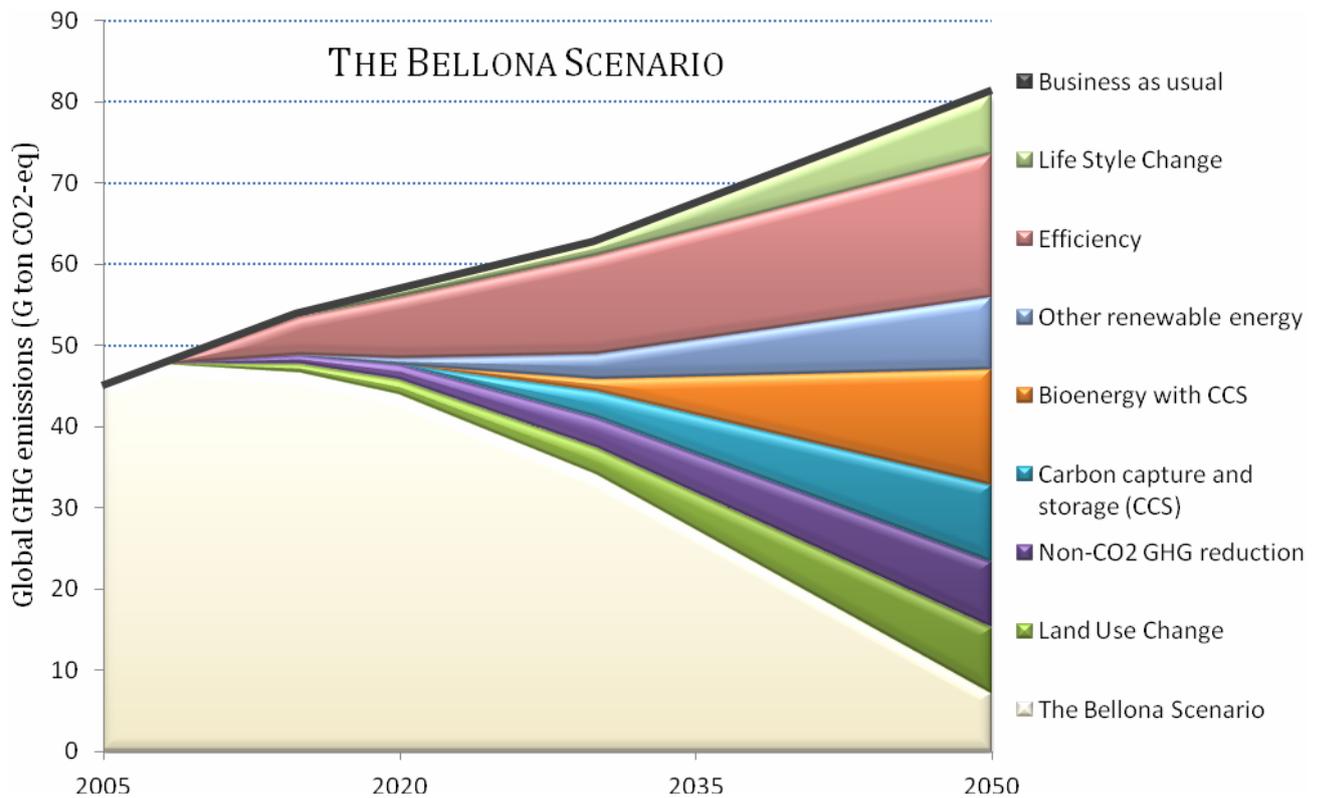


How to Combat Global Warming

- An ambitious but necessary approach to reduce greenhouse gas emissions



Prepared by the Bellona Foundation for the CC8 Conference,
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- An ambitious but necessary approach to reduce greenhouse gas emissions

Working paper prepared by the Energy and Climate
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Foreword

It is time to get serious about combating global warming!

Yes, it is a tremendous challenge, but it is not insurmountable. The very same human ability and industrial capacity that created the problem can solve it.

But we have to act now. We must encourage political and industrial leaders who are ready to commit their countries and companies to take on ambitious emission reductions to move forward. And even more importantly, we must commit to combat global warming at the United Nations Climate Change Conference in Copenhagen in December 2009.

Striking a fair but ambitious global deal on climate change will take great political courage. There are as many political priorities as there are players, and previous negotiations have generally proven very disappointing. This, I believe, has in part been due to a belief that combating global warming is just too big a challenge.

This apathy is not only destructive – it is also unfounded: As the Bellona Scenario shows, the necessary technologies and industrial practices already exist.

Since 1986 Bellona has been working to go from pollution to solution. We acquired our first electric car in 1989, we started looking into carbon capture and storage in 1992 and we have worked on fuel-cell powered ships since 2000. At the time of the Kyoto negotiations in 1997, none of these technologies were thought to be able to play any role in combating global warming. Now they are showing us that combating global warming really is possible. Imagine what solutions would come to the rescue in the future, once we truly make a global commitment!

One exciting opportunity is to combine algae bioenergy with carbon capture and storage to produce *carbon negative* power. Whether you were watching TV, vacuuming the house, or driving your electric car to visit friends and family, you would be *removing* CO₂ from the atmosphere! How exciting is *that*?

Funding for developing and demonstrating more climate solutions must be drastically increased and sustained over time. Market conditions must be changed to reflect the urgency of combating global warming, and investment in climate-friendly technologies must be made financially attractive. But most importantly, we must commit to a schedule for reducing emissions to the necessary level by 2050.

It is time political leaders across the globe step up to the challenge – failure is *not* an option.

Frederic Hauge

President of the Bellona Foundation
30 May 2008



Photo: Dag Thorenfeldt

Executive Summary

DRASTIC CUTS IN GREENHOUSE GAS EMISSIONS ARE ESSENTIAL

The fact that global warming is already taking place and is a problem caused by human activity is firmly established by an increasing number of scientific sources, amongst them the Intergovernmental Panel on Climate Change (IPCC).

Failing to tackle global warming could have dramatic consequences. Rising sea levels, retreating glaciers, and increased frequency of droughts, floods and tropical storms would put half of the world's species at the risk of extinction and hundreds of millions of people in desperate need of food and water.

To have a reasonable chance of avoiding such dire consequences, the global average temperature must not increase by more than 2 degrees Celsius above the pre-industrial level. According to the IPCC, this necessitates an overall 50 – 85 percent reduction of global greenhouse gas emissions from 2000 to 2050 with the peak in emissions occurring between 2000 and 2015.

There are several reasons to aim for reductions in the higher end of this interval. Firstly, emissions have increased steadily by 3 percent per year since 2000, so a peak by 2015 might be hard to achieve. A delayed peak in emissions means that the reduction target must be set relatively higher. Secondly, as the IPCC points out, the emission reductions necessary to meet a particular stabilisation level may have been underestimated owing to missing carbon cycle feedbacks.

We therefore assume, for the purpose of this study, that an 85 percent reduction from the current emission level must be achieved to combat global warming.

HOW TO COMBAT GLOBAL WARMING: - THE BELLONA SCENARIO

Bellona has set out to show how to combat global warming. Across the economy, we have searched for solutions that already are available or on the verge of becoming so. We have analyzed findings from both scientific publications and various reports prepared by industry and environmental organizations.

Bellona is certainly not the first to undertake such an effort; numerous studies have been published by academics, think-tanks, environmental organizations and governments alike. The problem is that few have shown how the needed 85 percent reduction in greenhouse gas emissions can be achieved by 2050.

The good news is that it *is* possible to reduce global emissions by 85 percent by 2050. Energy can be generated from biomass, water, wind, the sun and the sea, and can be used more efficiently. Industrial production, transportation and fossil power can be decarbonized, and land use can be managed better.

Yet, under the prevailing economic and political conditions, the needed technological shift is either happening far too slow or not happening at all. The challenge we face, together as a global community, is more of a political and economic nature than of a technical nature. The solutions exist – what is needed is national, regional and global political leadership to make it happen.

Several approaches can be taken to decide what climate solutions to include in a global warming mitigation scenario. The most common seems to be a cost-based analysis, which means that only those measures that are expected to cost less than a certain limit are included.

For the Bellona Scenario, we have chosen to focus less on cost, since the actual cost of a particular solution is subject to change as market conditions change. Furthermore, if we really *must*, as scientific evidence suggests, reduce emissions by as much as 85 percent by 2050, then how much it will cost is less relevant.

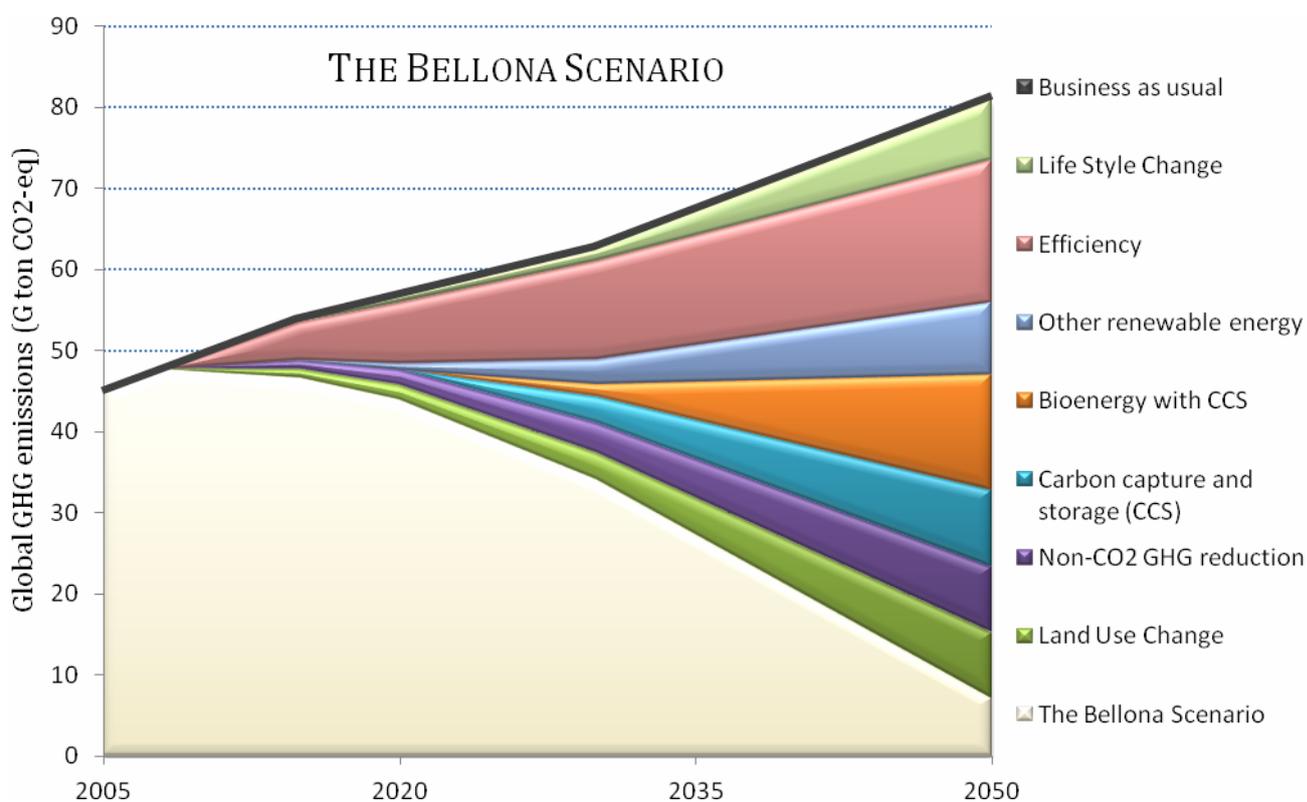
With this as the guiding principle, the Bellona Scenario shows a possible combination of solutions that together reduce emissions by 85 percent by 2050.

To produce the Bellona Scenario, we started with business as usual greenhouse gas emission scenarios published by the Intergovernmental Panel on Climatic Change, the International Energy Agency and the World Resource Institute. The business as usual scenario is represented by the black line in the chart above, and shows that annual emissions are expected to grow to 81 billion tonnes of CO₂-equivalents by 2050.

We then implemented the reductions provided by the identified solutions. The result is a trajectory taking us to 7.1 billion tonnes of CO₂-equivalents in 2050. This corresponds to an 85 percent reduction of current emissions by 2050.

The challenge is far-reaching, comprehensive and global: but it is manageable. The activities and technologies necessary to eliminate the bulk of the risks associated with climate change are already available or can be developed through appropriate policies to support innovation.

- Lord Nicholas Stern



As shown in the pie chart, increased efficiency, renewable energy and carbon capture and storage are all expected to play key roles. Furthermore, no single solution can do the job alone; a whole range of solutions are needed in all sectors of the economy.

