The current *stand-alone small-scale combustion plants* have relatively low conversion efficiencies, because of the relatively small scale of these plants compared to large-scale power plants. The advantage of small-scale stand-alone combustion plants however is that (1) they can be situated in the vicinity of the biomass resources, which lower the transportation cost for biomass and (2) they can be operated in CHP mode when the heat can be supplied locally, which increases the CO_2-savings.

A possibility to realise *large-scale biomass fired combustion plants,* with high conversion efficiencies against relatively low investments, is to convert (retired) power plants into biomass plants. In principle there are no technical limits to replace e.g. all coal input with biomass. The transformation costs are low compared to the construction of a new plant (about 80% lower)[18]. This also means that the biomass needs to be transported to places where the (old) power plants are located. This can lead to high transport costs if not enough biomass resources are in the vicinity of the plants. Due to the energy needed for transport it needs to be investigated if the option is still carbon neutral.

It is hard to tell which option (large or small scale) is most promising in which region. The economics and environmental impacts of small-scale and large-scale combustion

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[17] Eurelectric (1997). Co-firing of Biomass and Waste With Coal. Eurelectric, Brussels (Ref: 02003Ren9770)
[18] Van den Broek, R (2000). Sustainability of iomass Electricity Systems. Ph D Thesis (page 141)

will need to be judged on a project-by-project basis. In all cases the pros and cons will have to be weighed against each other, including issues such as:

- Do the higher efficiency and lower investment costs of large- scale (co)-combustion outweigh the probably higher transport cost.
- Is the large-scale project still carbon neutral when biomass has to be transported over large distances?
- Are the lower efficiency and higher investment costs of small-scale plants counter-balanced by low biomass cost and the possibility to put the heat to good use?

For the assessment of emission reductions for biomass we made some rough assumptions. It must be stressed that further in-depth analysis is needed to fully substantiate these assumptions. We assumed that:

- In the short term (until 2010) direct co-firing of biomass in existing coal-fired power plants will be the most promising options. For the period after 2010 indirect co-firing through gasification of biomass combined with STEG's will be implemented as well.
- The *most* exploited biomass options will be large-scale combustion of biomass. It is assumed that the higher transport cost will outweigh the higher efficiency and lower investment cost. It is furthermore assumed that the easiest options, transformation of retired coal-fired power plants into biomass plants, will be exploited first.

3.2.6 Wind power

The worldwide available potential for wind energy is large, estimated at 53,000 TWh/year. In fact, even if the share of land that is covered with wind turbines is restricted to 4%, the potential for wind amounts to 18,700 TWh/year (WEC, 2000)[6]. Availability of resources will not restrict increase in the installed capacity of wind turbines up to 2020. Furthermore numerous assessments have shown that wind capacity can penetrate up to a level of 20% of the total installed electricity capacity, without technical problems[19].

Countries with progressive policies for wind show growth rates in installed capacity over 30% per year[19][20]. Growth rates of 20-30% per year are very high for an industry manufacturing heavy equipment. The bottleneck for maintaining high growth rates is the ability of the industry to increase its manufacturing capacity. We assumed that the manufacturing industry is able to meet high growth rates of maximum 30% per year up to 2010. For the period 2010-2020 we assumed that the growth would slow in some regions, because the cheap and easily realisable potential has been implemented by then. For regions, which currently have a very limited amount of installed wind-power the annual growth is assumed to be 30% for the whole period up to 2020.

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[19] EWEA et al (1999) Wind Force 10. A Blueprint to Achieve 10% of the World Electricty From Wind by 2010.
[20] EC (2001). Renewable Energy Sources Statistics in the European Union. Data 1989-1998. Eurostat. Luxembourg.

3.2.7 Photovoltaic

The total installed world-wide capacity of PV in 2000 is approximatly 1000 MW_p (1 GW_p) of which 430 MW_p is grid-connected. It is hard to establish a realistic reduction potential for photovoltaic. In EU countries with progressive policies (i.e. either high feed-in tariffs or generous compensation schemes), annual growth rates of over 30% are realised. We assumed that on average for OECD countries growth rates of 30% per year can be realised for the period 2004-2010, and that the manufacturing industry is able to increase its production capacity accordingly. For the period 2010-2020 we assumed a slow down in growth in the OECD countries to 20% per year. Even with a high carbon tax photovoltaic is not expected to be able to compete with electricity production from other sources, at least not in OECD countries with most consumers connected to the grid. For the non-OECD countries we assumed that the growth rates is 20% per year for the whole period 2004-2020, because of high investments required for photovoltaic and shortage of investment capital.

3.2.8 Solar thermal electricity

Solar thermal electricity is currently an underdeveloped renewable energy technology. It is probably 20 years behind wind power in market evolution (WEC, 2000)[21]. In 1998 approximately 400 MW of solar thermal electricity capacity was installed, of which 350 MWe was installed in California. A recent study shows that the prospects for this technology are very promising, but as the market is still very immature it is hard to make realistic estimates on the installed amount in 2010 and 2020. We therefore took over the estimates on installed solar thermal power for 2010 and 2010 in Hofman *et al* (2002)[22], i.e. approximately 7 GWe in 2010 worldwide and 30-45 GWe in 2020.

3.2.9 Hydropower

We assumed no further exploitation of new large hydropower sites. The output of existing large hydro plants can however be increased through retrofitting of existing large-scale hydropower plants. The combined effect of improvements in technology, design and used materials results in increased efficiency and output, reduced losses, greater reliability and an extended service life. Alstrom (2002)[23] reports an average increase of 12% in the output of large hydropower plants resulting from refurbishment in the USA. For a hydro project in Switzerland an increase in output was reported of 4.4%[24]. We therefore

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[21] WEC (2000). World Energy Assessment: Energy and the Challenge of Sustainability. World Energy Council (chapter 5) (chapter 7)
[22] Hofman, Y, D de Jager, E Molenbroek, F Schillig, M Voogt (2002). The Potential of Solar Electricity to Reduce CO_2-Emissions. Ecofys, The Netherlands
[23] http://www.power.alstom.com/
[24] http://www.power-technology.com/projects/birsfelden/

assumed an average potential for refurbishment of existing large hydropower plants of 8%.

Most scenarios don't provide any information of the split between small and large-scale hydropower capacity. For those regions where information is available we assumed a very limited growth in large-scale capacity, evidently complying with socio-economic constraints as for instance put forward in the recommendations of the World Commission on Dams.