SOLUTIONS IN THE BELLONA SCENARIO

LIFESTYLE CHANGE

Bring about a change in consumer behaviour by means of emission-based pricing, increased awareness, and public and market based initiatives.

EFFICIENCY

Increase efficiency in the transformation of energy and materials into products and services. This is particularly relevant in industry, buildings, transport and power generation.

RENEWABLE ENERGY

Replace fossil energy in power generation, transport, industry and buildings with renewable energy. Most important sources are solar, bio- and wind energy.

CARBON CAPTURE AND STORAGE (CCS)

Capture CO₂ from power plants and industrial plants and store it permanently in geological formations.

CARBON NEGATIVE ENERGY

Absorb atmospheric CO₂ by growing modern biomass on non-agricultural land and use it in power plants fitted with CCS to achieve net negative emissions.

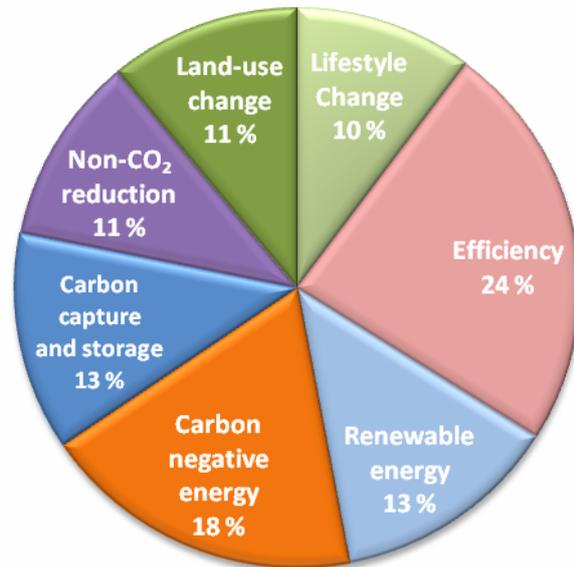
NON-CO₂ GREENHOUSE GAS REDUCTION

Reduce emissions of other greenhouse gases such as methane (CH₄) and nitrous oxide (N₂O) from waste, industry and agriculture.

LAND-USE CHANGE

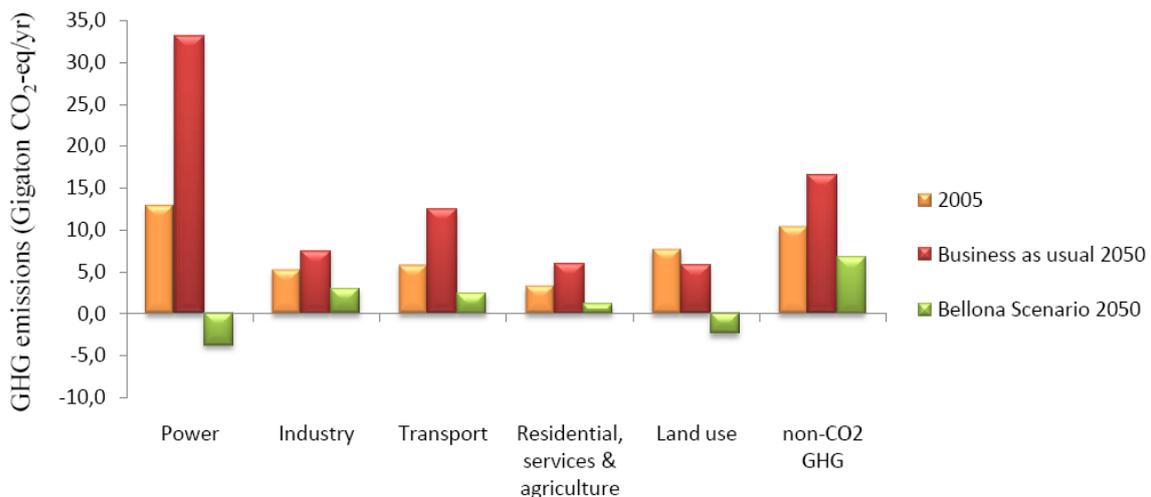
Manage forests better to enhance their role as natural sinks of CO₂.

SHARE OF REDUCTIONS FROM BUSINESS AS USUAL IN 2050



BELLONA SCENARIO EMISSION REDUCTIONS BY SECTOR

The graph below shows greenhouse gas emissions in 2005, the 2050 business as usual projection, and the 2050 emissions level if the Bellona Scenario is implemented. Deep cuts in all sectors of the economy are possible; some can even become net negative emitters. On the following pages, we describe the carbon negative energy supply system and how emissions can be reduced in all main sectors of the economy.



CREATING A SUSTAINABLE ENERGY SUPPLY

Fossil energy currently accounts for 80 percent of world energy use, and energy use is responsible for 60 percent of global greenhouse gas emissions. Energy security is a key national policy goal for both rich and poor countries, and the reserves of cheap, fossil energy are both vast and widely distributed. This leads the IEA to predict that fossil fuels will play an even bigger role in 2050 than today. That is, of course, if business is allowed to proceed as usual.

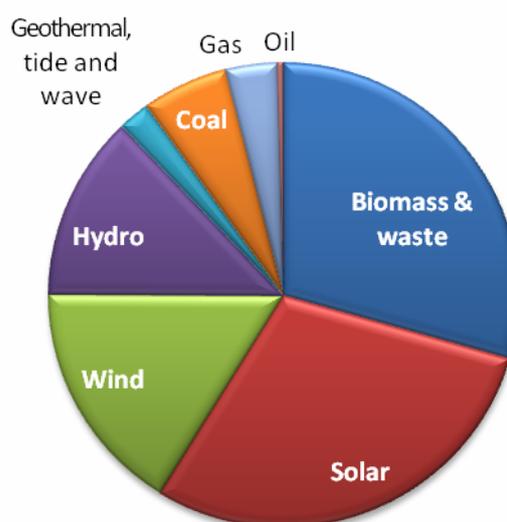
Immediate action to make energy supply more sustainable is needed. This means generating power from renewable instead of fossil energy resources, increasing power generation efficiency, and shifting to clean energy carriers, such as electricity, hydrogen and liquid biofuels.

In the Bellona Scenario, power will in 2050 be supplied as shown in the pie chart.

GENERATE POWER MORE EFFICIENTLY

There is a great potential for improving energy efficiency in the power sector. On average, existing coal-fired power plants convert only 37 percent of the energy in its fuels to useful energy – the rest is lost as heat. For gas-fired power plants, the current average is 50 percent. By 2050, a global implementation of state-of-the-art power plants could increase these figures to 50 and 63 percent respectively. For biomass power plants, which play a prominent role in our 2050 scenario, average efficiency is expected to increase from 26 today to 40 percent in 2050.

GLOBAL POWER SUPPLY IN 2050



REPLACE FOSSIL POWER WITH CLEAN, RENEWABLE POWER

Renewable energy resources - such as sunlight, wind, water, biomass and geothermal energy - are naturally replenished. While the technical potential for renewable energy is close to limitless, our ability to transform this potential into usable forms of energy has historically been limited. Recent technology development has finally brought a sustainable, renewable energy system within reach, both from a technical and economic perspective. The transition will, however, take time.

In our ambitious scenario, 90 percent of power generation in 2050 will be based on renewable resources, of which bio, wind and solar power will be the most important.

CLEAN UP FOSSIL ENERGY: CARBON CAPTURE AND STORAGE

While a renewable energy system is the ultimate goal, we do not expect this is to be fully achievable by 2050. From a climate perspective, however, there is hope: Fossil energy can be made close to climate neutral by means of carbon capture and storage (CCS). Here, fossil CO₂ is captured from power plants and transported through pipelines to safe geological storage sites. CCS can also be implemented at large industrial plants.

In the Bellona Scenario, carbon capture and storage is implemented at all remaining fossil energy power plants by 2050.

GENERATE CARBON NEGATIVE POWER

Carbon capture and storage can also be used to generate power with a net negative climate impact. In such a *carbon negative* process, CO₂ is first absorbed from the atmosphere through the production of modern biomass, such as algae. This production will be limited to non-agricultural land so as to not compete with food and feed production. The resulting biomass is then used to generate power in modern power plants fitted with carbon capture and storage, hence achieving a net negative emission.

Carbon negative power is already being implemented at some locations, and given an adequate development and demonstration effort, a large emission reduction from carbon negative power is feasible by 2050. In the Bellona Scenario, carbon negative power makes power generation a net negative emitter.

PHASE OUT NUCLEAR ENERGY

Nuclear power production does not lead to any direct greenhouse gas emissions, and substituting fossil fuelled power plants with nuclear power has been suggested as a solution to global warming. However, serious problems with nuclear power exist, such as nuclear waste handling, the risk of nuclear accidents, and proliferation of nuclear weapons.

Until these significant problems are solved, using nuclear power as a solution to combat global warming would be to fight one problem by creating another. In our scenario, nuclear energy is therefore phased out completely by 2050.

CUTTING EMISSIONS IN ALL SECTORS

START USING CLEAN CARS, TRUCKS, PLANES, SHIPS AND TRAINS

Transportation currently accounts for about 13 percent of greenhouse gas emissions, and most business as usual scenarios project a doubling of transport emissions towards 2050. This need not be; a transport system with near-to-zero emissions is technically possible. Key components are

improved energy efficiency and switching to climate neutral energy carriers. Hence, in our 2050 scenario,

- 75 percent of road transport is carried out by electric vehicles, the remainder runs on biofuels and fossil fuels,
- all aircraft run on biofuels, and
- ¼ of all ships run on hydrogen fuel cells, ¼ on biofuels and ½ on fossil fuels.

INCREASE INDUSTRIAL EFFICIENCY

Industry currently accounts for about 12 percent of global greenhouse gas emissions and uses about half of the electricity generated. Most important in terms of greenhouse gas emissions are the chemicals, cement, and steel industries. Increased energy efficiency is an important measure to reduce industrial greenhouse gas emissions. For example, state-of-the-art motor systems could reduce industrial electricity demand by 12 percent. Large emission reductions can also be achieved by improving manufacturing processes and increasing recycling.

In our scenario, industry emissions are reduced by almost 40 percent compared to the 2050 business as usual projection.

USE ENERGY SMARTER IN BUILDINGS

The dominant greenhouse gas emission from residential and commercial buildings is energy-related CO₂. The most important ways to reduce emissions are to reduce primary energy demand by improving energy efficiency and to replace fossil heating with renewable heating. In the Bellona Scenario, renewable energy and a range of energy-efficient technologies cut greenhouse gas emissions from buildings by about half.

PRODUCE FOOD WITH LESS CLIMATE IMPACT

Agriculture currently accounts for 13.5 percent of greenhouse gas emissions, of which methane from livestock and manure and nitrous oxide from agricultural soils make up the lion's share. While there are no technical 'quick fixes' to reduce agricultural emissions, improved agricultural practises, such as restoring cultivated organic soils and improving cropland management, can enable a 30 percent emission reduction compared to business as usual in 2050.

PRESERVE FORESTS AS NATURAL SINKS OF CO₂

As growing vegetation binds large amounts of CO₂, cutting down forests and letting grasslands turn into deserts (commonly co-termed 'land-use change') has a negative climate effect. While land-use change currently leads to a higher atmospheric concentration of CO₂, intelligent land management, reforestation, and measures to stop the deforestation of rainforests can make land-use change a net absorber of CO₂ by 2050.

DISPOSE OF WASTE WITHOUT WASTING THE CLIMATE

Waste water and landfills produce about 3 percent of global greenhouse gas emissions, in the form of methane and nitrous dioxide. Through a global adoption of readily available

technologies, such as land-fill and sewage gas recovery, emissions can be reduced by more than 90 percent in 2050 compared to business as usual.

LIVE SMARTER TO REDUCE CLIMATE IMPACT

Increased climate awareness and higher prices on emission-intensive products and services will encourage people to change their daily lives to reduce ecological impact. For instance, they will travel more by public transport, eat food with a lower carbon footprint, and lower indoor temperature. While such a lifestyle change clearly would reduce emissions significantly, calculating an accurate figure for 2050 is extremely complex. In our scenario, the emission reduction from lifestyle change is probably modest.

In addition to direct emission reductions, more ecologically aware voters and consumers will put pressure on politicians and business leaders alike to ensure that the technologies with the lowest possible carbon footprint are deployed.

THE WAY FORWARD

The Bellona Scenario shows that the solutions necessary to tackle global warming are available today. Courageous political leadership is key to implementing the scenario.

When world leaders gather at the United Nations Climate Change Conference in Copenhagen in December 2009, they need to develop a global policy framework that features:

- 1) A pledge to reduce emissions by 85 percent by 2050, and a plan for how to achieve it. This essentially means setting a global cap on emissions and a schedule for tightening it.
- 2) A radical increase in public funding for developing and demonstrating new climate-friendly technologies. While the needed technologies already exist, substantial efforts are needed to reduce costs and speed their implementation at large scale.
- 3) A change of market conditions to make it financially attractive to protect the climate. In essence essentially means giving climate-friendly technologies an advantage by putting a price on emissions and making the polluter pay.

The best way to predict the future is to invent it.
- Alan Kay

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Abbreviations

Abbreviation Description

ACT	Accelerated Technology
BAU	Business as usual
C	Carbon
CCS	CO ₂ Capture and Storage
CC8	Climate Conference 2008
CDM	Clean Development Mechanism
CH ₄	Methane
CO ₂	Carbon dioxide
CO ₂ -eq	Carbon dioxide equivalents
CSP	Concentrated solar power
EIT	Economies in transition
EJ	Exa Joule = 10 ¹⁸ J
EU	The European Union
EU ETS	European Union Emission Trading System
ETP	Energy Technology Perspective, IEA Report of 2006
EREC	European Renewable Energy Council
EPRI	Electrical Power Research Institute
FCEV	Fuel Cell Electric Vehicle
G	Giga = billion = 10 ⁹
GAI	Gross Annual Increment
GDP	Gross Domestic Product
GHG	Greenhouse gas
GJ	Giga Joule = 10 ⁹ MJ
GtCO ₂	Giga tonnes CO ₂ (billion tonnes CO ₂)
GtCO ₂ -eq	Giga tonnes CO ₂ equivalents (billion tonnes CO ₂ equivalents)
GTL	Gas-to-Liquids
GW	Giga watt = 10 ⁹ W
GWEC	Global Wind Energy Council
HFC	Hydrofluorocarbon
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IGCC	Integrated Gasification Combined Cycle
IPCC	Intergovernmental Panel on Climate Change
kW	Kilo Watt = 10 ³ W
kWh	Kilowatt-hour (1 kWh = 3.6·10 ⁶ J)
LCA	Life Cycle Assessments or Life Cycle Analysis
Li-Ion	Lithium Ion Batteries
MCFC	Molten Carbonate Fuel Cell
MIT	Massachusetts Institute of Technology
MJ	Mega Joule = 10 ⁶ MJ
MtCO ₂	Mega tonnes CO ₂ (million tonnes CO ₂)
MTU	Motoren und Turbinen Union
MW	Giga watt = 10 ⁶ W
N ₂ O	Nitrous oxide

Abbreviation Description

NiMH	Nickel Metal Hydrid Batteries
Non-OECD	All the countries that are not members of OECD
OECD	Organisation for Economic Co-operation and Development
PEMFC	Proton Exchange Membrane Fuel Cells
PFC	Perfluorocarbon
PHEV	Plug-in Hybrid Electric Vehicle
ppm	parts per million
PV	Photovoltaics
R&D	Research and Development
RD&D	Research Development and Demonstration
SF ₆	Sulphur Hexafluoride
TWh	Terawatt-hour (1 TWh = 3.6·10 ¹⁵ J)
UNFCCC	United Nations Framework Convention on Climate Change
US EPA	United States Environmental Protection Agency
USD	United States Dollar (currency of the USA)
WBCSD	Word Business Council on Sustainable Development
WEO	World Energy Outlook, studies prepared by IEA
Wh	Watt-hour (1 Wh = 3.6·10 ³ J)
WRI	World Resources Institute
ZEP	EU Technology Platform for Zero Emission Fossil Fuel Power Plants

1. Introduction

The global warming challenge

Global warming is already taking place and has become the biggest challenge of our time. According to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), global warming is caused by human activities ^[1] and if business proceeds as usual, anthropogenic greenhouse gas (GHG) emissions will increase the average global temperature from 1.1 to 6.4 °C during the 21st century. The global temperature is already 0.7 °C above the pre-industrial level, and a 2 °C increase is generally considered as the threshold above which dramatic and irreversible impacts will occur. Ecosystems may collapse and 15 to 40 percent of all species may become extinct. More draughts, floods and other extreme weather events will increase pressure on scarce food and water resources as the world population grows towards nine billion humans by 2050 ^[2,3,4]. As a consequence, hundreds of millions of people may become refugees or starve to death. This would have knock-on effects in term of social upheavals and large-scale conflicts. Other secondary effects may be the release of stored methane from the tundra and from the seabed, creating feedback loops that further exacerbate climate change.

To have a reasonable chance of avoiding such dire consequences of global warming, the average global temperature must not increase by more than 2 °C above the pre-industrial level. According to the IPCC, this corresponds to a 50 – 85 percent reduction of global greenhouse gas emissions from 2000 to 2050 and a peak in emissions no later than 2015 ^[1]. There are several reasons to aim for reductions at the higher end of this interval. For one, emissions have increased steadily by 3 percent annually since 2000, so a peak by 2015 might be unattainable. A delayed peak in emissions will necessitate setting the reduction target higher. Furthermore, as the IPCC points out, the necessary emission reductions to meet a particular stabilization level might be underestimated due to missing carbon cycle feedback loops.

For the purpose of this study, we therefore assume that an 85 percent reduction of global greenhouse gasses from the 2005 emission level must be achieved by 2050 in order to combat global warming.

Greenhouse gas emissions

If business is allowed to proceed as usual, the global energy demand will increase by more than 90 percent by 2050 ^[5]. Fossil fuels will constitute most of the increased energy production, and as a result considerably increase CO₂ emissions. If no measures are established, the global GHG emissions will nearly double by 2050 ^[5,6].

The good news – as this report aims to demonstrate - is that it *is* possible to reduce global emissions by 85 percent by 2050. Energy can be used more efficiently, and energy can be generated from renewable sources like biomass, water, wind and sun. Industrial production, transportation and fossil power can be de-carbonized, and forestation management can be improved.

Yet, under the prevailing economic and political conditions today, the technological shift needed is either occurring far too slowly, or not happening at all. The challenge we face together as a

global community is therefore more of a political and economic nature, than a technical nature. The solutions exist – what we need is a strong and resolute national, regional and global political leadership to make it happen.

Added value

The objective of our study is to identify a combination of solutions that can achieve the necessary 85 percent reduction in greenhouse gas emissions by 2050.

Bellona is certainly not the first to undertake such an effort; numerous studies have already been published by academics, think-tanks, environmental organizations and governments alike. The problem is that most other mitigation studies have used cost analysis to decide which climate solutions to include ^[5,6,7,8,9]. If the purpose is to identify the cheapest way to mitigate global warming, such a cost-based approach might be useful. However, when cost is used as the key analytical parameter, then we lose sight of the true objective. If we really must reduce emissions by 85 percent by 2050, as scientific evidence tells us, then it is more relevant to first show that this is indeed achievable both technically and practically.

With this as the guiding principle, the Bellona Scenario, which is established in this study, shows a combination of possible solutions that can reduce global GHG emissions by 85 percent by 2050 as indicated in the figure below.

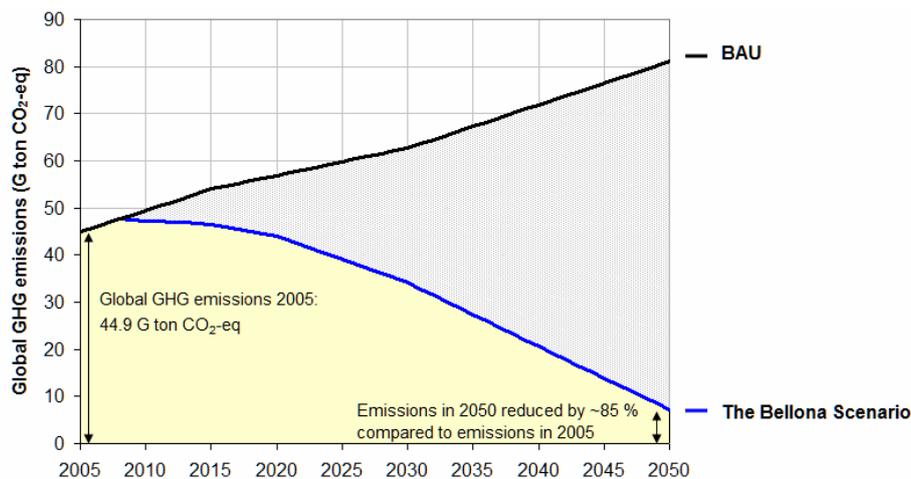


Figure 1.1. Global GHG emissions in a business as usual (BAU) Scenario compared with the Bellona Scenario where the emissions are reduced by approximately 85 percent compared to emissions in 2005. The BAU Scenario is based on reports from the International Energy Agency (IEA) ^[5,7], the Intergovernmental Panel on Climate Change (IPCC) ^[6], and the World Resources Institute (WRI) ^[10].

Future predictions for greenhouse gas emissions

There are a multitude of reports assessing the feasibility of climate change mitigation. The IPCC Fourth Assessment Report employs both top-down and bottom-up approaches to assess how different technologies can contribute to emission reductions ^[11]. Assessments are generally made at a fairly aggregate level, with reference to economic costs and CO₂ emission prices that would be required to reach different stabilisation targets.

The Stern Review of the Economics of Climate Change ^[4] demonstrates the cost-effectiveness of mitigation as an insurance against the potentially disastrous consequences of climate change. The Stern Review recommends stabilisation of atmospheric GHG concentrations in the range of 450-550 ppm CO₂ equivalents, in order to have a reasonable chance of staying below a 2-3°C global temperature increase. Exceeding that level will entail huge risks of irreversible and dramatic impacts of climate change, while staying within that range is not likely to cost more than one percent of global GDP (according to existing literature and the assumptions on discount rate and equity weights used in the Stern Review). This can be regarded as a low cost in comparison with the cost of climate change consequences in a business as usual scenario, which is expected to be from 5 to 20 percent of global GDP ^[4].

The International Energy Agency (IEA) has published a report entitled Energy Technology Perspective 2006 ^[5] which concludes in its most optimistic scenario that global CO₂ emissions can be reduced by 16 percent by 2050, compared to emissions in 2003, if technologies with a carbon cost lower than USD 25 per tonne CO₂ are deployed. In an updated version of this report, which will be published in June 2008, the most optimistic scenario, the Blue Scenario, concludes that global CO₂ emissions can be reduced by 50 percent by 2050 if technologies with a carbon cost lower than USD 200 per tonne CO₂ are deployed ^[12].

In the IEA report World Energy Outlook 2007 (WEO2007) ^[7] there is a scenario called the 450 Stabilisation Scenario where it is shown how to stabilize atmospheric GHG emissions at 450 ppm CO₂-eq – and thereby limit global warming to 2 °C. However, it seems as though the IEA regards this scenario as too optimistic and unachievable, because the WEO2007 focus mainly on its Reference Scenario and Alternative Policy Scenario, and in these two scenarios the global CO₂ emissions will increase onwards to 2050.

The Bellona Scenario

For all major sectors of the economy, we have searched for solutions that are already available, or on the verge of becoming so. In order to determine the emission reduction potential of various solutions we have analysed findings from both scientific publications and various reports prepared by governmental and environmental organizations, research institutes, and industry.

Bellona has developed a model for future CO₂ emissions based on emission reduction potentials as assessed in the literature. In this model, a business as usual (BAU) Scenario is first established based on data from the IEA ^[5,7,13,14], the IPCC ^[6], and the World Resources Institute (WRI) ^[10]. The emission reduction potentials for the different technologies and strategies are then implemented in the model to show how global GHG emissions can be reduced compared to the BAU Scenario. The resulting energy demand, power production and GHG emissions are called the Bellona Scenario.

It is important to note that the Bellona Scenario is *not* based on economic modelling. On the contrary, the objective is to show that it is technically possible to achieve large GHG emission reductions by addressing what experts and available literature consider ambitious, yet realistic.

In the Bellona Scenario we have addressed energy and process efficiency, more renewable energy production, carbon capture and storage (CCS), land-use change, and lifestyle change. Some technologies, like solar power and CCS, are in the early stage of development and will need long-term government support. However, we do expect that new low carbon technologies will arise from technological innovation and will help achieve the emission reduction target. For this to

occur, it is essential that governments help stimulate the development of various low-carbon technologies for power production, transportation and improved energy efficiency.