3.2.10 Geothermal

The worldwide resources of geothermal electricity are enormous. According to WEA (2000)[25] the world's useful accessible resources for electricity production account to approximately 12,000 TWh/year. For comparison in 1997 worldwide 44 TWh of electricity was produced by means of geothermal sources, of which 53% occurred in North America and 30% in Asia. The worldwide growth rate of geothermal thermal capacity was about 4% per year over the period 1990-1998. We made the rough assumption that given the large worldwide potential this growth rate can be doubled up to 2020.

3.2.11 CO_2-removal

In principle another way to reduce emissions of carbon dioxide is to recover and store the CO_2 . With CO_2 removal the objective is not to reduce the use of (carbon-rich) fossil fuels, but to separate the carbon component (often in the form of CO_2) and to store it underground to prevent it from entering the atmosphere. The storage potential of CO_2 is probably large. Worldwide the storage potential in oil and gas fields is estimated at about 500-1800 GtC[26].

While WWF does not, at this point, fully support the use of carbon storage due to a number of uncertainties that still exist, it does support pilot projects and research into the issue. For this reason, storage is included as an option in this analysis, but only one to show the future reductions that could be possible if the issues surrounding carbon storage are resolved and if meaningful deep and significant reduction targets are undertaken by industrialised countries.

Nowadays, the most intensively studied technology is the recovery from fossil fuel fired power plants and from natural gas winning activities. Another possibility could be to equip a biomass-fired power plant with a CO_2-removal unit. In this way a CO_2 sink

[25] WEC (2000). World Energy Assessment: Energy and the challenge of sustainability. World Energy Council (chapter 7)
[26] Holloway 1996 in Hendriks et al (2001)[14]

would be created; CO_2 would be taken out of the atmosphere, which would lead to a lowering of the CO_2 concentration.

It is very hard to make an estimate of a realistic emission reduction potential for CO_2 storage. Although there is a large reduction potential against potentially reasonable cost, a very limited number of projects have been realised so far. This means that we have no information on historical implementation trends. The implementation rate will depend strongly on progressive greenhouse gas policies and on the technologies needed to address issues such as leakage. We assumed that OECD countries start with a limited number of (demonstration) projects for CO_2-removal in the period up to 2010. For the period 2010-2020 we assume that all countries will take up CO_2-removal as a reduction option.

3.3 Demand side reduction options

The following demand side reduction options are described in detail below:
- Reduction of stand-by losses of household appliances
- Increased use of efficient appliances in households
- Efficient cooling for households
- Efficient lighting for households and services
- Recycling of aluminium
- Reduced electricity use in the Chlorine industry
- Efficiency motor technologies

3.3.1 Reduce stand-by losses in households

Several studies indicate that stand-by power losses are on average responsible for 5%-13% of the electricity use in households in OECD countries (Lebot *et al*, 2000)[27]. Replacement of existing appliances with those appliances having the lowest stand-by power losses would reduce standby power consumption by 72%. This more or less equals the savings when a maximum uniform standard for stand-by power is set of 1W, which is currently proposed for some policy programs. For the calculations we assume that as of 2004, the uniform standard of maximum 1W standby losses will be introduced. Furthermore we assumed that household appliances have an average lifetime of 15 years.

No information could be found on stand-by losses in the service sector. It can however be argued that there is a substantial reduction potential in this sector as well, because of the high penetration of appliances. We however included no estimates on reduction potential for this sector.

[27] Lebot B, A Meier, A Angelade (2000). Global Implication of Stand-by Power Use. IEA, France, LBNL, USA, Ademe, France (published in proceedings fo ACEEE Summer Study on Energy Efficiency in Buildings)

3.3.2 Efficient appliances

Appliances in *households* include wet appliances like washing machines, dishwashers and clothes dryers, and brown appliances like TV and VCR. Implementation of the current best practice can save approximately 30%[28] [29] on the average specific energy use of these appliances.

Most of the appliances in the *service sector* are typical office-appliances such as computers, monitors, printers and photocopiers. Office-appliances account for one of the fastest growing end-users of electricity in the service sector. Computers are responsible for the largest part of the electricity consumption. Electricity reduction can be achieved by power down management and LCD screens. The specific energy use of office-appliances can be reduced by 50% - 75%[28] through a combination of power management and LCD screens.

3.3.3 Efficient cooling

Efficient cooling in households consists of cold appliances like refrigerators, freezers and air conditioning equipment. Introduction of current best practice cooling equipment could lead to a specific electricity reduction of approximately 40%, compared to the current average level. In case new techniques are used, such as vacuum insulation, specific energy savings by 80% can be achieved compared to the current average energy consumption.[28]

The energy consumption for air conditioning has become significant in the services sector. Three tendencies are observed in the energy demand for cooling:

- Increase of the amount of equipment, causing higher cooling loads,
- Increased comfort demands, causing higher cooling loads,
- Increase of energy efficiency of lighting and equipment, causing lower cooling loads.

When these tendencies are taken into consideration it is expected that there will be an increased demand for cooling. There are generally two ways for energy conservation in this area: reducing the need for cooling and improving the efficiency of the cooling system. A variety of measures can be applied to reduce the specific electricity consumption for air conditioning.

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[28] Joosen S, K Blok (2001). Economic Evaluation of Sectoral Emission Reduction Objectives for Climate ChangeEconomic Evaluation of Carbon Dioxide Emission Reduction in the Household and Services Sectors in the EU. Ecofys Energy and Environment, AEA Technology Environment and National Technical University of Athens.

[29] Levine MD, JG Koomey, L Price, H Geller, S Nadel (1995). Electricity end-use efficiency: Experience with technologies, markets, and policies througout the world. Energy Vol 20, No 1.

3.3.4 Efficient lighting

Compact fluorescent lights (CFLs) are essentially folded fluorescent tubes. Nowadays there is an extensive assortment in shape and fitting. This means that in many cases CFLs can replace light bulbs. A CFL uses 60%-80%[28] [29] less energy compared to a standard light bulb, producing the same amount of light. We assumed a maximum penetration of 80% in the households sector.

Lighting in the services sector is mainly provided by three systems: incandescent lamps, fluorescent lighting and high-intensity discharge lighting. The following measures can conserve a considerable amount of energy:

- Incandescent lamps can be replaced by efficient fluorescent lamps (CFLs). CFLs can yield the same amount of light using 60-80% of the energy compared to ordinary incandescent lamps.
- The luminaire efficiency of all lamp types can be improved using better reflectors.
- A lighting control system detecting occupancy of a room or operating daylight or time independent can reduce the amount of burning hours.

The savings potential of the first two measures is determined to be 30%, and the total saving potential of all three measures is estimated to be 55%.

3.3.5 Recycling of aluminium

The production of primary aluminium from alumina (which is made out of bauxite) is a very energy-intensive process. It is produced by passing a direct current through a bath with alumina dissolved in a molten cryolite electrode. Another option is to produce aluminium out of recycled scrap. This is called secondary production. Secondary aluminium uses only 5 to 10% of the energy demand for primary production because it involves remelting of the metal instead of the electrochemical reduction process[30]. The share of secondary aluminium production in total aluminium production ranges from 97% in Japan to 2% in Oceania. It must be noted that the share of secondary aluminium production cannot be increased infinitely, because the product quality is affected by the use of scrap as a feedstock.

Just over 11.6 million tonnes of old and new scrap were recycled in 1998 worldwide, which fulfilled close to 40% of the global demand for aluminium. Of this total, 17% came from packaging. For example, Sweden and Switzerland have introduced successful recycling programmes for aluminium cans, respectively 92% and 88% of the aluminium cans are being recycled, 38% from transport, 32% from buildings and 13% from other products[31].

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[30] Phylipsen D, K Blok, E Worrell (1998). Handbook on International Comparison of Energy Efficiency in the Manufacturing Industry. Department of Science, Technology and Society, Utrecht University, The Netherlands.

[31] http://www.world-aluminium.org/environment/recycling/

Figures noted above show that the introduction of successful recycling system can increase recycling rates up to 90%. We assumed that this percentage can be met in Europe in 2020.

3.3.6 Reduce electricity use in the chlorine industry

Chlorine is produced by electrolysis of brine. Three different types of electrolysis processes are in operation: using a mercury flow, a diaphragm or an ion-selective membrane. Replacement of mercury by one of the other cell types is a way to reduce electricity consumption. The electricity demand of membrane and diaphragm cells is about 0.8-1.3 GJ/tonne chlorine lower than that of mercury cells (De Beer *et al*, 1994)[32] [33]. We assumed that capacity already in place in 1999 and making use of the mercury cell will either:

- Be retrofitted and converted to either diaphragm or membrane cells or
- Will be demolished and replaced by new capacity, which either makes use of diaphragm or membrane cells.

3.3.7 Efficient motor technologies

Electro-motors in the industry make up a large share of the electricity use in industry. Approximately 60% of the electricity use by industry is used to drive electro-motors. Several technologies are available to reduce electricity losses in motors including energy-efficient motors, electronic variable speed drives, and efficient mechanical transmissions systems. Annibal *et al* (1999)[34] and Nadel et al (1992)[35] conducted several studies aimed at estimating reduction potentials for different regions. The savings range from 10% to

[32] De Beer, J.G., M.T. van Wees, E. Worrell and K. Blok (1994). ICARUS 3 -The Potential for Energy Efficiency Improvement in the Netherlands up to 2000 and 2015, Department of Science, Technology and Society, Utrecht University.

[33] On the other hand, the heat demand for concentration of the alkali is about 0.5-1.0 GJ/tonne higher [Phylipsen et al., 1998][30]. We did not take this into account in our calculations.

[34] Annibal T. de Almeida, P Fonseca, F Ferreira (1999). Carbon Saving Potential of Enery-Efficient Motor Technologies in Central and Eastern Europe. Paper presented at the IEA International Workshop on Technologies to Reduce Greenhouse Gas Emissions. 5-7 May Washington, USA

[35] Nadel, S. M Shepard, S Greenberg, G Katz, Annibal T. de Almeida (1992). Energy Efficient Motor Systems. A Handbook on Technology, Program, and Policy Opportunities. American Council for an Energy Efficient Economy, Washington, DC, and Berkeley, California.

18% of the total electricity used in the industry. It must be noted that currently the penetration of more efficient electro-motors is growing very slowly. Some important barriers are described in Nadel et al (1992): they include lack of information within the industry and the fact that motors are only put out of operation once a motor has broken down.

4 Results for the European Union (EU)

4.1 Historic development in the electricity sector

Table 2 shows the historic development for some important indicators in the electricity sector in the European Union. The electricity production has on average increased 2% per year over the period 1990-1999. The increase is on the one hand caused by a growth in population of 0.3% per annum, and on the other hand by an increase in the amount of electricity consumed per capita. The CO_2 emissions due to electricity production have stabilised in the period 1990-1999, which means that the CO_2-intensity of electricity production has decreased. This was mainly caused by a decrease in coal consumption for electricity production and an increase in the consumption of natural gas (which simultaneously led to an increase in the average efficiency).

Table 2 Key indicator for the electricity sector in the European Union. Source: EC (2002)[36]

	Unit	1990	1995	1996	1997	1998	1999
CO_2-emissions electricity production	Mtonne	962	926	935	894	909	923
Electricity production	TWh	2,163	2,336	2,416	2,428	2,475	2,534
CO_2-intensity electricity production	kg CO_2/kWh	0.44	0.40	0.39	0.37	0.37	0.36
Electricity consumption per capita	kWh/capita	5,934	6,287	6,484	6,501	6,602	6,742

4.2 Business-As-Usual scenario

For the analysis of the emission reduction potential in the European Union we used the Business-As-Usual (BAU) Scenario of the European Energy Outlook (EC, 1999)[37]. The World Energy Outlook (IEA, 2000)[38] could not be used, as it does not provide figures on the level of European Union but only for Europe as a whole.

Main characteristics of the BAU-scenario of the European Energy Outlook are:

1. GDP growth of 2.3% per year for the period 2000-2010, and 1.8% per year for the period 2010-2020.
2. All EU policies currently in place will be continued. These include among others further improvement of energy technologies on the supply and demand side, continua-

[36] EC (2002). 2001- Annual Energy Review. European Commission.
[37] EC (1999). Energy in Europe. European Union Energy Outlook to 2020. Special Issue November 1999. The Shared Analysis Report
[38] IEA (2000) World Energy Outlook 2000. IEA/OECD, 2000

tion of support for renewable energy and co-generation and extension of the natural gas supply infrastructure.

The second assumption in the BAU scenario - that “all EU policies will be continued” - in our opinion results in too optimistic developments in the specific efficiency improvements for some sectors or applications in the BAU-scenario, and accordingly in very low additional reduction. We believe that the effect of current policies in place is in some cases overestimated. Therefore two cases were analysed for the EU:

1. *Standard* case: This provides the reduction potential per options compared to the BAU scenario of the European Energy Outlook, including the optimistic assumptions on the effect of current policies.
2. *Adapted* case: This provides the reduction potential per options compared to an ‘adapted’ BAU scenario. The ‘adapted’ BAU scenario describes the electricity use and CO_2 emission in case of ‘realistic’ estimate on the effect of current policies (the BAU scenario is e.g. adapted with regard to the effect of CHP policies and efficiency improvement of appliances). These two cases are explained below.

Table 3 provides an overview of the BAU development in the European Union (standard case).