The way forward

We need a global deal on climate change, and we need it fast. When world leaders get together at the United Nations Climate Change Conference in Copenhagen in December 2009, they need to set the world on course towards an 85 percent emission reduction by 2050. While this is an ambitious target, it is also an achievable target – we are *able* to do it. To make it happen, political leaders must step up and forge a global, ambitious agreement to tackle the problem. To their comfort, the Bellona Scenario shows that the solutions necessary to do the job are available. What they now must do is to develop a policy framework that will make sure the solutions are implemented. From our perspective, the fundamental features of this policy framework include:

1. A pledge to reduce emissions by 85 percent by 2050, and a plan for how to achieve it. This essentially means setting a global cap on emissions and a schedule for tightening it.
2. A radical increase in public funding for developing and demonstrating new climate-friendly technologies. While the needed technologies already are available, substantial efforts are needed to reduce costs and speed their implementation on a large scale.
3. A change of market conditions to make it financially attractive to protect the climate. This essentially means giving climate-friendly technologies an advantage by putting a price on emissions and making the polluter pay.

Structure of the report

The low emission technologies available and their GHG emission reduction potentials are analysed in Section 2 of this report. Section 3 describes how the emission reduction potentials are addressed in the Bellona Scenario. The calculated energy demand and GHG emissions are presented in Section 4. Conclusions are given in Section 5.

2. Technologies to Reduce GHG Emissions

In 2005, total greenhouse gas emissions were as high as 45 GtCO₂-eq. GHG emissions increase by 1.9 percent each year, and by 2050 the emissions could be 80 percent higher than today if no new strategies and regulations are implemented to reduce GHG emissions.

The challenge is to find ways for the world to switch from a path of increasing emissions to a path of more sustainable development where the majority of the GHG emissions are eliminated.

Before new development paths can be established, the main technologies to cut emissions and their potentials must be analysed. As a starting point it is crucial to understand where the emissions come from. In the figure below global GHG emissions are divided into different sectors. The sector with the largest GHG emissions is the power production sector with 28 percent of total emissions. In addition, there are also considerable emissions from industry, transport, residential, services and agriculture and land-use change. While CO₂ is the most important greenhouse gas, other greenhouse gases (i.e. CH₄, N₂O, SF₆, HFC, and PFC) have a significant share as they account for 23 percent of the total GHG emissions.

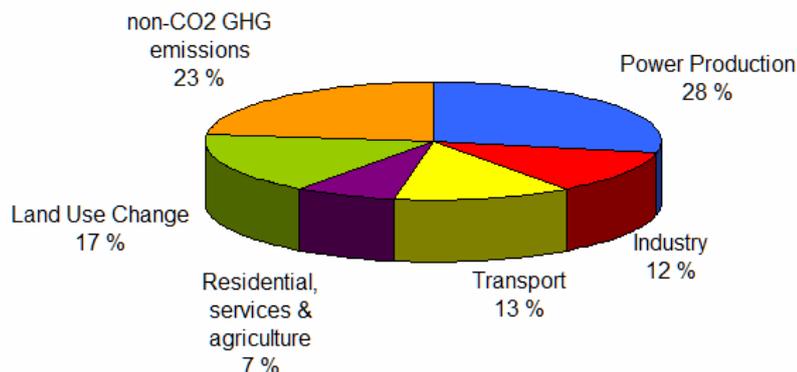


Figure 2.1. GHG emissions in 2005 from different sectors. The sectors Power Production, Industry, Transport, and Buildings & Agriculture represent energy and process-related CO₂ emissions. Land-Use Change is net CO₂ emissions due to deforestation, reforestation and harvest. All GHGs other than CO₂ (i.e. CH₄, N₂O, SF₆, HFC, and PFC) are included in the pie slice called non-CO₂ GHG emissions. The data in the diagram is calculated as described in Appendix 1 based on data from IEA [5,7,13,14], IPCC [6], and WRI [10]. The sectors in the figure above follow the definitions from IEA [7] and WRI [10].

When separating GHG emissions into sectors it is important to be clear on how the GHG emissions are accounted for. In the figure above the GHG emissions are counted in the sectors where they actually occur, i.e. electricity consumption in the Industry sector leads to GHG emissions in the Power Production sector and not in the Industry sector. This is due to the fact that electricity consumption in itself does not cause any GHG emissions, but production of electricity will produce CO₂ emissions (if power is produced from fossil sources).

On the other hand, if the GHG emissions are separated into end-use categories, as shown on the right hand of the figure below, a totally different separation of GHG emissions appears. In the figure below, GHG emissions from the industry sector equal 13.8 percent of global GHG

emissions (10.4 percent from energy related emissions and 3.4 percent from industrial processes). But if end-use industrial activities are summarised, the GHG emissions amount to one quarter of total GHG emissions.

World GHG Emissions Flow Chart

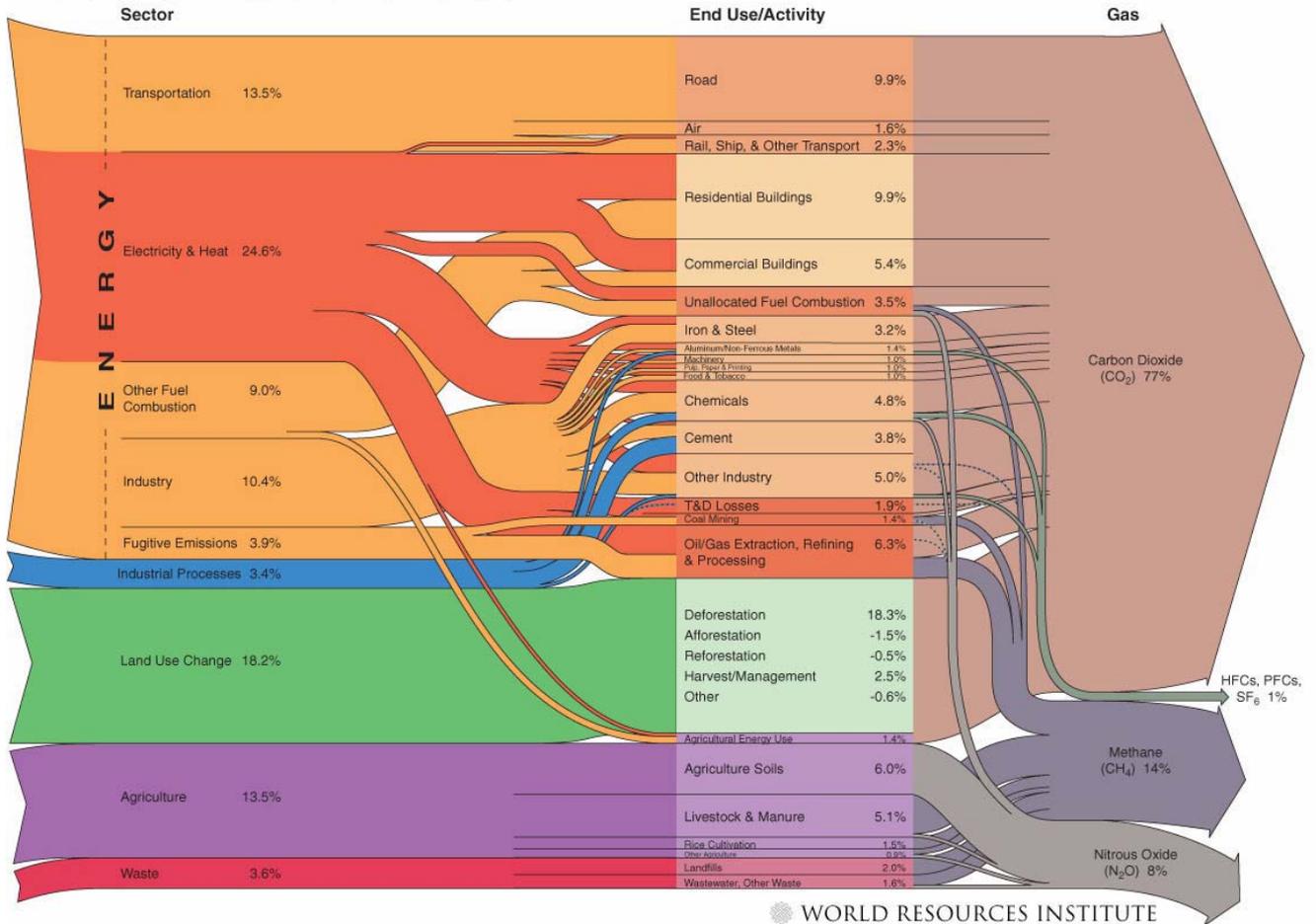


Figure 2.2. Chart copied from <http://cait.wri.org/figures.php?page=/World-FlowChart>. All data is for 2000. All calculations are based on CO₂-eq., using 100-year global warming potentials from the IPCC (1996), based on global estimate of 41,755 MtCO₂-eq. Land-use change includes both emissions and absorptions.

In order to reduce emissions by 85 percent by 2050 and limit global warming to 2 °C above pre-industrial levels, greenhouse gas emissions must be cut in all the sectors. In this chapter, available technologies to reduce these emissions are discussed and an analysis is given of their emission reduction potentials.

2.1. Lifestyle Change

Key messages

“In all regions, many options are available for lifestyle choices that may improve quality of life, while at the same time decreasing resource consumption and associated GHG emissions. Such choices are very much dependent on local and regional cultures and priorities. They are very closely related to technological changes, some of which can be associated with profound lifestyle changes, while others do not require such changes.”
IPCC ^[11]

The term lifestyle in our context captures the typical way of life of individuals and groups, specifically in terms of consumer behaviour, consumption patterns and related energy consumption and GHG emissions. As pointed out by IPCC already in 2001, lifestyle change can lead to reduced consumption, or changed consumption patterns, and can influence energy consumption and GHG emissions in many ways. Some of the changes can easily be considered win-win improvements for the consumer as well as for the environment. For example, increased use of broadband internet can lead to reduced commuting and travelling, by allowing more work from home and by encouraging the use of teleconferencing. Music and videos can be transferred online instead of on physical materials like CDs which can reduce energy use otherwise expended during production, distribution and consumption.

In order to influence consumer behaviours, it is essential to understand the institutional, social and economic aspects of energy-related systems. In addition, to understand how GHG emissions are influenced by changes in consumer behaviour and consumption patterns we need to regroup our sector-oriented energy and emission inventories into inventories based on consumer needs and consumer practices. Primary commodities such as electricity, fuels etc. are inputs to various production processes and services supporting underlying human needs like recreation and leisure, subsistence, shelter etc. ^[15] For example “private transport” can be divided into household needs, recreation and leisure, food, commuting, health and hygiene, clothing and education. Similar distributions can be made for other transport services and sectors. Without knowing these relations it is difficult to quantify the various effects lifestyle changes would have on energy demand and energy production.

As the IPCC ^[11] points out, current lifestyles, behaviours, and consumption patterns have developed within current and historical socio-cultural contexts and may be changed through a number of intertwined processes, such as:

- scientific, technological, and economic developments;
- alterations in dominant world views and public discourse;
- changes in the relationships among institutions, political alliances, or actor networks;
- changes in social structures or relationships within firms and households; and
- changes in psychological motivation ^[15]

Some of these changes can be expected to occur without specific policies. Technological developments will provide new opportunities and change the prices of products; increased awareness of environmental challenges will influence preferences and motivation, etc. Other changes should be inspired through targeted government policies. Improved transparency and improved consumer information regarding the environmental impact of a product can encourage consumers to take non-economic factors into account when considering a purchase; the need for transport could be reduced through improved urban planning, etc.

In this report we argue for profound technological change and improved use and management of natural resources, and we propose policy recommendations to move society in a less carbon-intensive direction. The changes we recommend will influence global energy use and GHG emissions partly through their effects on consumer behaviour; effects that will change fundamental economical relationships. If taken into consideration when rerunning the IEA-models these changes would alter projections for energy use and GHG emissions.

Although we acknowledge the very significant contribution lifestyle change can have towards reducing GHG-emissions, and although we encourage policies to back these changes, in our study we neither dive into the social and behavioural aspects of this change, nor rerun the IEA-models with changed assumptions. Our tools to quantify the reduction potentials for GHG-emissions through lifestyle changes are therefore very limited.

However, in order to make this important potential visible in our scenario, we have made some assumptions and attempted to quantify the effects of lifestyle change in a conservative way, as discussed in Section 3.3.1.

2.2. Energy Efficiency in Power Production

Key messages

- Today, the average efficiency of coal power plants is only slightly above 30 percent. Gas power plants have an average efficiency of 42 percent.
- RD&D actions can increase the efficiency of coal and gas power plants to 50 and 63 percent, respectively.
- CO₂ emissions from coal and gas power plants can be reduced by 40 and 33 percent, respectively.

Coal power plants

Coal power plants emit 28 percent of global energy and industry related CO₂ emissions. Many coal power plants are old and inefficient, and if they are replaced by new and more efficient plants there is a large potential for reduction in global CO₂ emissions.