Table 3 BAU scenario (standard case) for the electricity production sector in the European Union. Source: EC (1999)[39] and Harmelink *et al* (2002)[40 41]

	Electricity production (TWh)			Installed capacity (GWe)		
	1995	2010	2020	1995	2010	2020
coal	669	498	814	279	190	206
gas	324	1,084	1,316	46	254	385
oil	178	104	54	0	0	0
nuclear power	810	896	788	132	135	117
biomass	33	66	99	4	5	6
hydropower	286	309	334	107	111	112
wind	3	60	122	2	22	26
geothermal	2	6	5	1	2	2
solar/tide/other	0	0	1	0	0	0
total	2,306	3,024	3,531	570	717	872
	CO_2 intensity (kg CO_2/kWh)			CO_2 emissions (Mtonne)		
	1995	2010	2020	1995	2010	2020
total	0.50	0.39	0.40	1,149	1,190	1,411

In the BAU-scenario the amount of coal for electricity production decreases until 2010, and increases afterwards because it is assumed that coal will be more profitable as the price of natural gas increases. No growth is projected to take place in the amount of installed hydropower, whereas a strong growth is projected to take place in the use of wind power. The CO_2-intensity of the electricity production is expected to decrease from 0.5 kg/kWh in 1997 to 0.39 kg/kWh in 2010 and stabilise on this factor until 2020. Total CO_2 emissions from electricity production are estimated to increase to a level of 1400 Mtonne in 2020.

Table 4 holds an overview of the BAU development in electricity demand in the European Union. The table shows that electricity demand in all sectors is estimated to increase. Overall electricity consumption is projected to increase by 1.9% annually over the period 1995-2010, and by 1.6% annually over the period 2010-2020. Large growth in electricity consumption is expected to take place in the service sector due to continued penetration of cooling and an increase in the number of electric appliances, such as computers.

[39] EC (1999). Energy in Europe. European Union Energy Outlook to 2020. Special Issue November 1999. The Shared Analysis Report

[40] Data on installed amount of photovoltaic in the baseline scenario is taken from Harmelink et al (2002). PRETIR. Implementation of Renewable Energy in the European Union. Ecofys, 3E and Fraunhofer ISI.

[41] The BAU was adapted with regard to the phase out of nuclear energy. It was assumed that Germany, Belgium and Sweden will phase out large parts of their nuclear energy production capacity before 2020 and that no additional nuclear capacity will be installed as of 2003. Instead of 788 TWh of electricity produced with nuclear we took ~ 640 TWh. We assumed that the nuclear capacity will be replaced by more natural gas fired power stations.

Table 4 BAU scenario (standard case) in electricity demand in the European Union. Source: EC (1999)[42]

TWh	1995	2010	2020
Industry	858	1,046	1,122
Services	503	765	1,007
Households	582	747	873
Transport	55	100	111
Other	32	15	11
Total	2,030	2,673	3,124
Consumption per capita (kWh/cap)	**1995**	**2010**	**2020**
	5,456	6,970	8,121

4.3 Reduction potential for electricity consumption

Table 5 provides an overview of the estimated CO_2-reduction compared to the BAU scenario per option on the energy demand side in 2010 and 2020 for the European Union for the standard and adapted case.

Table 5 Estimated CO_2-reduction per option in 2010 and 2020 for the electricity demand side for the European Union compared to the standard BAU scenario and the adapted BAU scenario (Mtonne of CO_2)

No	Sector	Reduction option	2010 Standard	2020 Standard	2010 Adapted	2020 Adapted
1	Households	Efficient electric appliances	5-10	**10-25**	**10-25**	**25-50**
2	Households	Efficient cooling equipment	5-10	**10-25**	5-10	**25-50**
3	Households	Efficient lighting	1-5	5-10	Idem	Idem
4	Households	Reduce stand-by losses	1-5	**10-25**	Idem	Idem
5	Services	Efficient electric appliances	**10-25**	**25-50**	Idem	Idem
6	Services	Efficient lighting	**10-25**	**25-50**	**10-25**	**>50**
7	Services	Efficient cooling	1-5	**10-25**	Idem	Idem
8	Industry	Increase secundairy aluminium production	5-10	**10-25**	Idem	Idem
9	Industry	Efficient electricity use in the Chlorine industry	1-5	1-5	Idem	Idem
10	Industry	Efficient motor technologies	5-10	**>50**	Idem	Idem

Table 5 shows that large reduction potential can be achieved through (numbers refer to the numbers of the options in Table 5):

1,2 The implementation of best practice appliances and cooling equipment in the household sector.

3 The introduction of appliances with low stand-by losses (< 1W) in the household sector.

4-6 The introduction of energy efficient office equipment, lighting and cooling.

8 Increasing the amount of recycled aluminium to 90%.

10 The introduction of energy efficient motors in the industry.

[42] EC (1999). Energy in Europe. European Union Energy Outlook to 2020. Special Issue November 1999. The Shared Analysis Report

Total additional electricity savings (compared to the standard BAU scenario) amount to approximately 270 TWh in 2010, and 750 TWh in 2020[43]. This is equal to a saving of 9% on the total electricity consumption in 2010 and 27% in 2020. The savings for the year 2020 are illustrated in Figure 3.

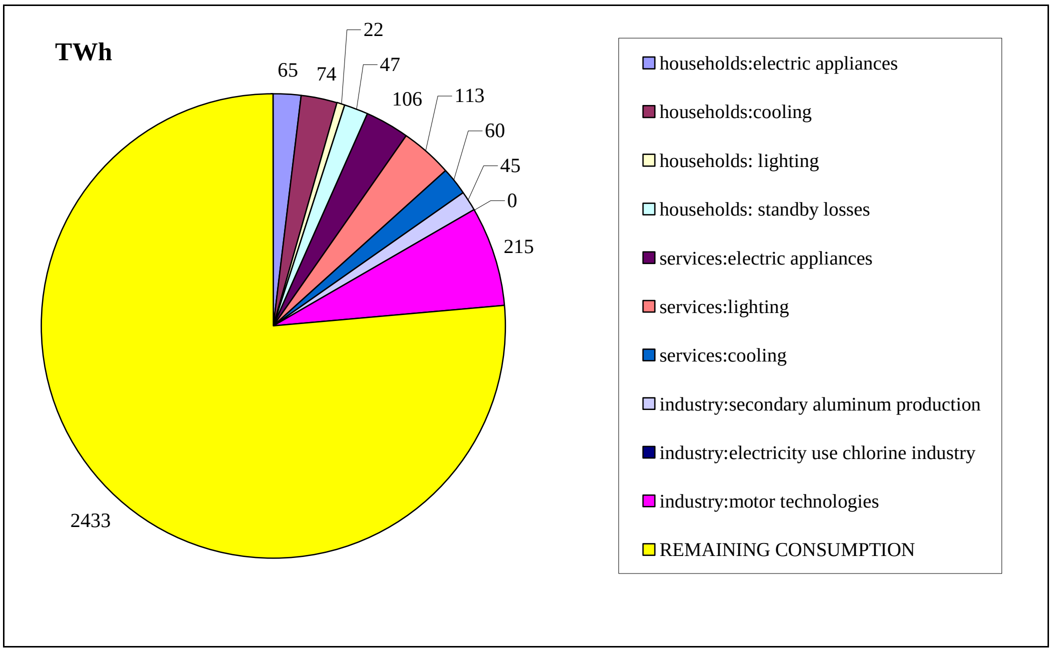

Figure 3 Additional electricity demand savings in the year 2020 compared to the BAU scenario for the European Union (TWhe)

4.4 Reduction potential on the supply side

The BAU scenario already includes several supply-side reduction options, of which the main options are:

- Energy efficiency improvements of existing fossil fuel production capacity
- Fuel switch from coal (and oil) to gas
- Increased share of renewable electricity production

Table 6 provides an overview of the estimated additional supply-side CO_2-reductions compared to the BAU scenario. The reduction potentials for the European Union are for the years 2010 and 2020 for the standard and adapted case.

[43] These data concern savings in electricity consumption. To determine avoided electricity production we corrected these numbers for transmission and distribution losses (11%).

Table 6 Estimated CO_2-reductions (in Mtonne CO2) from supply side options relative to the BAU scenario in the European Union.

No	Sector	Reduction option	2010 Standard	2020 Standard	2010 Adapted	2020 Adapted
1	Industry	Increase the amount of CHP	10-25	10-25	10-25	25-50
2	Households & Sevices	District heating and small-scale CHP	<1	<1	25-50	25-50
3	Coal fired power plants	Retrofit existing coal fired power plants	<1	<1	Idem	Idem
4	Coal fired power plants	Implement more efficient new power plants	<1	<1	Idem	Idem
5	Coal fired power plants	Fuel Switch: from coal to low carbon fuels	<1	>50	Idem	Idem
6	Coal fired power plants	Co-firing of biomass in existing coal plants	>50	25-50	Idem	Idem
7	Coal fired power plants	CO2-removal	10-25	>50	Idem	Idem
8	Oil fired power plants	Retrofit existing oil fired power plants	<1	<1	Idem	Idem
9	Oil fired power plants	Implement more efficient new power plants	<1	<1	Idem	Idem
10	Oil fired power plants	Fuel Switch: from oil to low carbon fuels	<1	<1	Idem	Idem
11	Oil fired power plants	CO2-removal	<1	<1	Idem	Idem
12	Natural gas fired power plants	Implement more efficient new power plants	<1	<1	10-25	10-25
13	Natural gas fired power plants	CO2-removal	1-5	10-25	Idem	Idem
14	Wind power	Increase installed capacity	10-25	>50	Idem	Idem
15	Photovoltaic	Increase installed capacity	1-5	5-10	Idem	Idem
16	Solar Thermal Electricity	Increase installed capacity	<1	1-5	Idem	Idem
17	Biomass	More biomass for electricity production	25-50	>50	Idem	Idem
18	Small hydro (< 10 MWe)	Increase installed capacity	5-10	5-10	Idem	Idem
19	Large hydro (< 10 MWe)	Retrofit existing large hydro plants	1-5	5-10	Idem	Idem
20	Geothermal	Increase installed capacity	1-5	1-5	Idem	Idem

The main additional supply side reduction options are:

- Increase of the amount of CHP production
- Additional fuel switching from coal (and oil) to gas
- Co-firing of biomass in existing coal-fired plants, especially lignite plants
- Increased use of wind and biomass for electricity production
- CO_2 removal

The Details on the reduction potentials and the underlying assumptions are included in Annex I.

4.5 Possibilities for carbon neutral electricity production

This section explores the possibilities for starting the introduction of a carbon neutral electricity system in the European Union. We examine the possibilities for new or retrofitted capacity to be carbon neutral in the period 2010-2020. The possibilities for carbon neutral electricity were examined on the basis of the following assumptions:

- High uncertainties exist on the implementation level of demand side electricity saving measures. Therefore two scenarios are used: a *high scenario* in which these demand side savings are very successful (i.e. the full reduction potential is achieved both in 2010 and 2020), and a *low scenario* in which only 1/3 of the full reduction potential is achieved.
- Existing large-scale coal fired plants will either be taken out of operation, or will undergo a full refurbishment after 30 years. For natural gas fired power plants the time period used is 25 years.

- The potential for wind, solar (photovoltaic, solar electricity), geothermal, hydro and co-firing of biomass in existing power plants will be fully exploited.
- Additional electricity production with biomass will be the key option to make new or retrofitted capacity carbon neutral in the period 2010-2020. If this is not sufficient to reach the targets set, CO_2-storage is considered.

Based on the analysis in earlier sections, the following consecutive steps are taken to determine the possibility of a carbon neutral electricity production:

- Determine electricity demand and supply side emission savings in the BAU scenario
- Calculate additional demand side emission savings (see section 4.3)
- Determine additional renewable electricity potential (see section 4.4)
- Calculate additional opportunities to switch to low-carbon fuels in existing fossil fuel production capacity (including co-firing of biomass)
- Calculate additional potential for using biomass in new power production plants
- (If necessary) use carbon storage

Figure 4 pictures the resulting CO_2 emissions from electricity production in the BAU and for the High Power Switch Scenario. The figure shows that in the high Power Switch scenario emission can be reduced by 50% in 2020 compared to 1997.