One example of a modern plant is the 335 MW IGCC coal power plant operated by Elcogas in Puertollano in Spain which has an efficiency of 42.5 percent ^[16]. It is expected that new components and optimised process integration can increase the plant efficiency to 50 percent.

Two-thirds of all coal power plants are more than 20 years old and have an average efficiency of only 29 percent. If all these plants were replaced by modern coal power plants with an efficiency of 45 percent, the global CO₂ emissions would be reduced by 1.4 GtCO₂ annually ^[5].

The efficiency of coal power plants is expected to increase to 50 percent or more by 2020 if funding is established to ensure RD&D activities ^[5,17]. A power plant with 50 percent efficiency will emit 40 percent less CO₂ than a traditional power plant with 30 percent efficiency.

Gas power plants

Gas power plants had an average efficiency of 42 percent in 2003 ^[5], but new gas power plants have considerably higher efficiency. The new gas power plant at Kårstø, Norway, which was commissioned in November 2007 has an efficiency of 58 percent ^[18]. With a strong focus on RD&D, the efficiency of new gas turbines could increase to above 63 percent by 2020 ^[17].

A future gas power plant with 63 percent efficiency will emit 33 percent less CO₂ than a traditional power plant with 42 percent efficiency. If all existing gas power plants were replaced

by modern plants with 58 percent efficiency, global GHG emissions would be reduced by 0.6 GtCO₂ annually.

Biopower plants

The efficiency of power production from biomass steam generation is in the low 20 percent range. However, with existing technology it is possible to achieve over 40 percent efficiency ^[19]. Most biomass power plants today are small, but by up-scaling future biomass power plants higher efficiencies will be achieved.

Biomass is often used for co-firing with coal in power plants, and existing co-fired power plants have efficiencies ranging from 33 to 37 percent ^[19]. The world's largest co-fired power plant, the Alholmen Power Plant in Finland has a capacity of 240 MW electricity and 160 MW process steam and district heating. The plant is fuelled by 59 percent biomass and peat in addition to coal, and the power production has an efficiency of 46 percent. The overall efficiency, including electricity, process steam and district heat is as high as 73 percent ^[20].

Grids

When electricity is transported to consumers, a certain percentage of the energy is lost in transmission due to electrical resistance in the cables in the grid. This loss depends on the distance from the power production to the consumer. Many metals and alloys lose their electric resistance completely when they are sufficiently cooled. This effect, dubbed *superconductivity*, can be exploited to transport electrical energy virtually without any dissipation of energy, and is increasingly finding uses in electric power systems. Ideas pursued include transformers, generators, motors, cables, magnetic energy storage systems and fault-current limiters.

2.3. Industry Emission Reduction Strategies

Key messages

- Direct industry emissions arise from manufacture processes and from using fossil fuels for energy and feedstock, and amount to about 15 percent of global GHG emissions. Key to reducing direct emissions is rolling out state-of-the art process innovations globally and switching to renewable feedstock.
- Indirect industry emissions arise from using purchased steam and electricity produced elsewhere, which adds another 10 percent of global GHG emissions. Key to reducing these emissions is using steam and electricity more efficiently, most importantly through improved electric motor systems, steam systems, and process integration.

2.3.1. Emission Profile

Industry emissions are either energy-related or process-related.

Energy-related emissions

Energy-related industrial greenhouse gas emissions arise in two ways:

- CO₂ from energy use, either directly through on-site combustion of fossil fuels or indirectly through consumption of purchased electricity and steam,
- CO₂ from fossil fuels used as feedstock in chemical processing and metal smelting ^[11].

IEA ^[5] estimates that roughly 50 percent of energy is used for generating heat (including steam at various temperatures), 15 percent is used as feedstock, 15 percent for motor drive systems, and 20 percent for other uses such as lighting and transport, see figure below. Energy consumption is expected to increase by about 75-80 percent by 2050 ^[5].

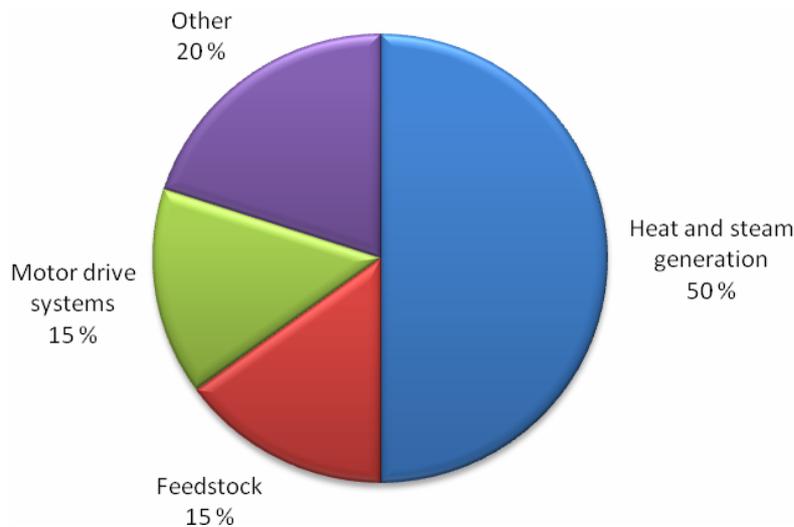


Figure 2.3. Heat and steam generation dominates industrial energy use (IEA ^[5]).

Energy-related emissions can be reduced substantially by generating heat and steam differently (i.e. switching to biomass or waste on-site or by switching to cleaner electric energy generated elsewhere) or by using energy more efficiently (i.e. new motor drive systems, cogeneration, and process integration). As such, it is estimated that the energy intensity of most industrial processes is at least 50 percent higher than what it could be according to thermodynamics ^[5].

Process emissions

Industrial activities also produce substantial GHG emissions that are not related to fossil fuels from the manufacture processes they use, in the form of:

- CO₂, particularly from the chemical process of cement and lime manufacture, or
- non-CO₂ GHGs, such as N₂O and CH₄ from the manufacture of chemicals, HFC-23 from the manufacture of HFC-22, PFCs from aluminium manufacture, SF₆ from electronics manufacturing ^[11].

Process emissions can be mitigated by introducing less emission intensive process designs, or by substituting fossil feedstock with biomass or waste.

2.3.2. Reduction Measures by Sector

The largest emissions from industry stem from producing raw materials, such as chemicals, metals, cement. Together, these processes account for about 70 percent of all industrial emissions. The remaining includes a range of smaller contributors, such as the food, tobacco and machinery industries. Emission reduction measures for the four most important industries are discussed below.

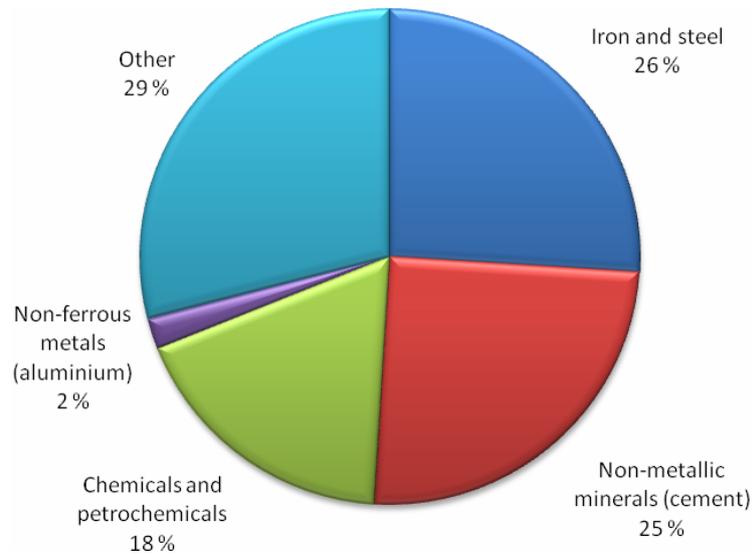


Figure 2.4. Industrial CO₂ emissions by sector according to IEA ^[5]. Other greenhouse gas emissions, mainly from the chemicals and petrochemicals sector, which make up 10 percent of industrial GHG emissions, are not included.

Iron and steel

The iron and steel industry is responsible for about 6 to 7 percent of world CO₂ emissions and about a quarter of industry emissions ^[1]. About 70 percent stems from the direct combustion of fossil fuels (i.e. combustion of coal to produce coke for energy generation and as a reduction agent), with the remaining 30 percent occurring indirectly through consumption of electricity and heat.



Photo: The Bellona Foundation

One way of reducing emissions from direct fuel combustion is to change to production processes (i.e. direct reduced iron) that allows coal to be replaced by natural gas. Modern direct reduced

iron plants emit about 55 percent less CO₂ than the average existing blast furnace plants. In 2004, only 5 percent of steel was produced by direct reduced iron plants. Blast furnace plants produced about 60 percent of steel ^[5]. Hence, a full switch from blast furnace to direct reduced iron would yield a 33 percent reduction in CO₂-emissions from the steel industry.

Another option is to bypass the usual conversion of coal to coke (an important feedstock to the process) by injecting the coal directly. In 2050, this could reduce another 9 percent compared to business as usual. It is also possible to replace coal by injecting plastic waste, charcoal, natural gas, hydrogen or electricity instead, which could reduce emissions even further. Large-scale plastic waste injection is already taking place, and could reduce sector emissions by 6 percent compared to 2050 business as usual (IEA 2006).

Further potential lies in adopting novel casting technologies, which slashes energy consumption tenfold compared to the most common technology today. IEA ^[5] estimates that this could reduce sector emissions by another 6 percent relative to their 2050 business as usual scenario.

Increased recycling is another way of reducing emissions from the iron and steel industry. Producing a tonne of steel from scrap metal requires about one-third of the energy needed to produce steel from iron ore. In 2004, about 35 percent of world steel production was using scrap metal. However, scrap availability does limit the extent to which recycling can help reduce emissions (IEA 2006).

Cement

Cement industry CO₂ emissions were about 1.6 GtCO₂ in 2003 ^[5]. Of these, process emissions account for about 50 percent, combustion of fossil fuels 40 percent, transport five percent and electricity generation five percent. Large-scale GHG emission reductions can hence be achieved by a combination of energy- and process-directed measures. On the whole, the WBCSD ^[21] finds that emissions can be reduced by 30 percent by 2030.

Energy measures

Most of the energy consumed at cement factories is generated by combustion of fossil fuels. Energy efficiency could significantly lower these energy-related emissions. Combining various measures for energy efficiency, WBCSD ^[21] finds a potential for an annual improvement of 0.5 – 2.0 percent (depending on country), amounting to a worldwide reduction of 11 percent from 2002 to 2020. IEA ^[5] finds that application of already existing kiln technologies alone can achieve emission reductions of up to 400 MtCO₂ (25 percent) by 2050.

The largest consumer of electric energy is grinding, a process which currently only achieves efficiencies of 5-10 percent while converting the remainder to heat ^[5]. Improved grinder technology and improved heat integration should be capable of yielding significant gains in energy efficiency. No exact figure is given by IEA ^[5], but a 20 percent improvement would mean a 1 percent reduction of emissions from the cement industry, directly through reduced electricity use and indirectly by reducing the need for heat generation from fossil fuels.

Another important energy-related reduction measure is substituting fossil fuels with alternative fuels, such as biomass and waste. While estimating the reduction potential this measure presents is complex due to its interface with other sectors, WBCSD ^[21] estimates that this could reduce emissions by 12 percent by 2020. On a global scale, IEA ^[5] estimates that the use of alternative fuels could be doubled from 1 to 2 EJ (278 to 556 TWh).

Process measures

Process emissions from cement production arise due to the chemical nature of the cement-clinker production process. These process emissions account for about half of the emissions from the cement industry. The most significant measure to reduce process emissions is switching to cement types containing other feedstocks, such as pozzolana (volcanic ash), fly ash or granulated blast furnace slag. This measure reduces emissions by reducing the amount of emission-intense clinker needed to produce cement. IEA (2006) estimates an emission reduction potential of up to 400 MtCO₂ (25 percent) by 2050.

Another way to reduce emissions from cement production is producing less of it. This can be done by switching to cement types that give stronger concrete. Stronger concrete allows the construction industry to use less concrete and the concrete industry to use less cement, hence reducing overall emissions.

Chemicals

The chemical industry represents one of the largest sectors of the world's economy, with thousands of companies producing tens of thousands of products in quantities varying from a few kilograms to thousands of tonnes. Due to this complexity, figures on GHG emissions are not very reliable ^[11]. Yet, it is estimated that this sector is responsible for about 18 percent of industry GHG emissions, of which energy related emissions make up 80 percent. The remaining 20 percent is process emissions of non-CO₂ GHGs, such as N₂O, HFCs and HCFC-22 ^[10].