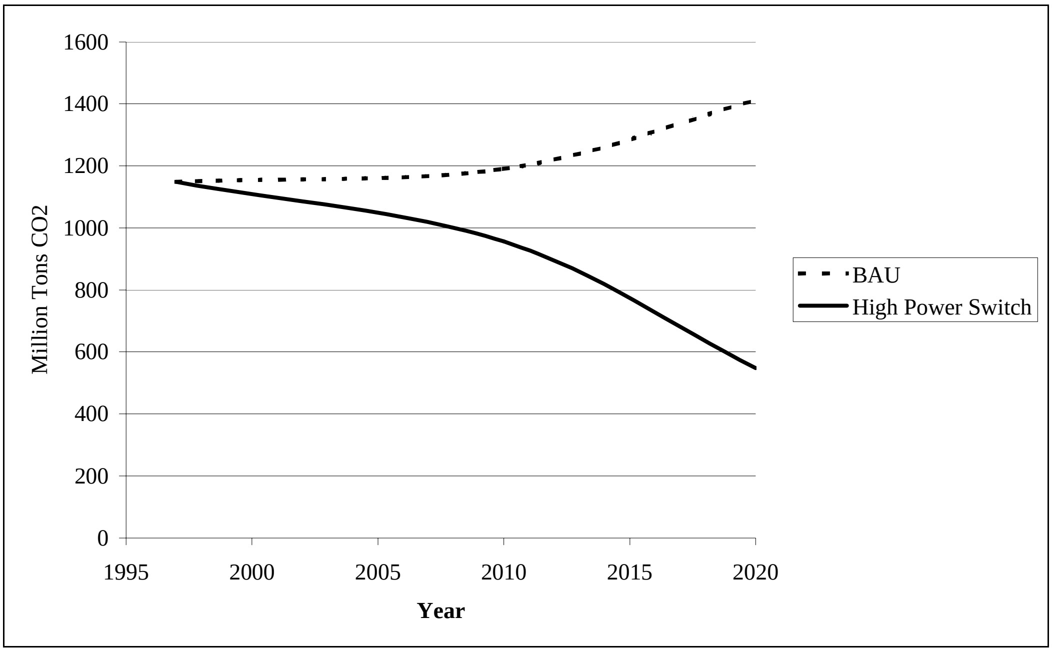

Figure 4 CO_2 emissions in the European Union in the BAU scenario and in the High Power Switch scenario.

Figure 5 pictures the corresponding electricity production in 1997 and in 2020 for the BAU and the High Power Switch Scenario. The picture shows that the crucial renewable energy options for 2020 are wind and biomass. The results of our analyses indicate that the overall share of renewable electricity production (including large hydro) will have to increase to approx. 26% in 2010 and 60% in 2020 (excluding large hydro these figures are 14% in 2010 and 47% in 2020).

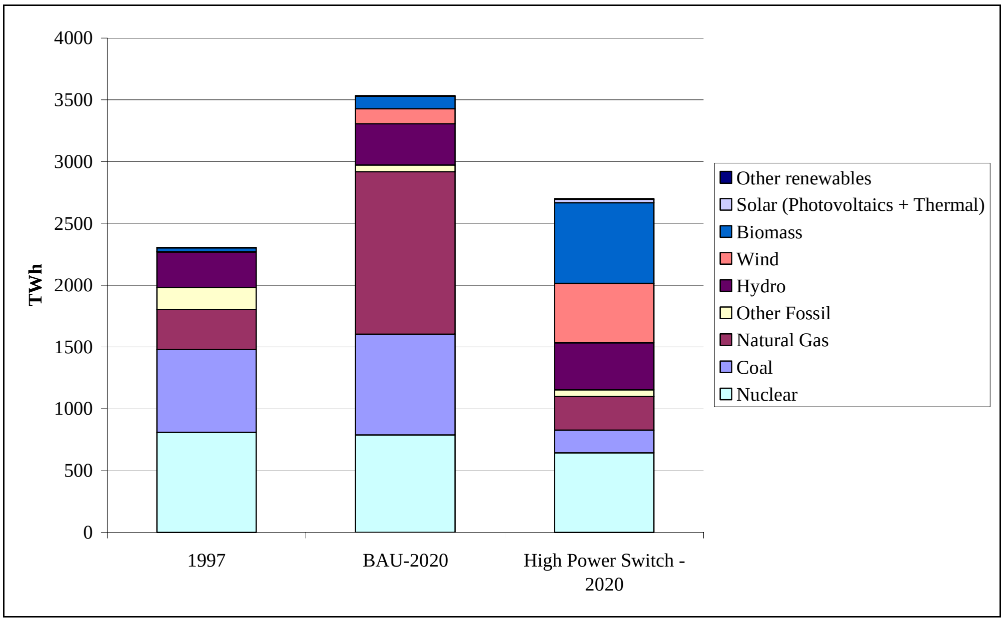

Figure 5 Electricity production in 1997 and in 2020 in the BAU and for the High Power Switch scenario.

4.6 The costs of low-carbon electricity systems

The aim of this study was to sketch a broad outline of a low-carbon electricity system for the European Union. A detailed economic analysis is beyond the scope of this study. However, a brief discussion of the costs of a transition to a low-carbon electricity system may be useful.

A low-carbon electricity system may be attained through demand-side and supply-side measures. On the basis of several studies carried out for a variety of situations[44], we can provide the following considerations.

[44] See for instance the following reports:
Nadel, S., M. Shepard, S. Greenberg, G. Katx, A.T. de Alemida (1992). Energy Efficient Motor Systems. A Handbook on Technology, Program, and Policy Opportunities. American Council for an Energy Efficient Economy, Washington, DC and Berkeley, California.
B. Metz, O. Davidson, R. Swart, J. Pan: Climate Change 2001: Mitigation, Contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK, 2001.
Hendriks, C., D. de Jager, J. de Beer, M. van Brummelen, K. Blok and M. Kerssemeeckers, Economic Evaluation of Emission Reduction of Greenhouse Gases in the Energy Supply Sector in the EU – Bottom-up Analysis, European Commission, DG Environment, http://europa.eu.int.comm/environment/enveco.

Demand-side measures mainly are measures to improve the energy efficiency of lighting, electric appliances, and motor systems. A range of studies has shown that a substantial potential for these measures exist where the benefits over the lifetime of the measures are larger than the costs. Therefore, we expect that the net costs for the energy user will be modest or even negligible.

However, there may be costs for governments or other agencies to stimulate the adoption of the new technologies; in addition there may be transaction costs for the energy users. The magnitude of these costs highly depends on the policy instruments that are used for stimulating the energy-efficient technologies. For instance, if investment subsidies are offered, the costs for the government will be higher than when efficiency standards are implemented.

The main *supply-side measures* are biomass energy, wind energy and carbon dioxide removal. In all the cases the costs for power production are expected to be higher than those of conventional power generation. This most probably will always remain the case for carbon dioxide removal. For the renewable energy sources it is expected that technological learning will occur, leading to lower costs per unit of electricity production in the long run. However, for the period considered 2010 or even 2020 it is not likely that competitiveness will be attained. Many factors have influence on the net costs of adding more renewables or carbon dioxide removal, e.g. fossil fuel prices, the supply and demand situation on the EU electricity market, the rate of technological development in the area of renewables etc. Therefore, the costs for the supply side options are uncertain.

- For biomass electricity costs depend on the development of conversion technology and biomass prices – they may range from 10 – 60 € per tonne of CO_2 avoided[45].
- For wind electricity costs depend on the learning rates for wind turbine technology, but also on siting policies. Some estimate that costs might come down to those of conventional electricity by 2020[46]. We expect that learning will be less fast and partly offset by the need to use less windy sites; costs could be between 20 and 40 € per tonne of CO2 avoided.
- For carbon dioxide removal costs are estimated to be mainly between 20 and 50 € per tonne of CO_2 avoided[47]. For large scale project the costs can even be lower with favourable transport and storage conditions but costs can also be much higher in case of small projects and large transport distances.

From these figures we see that supply-side options typically will cost between 10 and 50 € per tonne of CO_2 avoided (all are calculated at social discount rates). We assume that in 2010 costs will be rather in the higher end of the range and in 2020 in the lower end. For

[45] Derived from: R. van den Broek (2000). Sustainability of Biomass Electricity Systems, Ph.D. Thesis, Utrecht University.
[46] EWEA/Greenpeace (2001). Wind Force 12 – A Blueprint to Achieve 12% of the World's Eelectricity from Wind Power by 2020, EWEA, Brussels.
[47] C.A. Hendriks, W. Graus, F. van Bergen (2002). Global Carbon Dioxide Storage Potential and Costs, Ecofys, Utrecht, The Netherlands.

the images presented in the Power Switch scenario these options are utilized for about 100 Mtonne of CO_2 emission reduction in 2010 and about 700 Mtonne in 2020. This translates to costs on the order of 10 € per capita per year in 2010 and on the order of 30 € per capita in 2020.

An important synergetic effect is that strong efforts to improve energy efficiency on the demand side will have a downward pressure on the electricity prices in the European Union. Hence – despite higher average production costs in a low-carbon development – it might well be that the total costs of the electricity production/consumption system remain the same or even decrease. Further analysis should determine whether this will be the case.

4.7 Conclusions

The following key overall conclusions are drawn:

- The *potential for additional electricity savings on the demand side* (compared to the BAU scenario) ranges from 9% in 2010 to 27% in 2020. In the scenario with a low level of electricity savings – assuming only 1/3 of the full savings potential is implemented – results in 4% savings by 2010 and 11% savings by 2020.
- The estimated *potential for renewable electricity production* is 587 TWh in 2010 to 1158 TWh in 2020. This results in an overall share of 25% renewables by 2010 and approx. 60% renewables by 2020 (including large hydro). The main share of this potential must comes from co-firing of biomass (16 GWe in 2010, and 9 GWe in 2020) and from wind (60 GWe in 2010, and 150 GWe in 2020).
- Implementing more biomass-fired plants, and/or storing the emitted CO_2 in the underground can reduce the emissions of the new or retrofitted plants. Assuming that the White Paper target of 135 Mtoe[48] biomass fuel input will be met in 2010, and that in the period 2010-2020 electricity production through biomass grows with 10% per year respectively, 32 Mtonne of CO_2 is avoided in 2010 and 180 Mtonne in 2020. This means that in 2010 approximately 40 GWe additional (compared to the BAU scenario) biomass capacity needs to be installed, and in 2020 approximately 225 GWe. With regard to CO_2-removal we assumed 10 experiments before 2010, and 40 additional plants with CO_2-removal after 2010.
- In the case of full implementation of the electricity saving potential on the demand side (the high scenario), and almost full implementation of the biomass potential, CO_2-storage is not necessary in the period 2010-2020 to reach carbon neutrality for new or retrofitted capacity (the share of renewable reaches a level of 60% of total electricity production (including large hydro)).

[48] European Commission, Energy for the Future: renewable sources of energy, White Paper for a Community Strategy and Action PLan, COM(1997)599 final, 26.11.1997.
1Mtoe equals 41.9 PJ

- In case of disappointing savings on the demand side, an additional reductions of CO_2 is needed in the period 2010-2020 to reach carbon neutrality for new or retrofitted capacity.
- Instead of implementing additional biomass it is also possible to implement additional CHP. Each kWh of electricity produced by means of CHP saves between 0.07 – 0.32 kg CO_2/kWh (all savings attributed to electricity). Additional electricity production through biomass saves 0.34 – 1.0 kg CO_2/kWh. This means that instead of implementing 1 MWe of biomass capacity, 3 MWe of CHP should be installed to reach the same reduction.

Annex I: Detailed results of supply-side emission reductions

Table 7 in section 4.4 lists the additional supply side CO_2-reductions compared to the BAU scenario. This annex contains background information on the estimated CO_2 reductions

Table 7 Estimated additional CO_2-reductions from supply side options (Mtonne CO2). Data for the European Union; years 2010 and 2020.

No	Sector	Reduction option	2010 Standard	2020 Standard	2010 Adapted	2020 Adapted
1	Industry	Increase the amount of CHP	**10-25**	**10-25**	**10-25**	**25-50**
2	Households & Sevices	District heating and small-scale CHP	<1	<1	**25-50**	**25-50**
3	Coal fired power plants	Retrofit existing coal fired power plants	<1	<1	Idem	Idem
4	Coal fired power plants	Implement more efficient new power plants	<1	<1	Idem	Idem
5	Coal fired power plants	Fuel Switch: from coal to low carbon fuels	<1	**>50**	Idem	Idem
6	Coal fired power plants	Co-firing of biomass in existing coal plants	**>50**	**25-50**	Idem	Idem
7	Coal fired power plants	CO2-removal	**10-25**	**>50**	Idem	Idem
8	Oil fired power plants	Retrofit existing oil fired power plants	<1	<1	Idem	Idem
9	Oil fired power plants	Implement more efficient new power plants	<1	<1	Idem	Idem
10	Oil fired power plants	Fuel Switch: from oil to low carbon fuels	<1	<1	Idem	Idem
11	Oil fired power plants	CO2-removal	<1	<1	Idem	Idem
12	Natural gas fired power plants	Implement more efficient new power plants	<1	<1	**10-25**	**10-25**
13	Natural gas fired power plants	CO2-removal	1-5	**10-25**	Idem	Idem
14	Wind power	Increase installed capacity	**10-25**	**>50**	Idem	Idem
15	Photovoltaic	Increase installed capacity	1-5	5-10	Idem	Idem
16	Solar Thermal Electricity	Increase installed capacity	<1	1-5	Idem	Idem
17	Biomass	More biomass for electricity production	**25-50**	**>50**	Idem	Idem
18	Small hydro (< 10 MWe)	Increase installed capacity	5-10	5-10	Idem	Idem
19	Large hydro (< 10 MWe)	Retrofit existing large hydro plants	1-5	5-10	Idem	Idem
20	Geothermal	Increase installed capacity	1-5	1-5	Idem	Idem

Table 6 shows that (numbers refer to the numbers of the options in Table 6):

1 A large reduction potential exists for *CHP in industry*. Given the investment climate for CHP in the EU after liberalisation of the energy markets, it is very questionable that any growth in CHP capacity will take place. In the adapted BAU we therefore assumed that the CHP would stay on the current level (for the industry a coverage of approximately 45%). It is assumed that all new CHP plants in the industry will be natural gas fired with a power efficiency of 43% and a heat efficiency of 33%. For the reference system a natural gas fired boiler with an efficiency of 90% is taken, and for the electricity production a natural gas fired plant with an efficiency of 55%. If instead of taking the marginal production capacity for electricity the mix is taken in 2010 and 2020, the reduction potential increases with a factor 2 to 3.