Separation of chemical substances consumes about 40 percent of the energy used in the chemical industry. The most commonly used separation processes are distillation, fractionation and extraction, all relatively energy intensive processes. A more efficient separation process can be achieved by means of membranes, which use differences in molecular sizes or solubility to achieve separation ^[5]. Membranes are not yet in use for large bulk chemicals, but could, if applied widely, reduce fuel consumption of the chemical industry substantially. Ecofys ^[22] estimates a figure of 35 percent by 2050.

Large emission reductions can also be achieved through improved processes throughout the chemical industry. Fertilizer manufacture, for example, consumes about 1.2 percent of world energy consumption, of which 90 percent is used for ammonia production. Here, energy intensity could be reduced by about 30 to 40 percent ^[11].

Aluminium

Aluminium production is responsible for approximately 0.8 percent of world GHG emissions, and consumes some 3.5 percent of world electricity supply. Indirect CO₂ emissions from electricity consumption account for 61 percent, process emissions of CO₂ and PFCs (perfluorocarbons) 12 percent and 20 percent respectively, and CO₂ from direct combustion of fossil fuels 7 percent ^[10].

Though still under technical development, inert anode and bipolar cell are promising large reductions in annual CO₂ emissions in the mid- to long-term. Inert anodes would end the use of carbon anodes. Adopted globally by 2050, this technology could eliminate process emissions of CO₂ and PFCs, which currently account for 32 percent of GHG emissions from the aluminium industry, and reduce electric energy consumption equivalent to 50 MtCO₂ by 2030 and 200 MtCO₂ by 2050^[13].

Another way to reduce emissions from aluminium production is to increase recycling. Recycling aluminium requires a mere five percent of the energy of primary aluminium production. Recycling currently accounts for about 33 percent of world aluminium supply, a figure that is estimated to rise to 40 percent by 2025 ^[11]. Recycling depends on the stocks and flows of aluminium in manufactured goods; as long as demand for aluminium is rising, there is simply not enough aluminium available for recycling. In this light, a 60 percent share of recycling in 2050 does seem technically feasible, which would reduce energy consumption by around 35 percent compared to today according to the IEA ^[5]. Ecofys ^[22] operates with a higher energy reduction potential, but this is due to their calculation that only 22 percent is recycled today.

2.3.3. Industry-wide Emission Reduction Measures

Increased efficiency of equipment used across various industry sectors adds to the measures identified for each industry sector ^[5,11,22,23]. The most important are discussed below.

Electric motor systems

Electric motor drives are used extensively in the industry to convert electrical energy to mechanical energy. They account for about 60 percent of industry electricity consumption, and more than 30 percent of all electricity use ^[11].

Improved energy efficiencies for electric motor-drives could be achieved by:

- a) improving the motor itself
 - reducing losses in the windings
 - using higher quality magnetic steel, or
 - improving the aerodynamics of the motor
 - improving manufacture tolerances
 - introducing radically new designs, such as superconductive motors
- b) reducing losses in electrical and mechanical energy transmission
 - compressed air systems
- c) optimizing operational control of the motor to suit the load
 - variable speed drives
 - other control systems
- d) reducing losses in end-use devices receiving mechanical energy from the motor
 - selecting the right component (pumps, fans, compressors) for the given application and conditions
 - using more efficient designs

For the European industry, it is estimated that energy use could be reduced by more than a third, and similar figures are published for other industrialised countries ^[5]. The expected potential is even higher in developing countries. Ecofys ^[22] estimates a global average of 40 percent energy reduction potential from electric motor drives by 2050. Hence, more efficient motor drives could reduce global electricity consumption by more than 12 percent from today.

Steam supply

Steam is one of the main utilities of industrial systems, and the main means for distributing heat energy. Steam supply systems include boilers which combust fuel to generate steam, and piping for distributing the heat to its uses. Such boilers, generating steam at between 100 and 400 °C, account for some 15 percent of industry energy demand ^[5]. Steam is also generated in heat

exchange systems, which recover heat from higher temperature processes and redistribute it to other uses. This means that virtually a full half of industry energy demand could be improved by means of more efficient steam supply systems.

Improving steam supply systems is possible through improvements in both boilers and distribution pipes. Current average boiler efficiency in China is about 65 percent, while the best available boilers deliver an efficiency of 85 percent. By 2050, this could be further improved to 94 percent or more ^[11]. Assuming a global average boiler efficiency of 70-75 percent means that improved boiler efficiency could reduce energy consumption for steam generation by around a third, reducing total industry energy demand by around five percent compared to today.

Steam pipes distribute heat energy from boilers and heat exchange systems. It is estimated that as much as 20 percent of compressed air is lost through pipe leakage ^[11]. Heat is also lost through pipe walls. Mending these losses could reduce the amount of steam that needs to be generated by boilers. If we estimate that on average, 15 percent of heat is lost through steam leakage and heat loss in pipes, and that this could be reduced to five percent, improved steam distribution systems could reduce industry energy demand by around five percent compared to today.

Process integration

Industrial processes typically involve several series of heating and cooling of input and product streams. As such, heat and steam generation is by far the most energy consuming processes of the sector, accounting for about half of industrial energy use. Process integration (by means of pinch analysis) can help reduce emissions by linking the cooling and heating processes, so that waste heat from cooling is used in heating processes ^[24].

Ecofys ^[22] estimates that process integration could reduce energy demand (mainly heat provided by on-site fuel combustion) by about 20 percent by 2020 at 75 percent of existing industrial plants (that are not already integrated). This adds up to a 15 percent reduction in energy consumption across all industries.

Industrial symbiosis

Process integration could yield even larger energy savings if applied across several process plants. This has been done at the Kalundborg eco-industrial park in Denmark, in which plants as differing as power plants, cement plants, fish farms, refineries, and chemical plants are integrated. This cluster of industries achieves ‘industrial symbioses’ by integrating waste heat and material flows across businesses and plants, hence reducing emissions substantially.

In addition to the emission reductions achievable through inter-plant and inter-firm process integration, eco-industrial parks help the implementation of other reduction measures identified for each individual industry. In Kalundborg, for example, the cement factory uses gypsum from the near-by coal power plant to replace emission-intensive cement clinker. Carbon capture and storage technology is also easier to implement when large sources of CO₂ are co-localised. Eco-industrial parks are being set up in many parts of the world. (Source: Industrial Ecology ^[25]).

2.4. Energy Efficiency in the Residential, Commercial and Public Services Sector

Key messages

- Energy end use in buildings is responsible for a third of global energy related CO₂ emissions.
- The energy efficiency potential in buildings is 50 percent reduced energy demand by 2050 compared with business as usual.

2.4.1. Low Emission Strategies

The potential for increased energy efficiency in buildings, both commercial and residential, is by far one of the most promising sectors for making fast and cost effective reductions of global GHG emissions. Today, buildings are responsible for a third of global energy related CO₂ emissions ^[26]. There are different measures that can be implemented in the residential and commercial sector.

New buildings and improved heat

A “Passivehouse” is an extreme energy-saving house, even when compared to new buildings. A passivehouse has heating energy consumption under 15 kWh per square meter per year (not including warm water, electricity, and so forth). The first passivehouse constructed as a multifamily residence was built in 1999, in Freiburg im Breisgau, Germany. In Passivehouse “Wohnen & Arbeiten”, a 79 percent primary energy saving (including electrical power) is proven possible, without sacrificing comfort, at a 7 percent extra cost compared with the cost of a conventional new building. Due to the reduction in annual energy expenditures, the full return on the initial investment can be expected within 10 to 20 years time ^[27].

Efficient appliances

Appliances in households include wet appliances like washing machines, dishwashers and clothes dryers, and brown appliances like TVs and VCRs, and refrigerators. With increased efforts in innovation, the energy consumption of appliances can be reduced by 75 percent within 50 years in comparison to baseline energy consumption ^[32].

Efficient lighting

Examples from the fields have shown that 30 – 50 percent of the electricity used for lighting could be saved by investing in energy efficient lighting. In most cases these investments are not only profitable, but also maintain or improve lighting quality ^[28]. One example is light-emitting diode (led), which has a lifetime 50 times longer than an incandescent lamp.

New equipments with lowest stand-by power

Numerous scientific studies show that in European households, at least 10 percent of electricity consumption is wasted through leakage ^[29]. Replacement of existing appliances with those appliances having the lowest stand-by power losses would reduce standby power consumption substantially. In the medium and long-term, leaking losses can be reduced by ~ 80 percent by applying simple standards such as the US Presidential 1 Watt Order, which prescribes a maximum leaking loss of 1 Watt for a number of appliances ^[30].

Reducing energy outside office hours

Offices are used approximately 2,000 hours a year. In many cases, the electricity consumption outside of office hours can be reduced substantially. Often ventilators, computers, printers and faxes continue operating, or are in standby mode. Simple measures can reduce this power consumption by 90 percent ^[22].

Efficient cooling

Cooling energy can be reduced in three ways: One possibility is to reduce the cooling load on a building; a second alternative is to use passive techniques to meet some, or all, of the load; and a third option is to improve the efficiency of cooling equipment and thermal distribution systems ^[11].

Introduction of current best practice cooling equipment could lead to a specific electricity reduction of approximately 40 percent, compared to the current average level. In the event new techniques are used, the potential for energy savings are 80 percent compared with the current average energy consumption ^[31]. There is also a significant potential for more efficient cooling in non-OECD-countries ^[13].

Most of the measures related to increased energy efficiency are considered to be cost-effective. Several studies suggest that energy efficiency measures can provide less demand for energy both in industrial economies, as well as in developing and transition economies.



Plushouse from Freiburg, Germany. The whole roof is photovoltaic.
Source: <http://live.pege.org/2005-plus-energy-village> .

2.4.2. Studies on Energy Efficiency

IPCC

The IPCC Fourth Assessment Report, Working Group III ^[11] argues that measures to increase the energy efficiency in buildings can cost effectively contribute to a 29 percent reduction in the global CO₂ emissions from buildings, within 2020. This potential can be increased by an extra three percent with a carbon price at 20 USD. With a carbon price in the range of 20 to 100 USD, the global potential is estimated at a 36 percent reduction in CO₂ emissions in the building sector by 2020 compared to the reference scenario. The IPCC report ^[11] considers a wide range of measures ranging from deployment of low emission technologies, to increased energy efficient lighting and better insulating building materials.

The analysis made by the IPCC is based on 80 different studies of the potential for energy efficiency in buildings. Because there are significant uncertainties regarding the emission reduction potential in several countries, different methodologies are used for different regions.

The Central European University

A study made by the Central European University ^[26] considers the potentials and costs of carbon dioxide mitigation in the world's buildings based on the IPCC, by presenting the potential for global reduction of CO₂ emissions and following cost estimates in the IPCC report. This report concluded that the actual potential for emission reductions is most likely higher than what was presented by the IPCC. This is because available studies concerning the topic often do not address all available measures. In addition, there is a lack of research covering the potential for reduction of CO₂ emissions. This is essential because the potential for low-cost measures in buildings in developing economies is considered to be greater than in the industrialised countries.

IEA

The International Energy Agency (IEA) states that one of the largest global GHG emission reduction potentials is energy efficiency improvements in the end-use sector. In the Energy Technology Perspective 2006 ^[5] IEA presents the Accelerated Technology (ACT) scenarios, which are used as possible scenarios that anticipate the development in global energy demand and GHG emissions in 2050. In several of the ACT scenarios the final energy demand is reduced by 23 percent in comparison with the Baseline Scenario. 18 percent of this reduction occurs in the service sector, and 34 percent in the residential sector.

MIT

A study by Massachusetts Institute of Technology (MIT) ^[32] concludes that the potential for energy efficiency from new equipments, installation and buildings are five percent, or more, per year. For industrialized countries there is a potential for efficiency in total energy use of 50 percent by 2050. Such significant improvements require large innovations in energy efficiency and policy.

EU

The EU target is 20 percent increased energy efficiency by 2020 ^[33] compared with a business as usual scenario. In the action plan for energy efficiency the potential for reduced energy consumption in the residential and commercial building sector is calculated to be in the range of 27 to 33 percent by 2020.

Ecofys

The Ecofys ^[22] study concludes that the potential for energy efficiency in residential, commercial and public services is around 50 percent by 2050 compared with the reference scenario. This scenario is called the Ambitious Scenario and contains current best practice technologies and available technologies in the future. Ecofys has also a constraint scenario which is more moderate. This Ambitious Scenario takes implementation constraints of energy efficient technologies in terms of cost and other barriers into account. According to this scenario the potential of energy savings in these sectors is approximately 15,400 TWh by 2050.

The study defines six measures to reduce energy demand in residential, commercial and public services as summarised in the table below.