2 A substantial reduction potential exists for *CHP in the service sector*. The reduction potential for *CHP in the service sector* is much harder to determine because of

lack of good data in the BAU scenario. Hendriks et al (2001)[49] calculated a reduction potential for CHP in the residential and service sector of 31 Mtonne in 2010. They used an approach comparable to the one we used to determine the potential for CHP in the industry, and therefore considered this a realistic potential.

3 There is (almost) no additional potential for CO_2-reduction through '*small' retrofit improvements of existing coal-fired power plants*. A large part of existing coal fired power plants will be demolished in the period 1995-2020. This means that the most inefficient plants will be closed and that the potential for retrofit of existing plants is very small.

4 No additional reduction potential exists from *more efficient new coal fired power plants*. In the period up to 2010 the BAU scenario assumes that no new coal fired power plants will be build but it is assumed that they already have a very high efficiency.

5 A large additional reduction potential exists for *fuel switch to low carbon fuels*. For the period 2010-2020 it is assumed that instead of building or retrofitting new coal fired plants, new gas fired will be installed. This brings with it an increase in the growth of installed natural gas fired capacity.

6 There is a large reduction potential for *co-firing of biomass in existing coal power plants*. It is assumed that biomass will be co-fired in existing coal power plants up to maximum of 11% (energy based). This means that in 2010 approximately 47 TWh electricity is produced by means of co-fired biomass in existing coal power plants, and in 2010 approximately 34 TWh.

7, 13 If issues of uncertainty and others are resolved, there is a large reduction potential for *CO_2-removal* in the period 2010-2020. It is assumed that 10 full-scale experiments with CO_2-removal will be implemented in Europe before 2010: 5 with coal fired power plants and 5 with natural gas fired power plants. For the period 2010-2020 it is assumed that additional 40 full-scale projects will be realised (20 with coal fired power plants and 20 with natural gas fired power plant). This means that in 2010 ~4.5GWe of production capacity is equipped with CO2 removal, and ~22,5 GWe in 2020.

8-11 There is no reduction potential in *oil fired power plants*. No new investments in oil fired power plants are planned, and the total installed capacity decreases at 6-8% per year. We therefore assumed that investments in reduction options for oil fired power plants will not be made.

12 Introduction of *more efficient new natural gas fired power plants* may result in small additional emission reductions. The BAU scenario assumes that new installed plants are already very efficient. It can be questioned if these very efficient plants will actually be installed. In the adapted baseline scenario we assume that the efficiency of new installed plants will be 2%-point lower than assumed in the standard scenario.

[49] Chris Hendriks, David de Jager, Jeroen de Beer, Margreet van Brummelen, Kornelis Blok and Manon Kerssemeeckers (2001) Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change: Economic Evaluation of Reduction of Greenhouse Gases in the Energy Supply Sector in the EU. Ecofys, The Netherlands.

14 A large reduction potential exists for *wind power* after 2010. The installed amount for 2010 is projected to increase to 60 GWe, and a further growth of 18% per year for the period 2010-2010 amounting to 150 GWe in 2020 (of which about 30% is offshore) in 2020. This is equal to the projections of EWEA (2002)[50]. The amount in 2010 exceeds the White Paper target of 40 GWe.

15 The reduction potential from *photovoltaics* up to 2020 is very limited. For 2010 the projected installed amount is 3 GWe, equalling the White Paper target. For the period 2010-2020 a growth of 20% is assumed leading to an installed amount of 16 GWe in 2020.

16 *Solar Thermal Electricity* may contribute only to a limited extent in reducing emissions up to 2010. The study of Hoffman *et al* (2002)[22] shows that the European Union does not have very favourable conditions for solar thermal electricity compared to other world regions. It is therefore assumed that 10% of the total predicted global potential for solar thermal power will be installed in the EU[51].

17 A large reduction potential exists for electricity production from *biomass*. For 2010 it is assumed that the White Paper Target of 230 TWh is going to be met, and that this will be met by means of co-firing, and transformation of retired coal-fired power plants into biomass-fired plants. In order to meet the White Paper target in 2010 approximately 80 old coal power plants (~50 GWe) need to be transformed into biomass plants (about 2/3/ of the capacity that is going to be taken out of production). The total production of 230 TWh requires an input of biomass of approximately 3.2 Exajoule. Therefore, meeting the target of 230 TWh in 2010 requires biomass electricity generation to grow by 25% annually over the period 2003-2010. The growth in the period 1995-1999 was approximately 10% per year. For the period 2010-2020 we assumed a growth of 10% per year in electricity production through biomass sources, realised through large scale biomass powered plants (50% through transformation of large-scale fired coal fired power plants and 50% through gasification and firing the gas in a gas turbine). This would require a total input of biomass of approximately 6 Exajoule. The total electricity production through biomass sources amounts to 600 TWh. For comparison the practical attainable potential when all residuals are used in Western Europe are estimated at 458 TWh[52].

18 There is a modest reduction potential for *small hydro*. It is assumed that the White Paper target of 14 GWe in 2010 will be met, and that in the period 2010-2020 a growth of 2.5% per year will be realised.

19 In most EU Member States the potential sites for *large hydropower* production within current environmental constraints are fully saturated. Some existing production facilities may increase their production output through retrofitting or increase of operating hours. A small reduction potential is thus assumed from increase in the output of existing large hydropower plants. New locations are not foreseen.

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50 www.ewea.org

51 Hofman et al (2002). The Potential of Solar Electricity to Reduce CO_2 Emissions. Ecofys, The Netherlands (commissioned by IEA)

52 UCE (2000). GRAINS: Global Restrictions on Biomass Availability for Imports to the Netherlands. Utrecht Centre for Energy Reseach, Utrecht, The Netherlands (August 2000).

20 A limited reduction potential exists from increased use of *geothermal electricity*. It is assumed that for 2010 the White Paper target of 7 GWe will be met, and that up to 2010 an annual growth rate of 8% will be realised.