Table 2.1. Measures for reducing energy demand from residential, commercial and public services according to the Ecofys study ^[22].

Measures	Total electricity consumption (%)	Reduction potential by 2050 (%)
Efficient appliances	25 (household and services)	75
More efficient cooling	15 (service sector)	60
Efficient lighting	33 (buildings)	50
New equipments with lowest stand-by power	5-13 (OECD-countries)	70
New buildings and improved heat		40 in OECD, 20 other regions
Reducing energy outside office hours	25	90

For energy use in agriculture, as well as in none-specified sectors, it is assumed that the energy saving potential is the same as in the household and public and commercial sector.

The Ecofys Scenario ^[22] is achievable based on the assumption of continuous innovation in energy efficiency. Climate change and growing energy demand are going to change the way we consume energy. In previous periods with energy supply constraints a reduction in consumption was observed. During the period from 1973 to 1985, oil crises, higher energy prices and enhanced energy policy led to declined energy consumption ^[32]. It can be assumed that climate change will trigger robust policy efforts on energy efficiency, especially because this is one of the most cost-effective climate measures. The Bellona Scenario is based on the assumptions in the Ambitious Scenario in the Ecofys study ^[22].

2.5. Emission Reduction Strategies in the Transport Sector

Key messages

- Energy use and emissions from transportation will continue to grow faster than most other sectors of society and increase by almost 50 percent from 2004 to 2030 if we do not take action.
- Turning to new technologies and clean and renewable transport fuels can significantly reduce energy use and GHG emissions: In the Bellona Scenario energy use is reduced by one-third, and fossil fuels are projected to decrease their market share from 93-95 percent to less than 25 percent.
- Electrical propulsion is the most energy efficient technology available and should be implemented where technologically and economically feasible. Due to technological constraints and large diversity in transport needs alternatives like biofuels and hydrogen will also need to be developed.

Greenhouse gas emissions from the transport sector comprise approximately 20 percent of total global energy-related CO₂ emissions or 13 percent of all GHG-emissions, ref Figure 2.1. Energy use is growing faster in this sector than in most other sectors of the society, and this trend is expected to continue. IEA projects energy needed for transportation to increase by almost 50 percent from 2004 to 2030. In this projection air transport - the most energy intensive mode of transport – has the strongest growth with 3.3 percent annually. Transportation by bus is projected to decrease both in total volume and in market share and the relatively energy-intensive use of medium-sized trucks has the largest projected growth for cargo transport. (WBCSD 2004 ^[34] page 31)

These developments are caused by general trends in society. Per capita income is increasing throughout the world. This leads to increased consumption and increased demand for raw materials and products. Global integration increases freight transportation volumes as well as transportation distances, and the need for frequent and predictable deliveries favour road transport. Also, passenger transportation is increasing – both due to longer commuting distances and more work and holiday-related travel.



If we do not act with determination, energy use for transportation is expected to double within the coming 40 years. Photo: Istock.

The task of reducing energy consumption and GHG emissions from transportation needs to take a wide range of factors into consideration. Projected growth in transportation demand can be addressed either through measures to reduce consumption, or through measures to reduce the transportation related to the production, distribution and consumption of goods and services. These measures are challenging since they involve trade systems and go to the core of how we arrange our societies and live our lives today. In addition, the environmental consequences of production vary from place to place, and long distance transport does reduce life cycle emissions for some products. Therefore, analytical tools are needed to assess the life cycle consequences of both production and logistic chains.

Another way to reduce GHG emissions from transportation is to increase the share of the more energy efficient transportation forms (using ships instead of trucks, trains and busses instead of cars and planes, etc.) and by using them more efficiently (fully loaded, optimized routing, etc). In addition, the energy efficiency of each vehicle, plane, ship, etc. can be improved and clean and renewable fuels can replace carbon-intensive fossil fuels.

Literature on energy use and GHG emissions from transport can typically be divided into two groups. The first group consists of IEA-dominated projections of energy-use and GHG emissions. The second group of literature analyzes the various technological options at hand – providing descriptions and efficiency characteristics, as well as life cycle energy use and GHG emissions – but does not describe implementation scenarios. Both approaches will be discussed and used when creating the Bellona Scenario.

In the following paragraphs we establish criteria to evaluate and compare a number of transport technologies and assess their role in improving the environmental performance of transportation.

We also show how implementation of new technologies can reduce energy use and GHG emissions. Although improving the transport sector through technology alone is a limited approach compared to the wide range of options described above, improved transport technologies can make significant contributions. However, when working to reduce energy use and CO₂ emissions from transportation all options should be explored. Clean and renewable energy carriers and fuels will be in limited supply for years to come, and without economizing on their use, the emission reduction potentials available in the transport sector will not be realized.

2.5.1. Energy Projections

IEA

Table 2.2 below is based on IEA data from the World Energy Outlook 2006 (WEO) ^[13] and the World Business Council on Sustainable Development 2004 (WBCSD) ^[34]. Data, especially for shipping vary from source to source. For example, the International Maritime Organization has in a recent and thorough study calculated consumption figures for shipping significantly higher than IEA/WBCSD, and projects a consumption of 6,560 TWh in 2030. (IMO 2008 MEPC 57-4). But for the sake of consistency, we have used the IEA-based sources for all transport modes.

Table 2.2. *Business as usual scenario for energy demand in the transport sector. Energy data adapted from WEO 2006 ^[13] and WBCSD 2004 ^[34], all figures in TWh.*

	2005	2010	2015	2020	2030	2040	2050
Road	18,600	20,200	21,900	23,600	27,000	30,400	33,700
Aviation	2,900	3,400	4,000	4,500	5,600	6,700	7,700
Shipping	2,300	2,500	2,800	3,000	3,500	4,000	4,400
Rail	380	410	450	490	570	640	720
Total	24,100	26,600	29,100	31,600	36,600	41,600	46,600

Expected growth is greater than projected efficiency improvements¹ leading to a projected doubling in energy consumption in the transport sector.

IEA also develops more technologically optimistic scenarios, but as the main principles of the model are left unchanged, the projections are not fundamentally altered. For example the IEA *alternative scenario* projects energy use for transportation to be only 10 percent below projections in the business as usual Scenario (BAU).

The Vattenfall report

There are examples of more policy-related analyses, like Vattenfall's "*The Landscape of Global Abatement Opportunities up to 2030*" ^[35]. This analysis is also based on IEA scenarios and WBCSD transport models, but unlike these publications the Vattenfall report includes specific policy measures and the resulting emission reductions and costs. The report identifies some true win-win measures with negative abatement cost as shown in the figure below.

¹ 18 percent for light duty vehicles and 29 percent for heavy duty trucks and airplanes over the 2000-2050 period, WBCSD 2004: 37 ^[34]

		Abatement potential, Gt CO ₂ e/year, 2030	Marginal abatement cost, EUR/t CO ₂ e, 2030
1. Fuel efficient technologies	Powertrain and non-engine tech.	0.9	-50 ¹
	Hybrids	0.03	200 ²
	Plug-in hybrids	0.2	90 ³
2. Fuel switch ⁴	Grain ethanol	<0.01	780
	Sugarcane ethanol	0.5	-25
	Cellulosic ethanol ⁵	0.8	6
	Biodiesel	0.1	70
3. Demand reduction	VMT reduction from CO ₂ tax	0.2	40
	Smart transit	0.2	0
Total, million tons		3.0	

Figure 2.5. Abatement potentials and marginal abatement cost. Source: Vattenfall 2007:10^[35].

The above measures can reduce GHG emissions from transportation by three million tonnes CO₂-eq relative to the IEA projection for 2030 – but are not enough to reduce emissions from today’s levels. However, Vattenfall does describe additional reduction potentials: Reductions of ~two billion tonnes CO₂-eq are available “...if policies are pushed harder (e.g. smart transit, or renewable fuels mandates) and/or innovation support advances key technologies (e.g. cheap batteries for hybrids and pure electric vehicles, advanced aircraft and biomass to liquids with CCS)” (page 1).

In a 40 Euros per tonne CO₂ abatement scenario, plug-in hybrids reach 10-20 percent sales share in the various vehicle segments by 2030, hybrids 15-20 percent (page 16) and biofuels more than 40 percent of the market share (page 25). The study has thus identified options that will reduce 2030 emissions below present figures.

To put these figures in perspective; 40 Euros per tonne CO₂ calculated on crude oil corresponds to an additional cost of around USD 25 per barrel². Oil prices in 2007 World Energy outlook are assumed to average USD 63 in 2007 and to fall to USD 57 in real year-2006 dollars by 2015³. This indicates that high oil prices alone⁴ may represent incentives well beyond a CO₂-tax of 40 Euros per tonne. The Vattenfall assumptions range from USD 27 to USD 40 per barrel. It is therefore likely that IEA’s BAU projections are out-dated and that efficiency improvements and fuel and technology shifts will progress faster than projected.

2.5.2. Technology Descriptions

This group of literature analyzes the various technological options at hand – providing efficiency characteristics and data on GHG emissions. The *Concawe/Eucar project*^[36] is one comprehensive and much quoted example of this approach, analyzing a wide range of fuel and technology options. The project however, does not include electric- or plug-in vehicles, so other sources will

² Combustion of typical transport fuels leads to around 3.1 – 3.2 kg of CO₂/kg fuel.

³ WEO 2007:63^[7]

⁴ Oil prices are presently over USD 100 per barrel and are still increasing

be consulted. WWF's *Plugged IN, the End of the Oil Age*^[37] is a systematic review of available literature on alternative fuels, including electricity.

The Bellona Scenario does not modify the IEA estimates on energy efficiency developments for traditional technologies. Although we believe political initiatives would be able to contribute significantly to improved efficiencies, we will not alter these IEA projections. We do not analyze alternative fossil fuels like Methane, Propane, and Gas-to-Liquids (GTL). These fuels may play a future role in the transport sector for reasons of supply and energy security, but since life-cycle emissions from these fuels are about as high as those from diesel and petrol they will not be discussed further here. Similarly, since the objective of the Bellona Scenario is to identify improvement opportunities, neither Coal-to-Liquids nor other fossil-based synthetic fuels are covered.

Traditional propulsion technologies.

As noted above, the IEA BAU Scenario projects mainly the use of combustion engines up to 2030. In order to assess the potential for improvements, some important characteristics of this technology need to be described. Typical estimates on efficiencies for light vehicles range from 10-20 percent for gasoline, and 15-25 percent for diesel engines⁵. This means that 10-25 percent of the energy available in the fuel is transformed to mechanical energy to move the vehicle; the rest is wasted, mainly as heat. Bellona uses the well-documented efficiency estimates from *Plugged In*, quoted above: 18 percent for gasoline engines and 23 percent for diesel engines. These figures appear to be quite low considering that technology has been developed and refined for more than 100 years. These are not the efficiencies for engines operating at optimal load conditions, but averages for cars when tested under conditions similar to real life use – the so-called standardized test cycles. Efficiencies under optimal conditions are close to double.

Heavy duty vehicles have more efficient engines and larger proportions of their driving occurs on uncongested roads and outside cities, so efficiencies for these engines are estimated at 30 percent. In ships, the use of large slow speed engines improves energy efficiencies further, today approaching 55 percent at optimal loads.

Fossil fuels

Well-to-tank efficiencies for diesel and gasoline – i.e. extraction, refining and transport - are usually calculated around 85 percent.

Hybrids

Hybrid technology combines a combustion engine with batteries and electrical engine(s). This reduces energy consumption due to improved energy management and due to regenerative braking and reduced idling. Efficiency improvements in hybrids compared to traditional technologies depend significantly on driving conditions. Urban vehicles, busses in particular, have high improvements of up to 40 percent due to abundant acceleration and braking. Typical highway vehicles – like heavy duty long haul vehicles - have minimal gains from hybridization. Smaller vehicles improve their efficiency around 25 percent through hybridization. A number of light vehicle hybrids are on the road today (Toyota has sold more than 1 million Prius vehicles),

⁵ The figures vary quite significantly, since they may be based on different vehicles (size, age, etc.), and different driving conditions (or test cycles).

and the technology is used in busses in a number of research, development and deployment projects around the world.

Plug-in hybrids

Plug-in-hybrid electric vehicles combine battery-electrical technologies and combustion-engine technologies. But, unlike the classical hybrids, they can be charged from the grid and have sufficient battery and engine capacities to function as battery-electrical vehicles for longer distances. The hybrid technology improves vehicle efficiencies and, more importantly, make substitution of fossil fuels by electricity possible. Larger battery capacity also means that longer distances can be based on grid electricity. Estimates based on American travelling patterns show that plug-in-hybrids with battery capacity sufficient for 48 km of electric driving can base their energy consumption on grid electricity for fifty percent of all driving⁶.

Plug-in hybrids have been available in small series from a few producers for years. A version of Renault Kangoo with a 150 km electricity-only range entered the market in 2001 and several large car manufacturers have announced market introduction of plug-in-hybrids in the years to come. Toyota Prius, Chevrolet Volt, BYD and others have announced models coming in 2009/2010 .

For some transport segments plug-in-hybrids can represent a very interesting bridging technology on the way to battery electric vehicles, while for other segments they may play a more long-term role.

Battery-electric and grid connected vehicles

Electric engines convert around 85 percent of the energy in the battery to mechanical energy, but due to losses in energy conversion and regulation the overall efficiency for battery electric vehicles is around 65 percent for on-the-shelf technologies today (*Plugged In*, quoted above). For more advanced technologies, overall vehicle efficiencies are estimated to be around 75 percent⁷. Grid connected trains and busses have higher overall efficiencies since battery losses are avoided.



*Kewet Buddy: A Norwegian built urban electrical vehicle
Photo: The Bellona Foundation.*

⁶ “Plug-In Hybrids: An Environmental and Economic Performance Outlook”, American Council for an Energy Efficient Economy, September 2006 ^[38], quoted in WWF 2008:121 ^[37].

⁷ IEA, Prospects for Hydrogen and Fuel Cells, p.61 ^[39], and M. Åhman, “Primary Energy Efficiency of Alternative Powertrains in Vehicles” ^[40], both quoted in *Plugged In*.

A number of battery-electric vehicles are on the market today. Most of them are either rebuilt conventional cars or small manufactured electrical vehicles. Several battery technologies are available, and their capacity to store energy varies. Lead-acid batteries can store around 30-40 Wh per kg battery, nickel metal-hydrid batteries (NiMH) two to three times more, and Li-Ion more than four times more energy; 100 kg of Li-Ion battery can store around 16 kWh. Other batteries are under development, including lithium titanate batteries with significantly improved durability and fast-charge capabilities (full charge in 10 minutes).

Sixteen kWh would be sufficient for around 100 km driving in a typical light vehicle. Technology development has been significant in recent years, both on price, volume, weight, fast-charge capacity and durability, and the electrical car is very close to a technological breakthrough, becoming competitive in major light vehicle segments. Although some actors like Nissan and Renault have announced that they will offer electrical vehicles commercially in the coming years – probably from 2010/2011 - technology development and market introduction has so far been dominated by the more unconventional actors like Micro Vett, Think, Tesla, Phoenix, and others.

Hydrogen Fuel Cell Electric Engines

Fuel cell technology is still mostly in the research and development stage of development. Hydrogen fuel cells are presently available with capacities up to more than 150 kW for road applications (PEM cells). The present research target cost for a fuel stack is 100 Euro per kW^[41]. Hydrogen fuel cells also deliver electrical power in submarine applications: Siemens PEM FC with 120 kW power has demonstrated electrical efficiencies ranging from 62 percent (full load) to 72 percent (20 percent load).^[42]

Other types of fuels cells, like the MCFC high temperature fuel cell from MTU, are presently available with a power of 363 kW electrical and an additional 250 kW thermal. New generations are planned, including a 1 MW version^[43]. MTU cells are presently running in a number of stationary power supply systems, and work is being done to adapt the fuel cell to work in the power supply system of a Norwegian supply vessel^[44].

Fuel cells have also been tested in air planes. Boeing performed a 20 minute hydrogen-powered test flight in April 2008, but the road to full-scale commercial applications is still long.

There are still challenges related to hydrogen storage and distribution. The volumetric energy density of hydrogen is low. When stored as a liquid, the energy density is 2.6 kWh per litre, around 25 percent of fossil fuels (which means that you need four times the volume of a diesel tank to store the same quantity of energy), and when stored as compressed hydrogen or as metal hydride, even lower. By mass, hydrogen is more power dense than any other relevant fuel: 39 kWh per kg (excluding storage).

Life cycle efficiencies of hydrogen depend on the resource (fossil energy or renewable electricity), and are lower than efficiencies for battery electrical applications for all resources, applications and technologies, ref. Figure 2.6 and Figure 2.7 below.

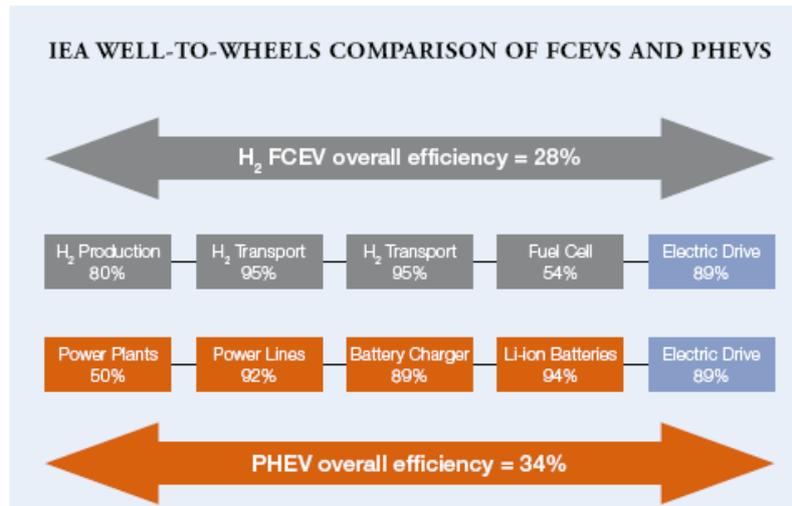


Figure 2.6. Comparison of efficiencies for fuel cell electrical vehicles (upper grey arrow) and battery electrical/plug-in hybrid vehicles (lower arrow), when the primary energy source is natural gas. Source: Plugged In: 145^[37].

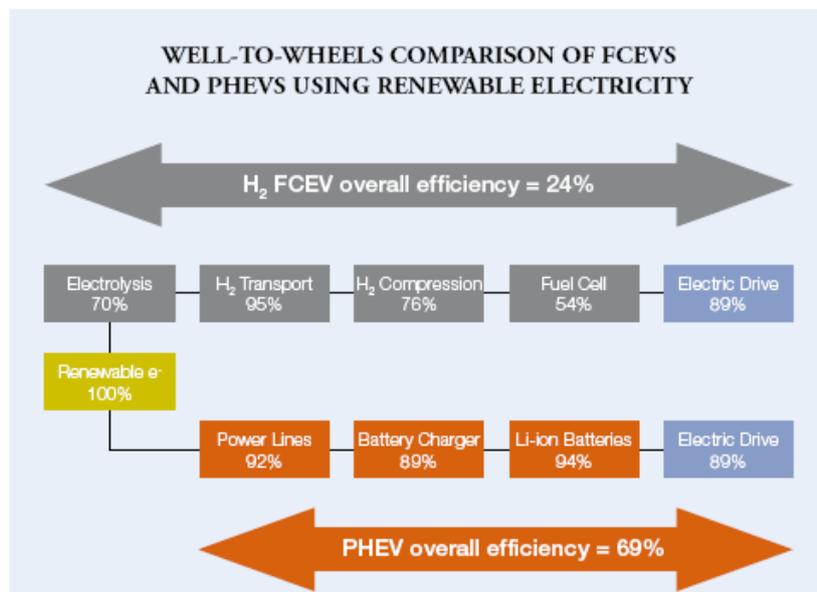


Figure 2.7. Comparison of efficiencies for fuel cell electrical vehicles (upper grey arrow) and battery electrical/plug-in hybrid vehicles (lower arrow), based on renewable electricity. Source: Plugged In: 146^[37]

Biofuels

There are some practical challenges related to using biodiesel, bioethanol and biogas in conventional engines today, but a large range of smaller and larger engines capable of running on biofuels are available, some of them in bi-fuel or flexi-fuel versions, capable of running on several fuels. Second generation biodiesel (based on cellulose) can be used in any diesel engine, resulting in tailpipe GHG emissions slightly below that emitted by fossil fuels. Life-cycle calculations depend on production pathways and vary from unacceptable (when replacing tropical forests or peat land) – through slightly better than fossil fuels (some maize and wheat-based fuels)

to around 90 percent GHG reductions (ethanol from sugar cane and second generation biofuels) ^[45].



*This vehicle is running on biogas made from waste, a very good example of win-win solutions for the transport sector.
Photo: Närkefrakt.*

Emission Reduction Potential in the Transport Sector

The business as usual scenario is founded on IEA projections, which are based on a large range of assumptions on extended economic growth, and extended energy use and transport trends as we know them today. By not taking specific measures to combat climate change into account, the business as usual scenario offers quite significant opportunities for improvement. Below, the focus will be on the technological options available to reduce emissions – mainly through phasing in clean and renewable fuels and their associated technologies. This does not mean that other areas and solutions are seen as unimportant. The work on emission reductions is challenging and no potential solution should be left unexplored. Actions regarding other opportunities, like reducing transport demand, or improving public transport systems, are very welcome and would reduce the costs and efforts required to reduce GHG from the transport sector.

The IEA projections are true business as usual projections. Projections are based mainly on the extension of existing policies and technologies and predict continued domination of combustion engines and of fossil fuels: 93-95 percent of all energy use in the transport sector in 2030 is predicted to be based on fossil fuels. These projections are therefore of limited help when attempting to describe future energy scenarios capable of addressing the challenges of climate change. A transport sector growing more than 2 percent annually⁸, and totally dependent on fossil

⁸ From 2000-2050: Light duty vehicles: 123 percent; heavy duty vehicles: 241 percent; air transport: 400 percent. WBCSD 2004^[34].

fuels and technologies with very moderate efficiency gains will lead to an increase in GHG emissions from approximately 5 GtCO₂ annually in 2000 to approximately 12 GtCO₂ in 2050⁹ – resulting in a truly unsustainable future.

We need to turn to new technologies and new transport fuels to significantly reduce emissions from the transport sector. The following section will discuss how improved energy fuels and technologies can be phased into the various transport modes and transport functions. The result of this discussion is not a projection, since consistent political decisions are needed to overcome barriers related to acceptance and cost of new technologies, as well as requirements for new infrastructure. However, the technological challenges are surmountable and the long-term benefits are significant, so it is time for action.

It is possible to identify markets, both geographically and by function, that offer good starting points for improved technologies. Technologically advanced countries in North America, the EU and Asia, as well as some emerging economies, provide good starting points for electric and plug-in hybrid vehicles. Densely populated areas and urban transport systems are the easiest places to start; long haul transport systems are more challenging.

As history has shown, speculating on technological development is a risky business. This is particularly relevant when discussing and comparing the future of hydrogen versus electricity as the preferred energy carrier in the transport sector. Hydrogen and electricity have their similarities. Both are energy carriers that can be produced from renewable energy sources, or from fossil fuels with CCS, and both energy carriers have challenges to overcome before they can be widely implemented in the transport sector. Cost reductions and improved capacities to store energy are needed for both technologies. In addition, the hydrogen fuel cell still needs improvements in durability in order to serve the transport market.

The superior life-cycle energy efficiency of electrical vehicles makes electrical propulsion the better choice – where electricity can be implemented. We have seen that grid to wheel efficiency of a fuel-cell-electric vehicle is around 25 percent compared to almost 70 percent for battery electric and grid connected vehicles. Overall efficiencies based on natural gas are 34 percent for electrical vehicles compared to 28 percent for fuel cell vehicles.

Life cycle comparisons of fuel cell technologies and combustion engines depend on driving conditions. Fuel cells perform better in applications with variable loads (busses, ferries, etc.), due to the large efficiency loss of combustion engines at partial loads, but efficiency gains in a life-cycle perspective are more uncertain for larger applications running at optimal loads (long haul trucks, and deep sea shipping).

But even with historical and projected developments reducing cost, and improving durability, storage capacity and charging speed, battery-electric propulsion systems cannot replace fossil fuels for all transport modes and markets. Batteries with energy densities 3 times today's Li-ion batteries would provide an energy density of around 500 Wh per kg, giving 100 kg of batteries a capacity of 50 kWh, enough for more than 300 km of light vehicle driving. With fast charging capacities this makes electrical vehicles technically capable of serving most of the light vehicle market by 2030. A tripling of energy densities within more than 20 years is a moderate assumption, compared to historical developments, and batteries with fast-charging capacity are already available today.

⁹ WBCSD 2004^[34], quoted in IPCC 2007:334 ^[1].

For trucks and busses that drive long distances and cross national borders and sparsely populated areas, the use of battery electric propulsion systems will still be challenging in 2030. Typical consumption figures for a traditional 40-ton vehicle are around 350 kWh or 35 liters of fuel per 100 km. Electric propulsion would reduce energy consumption for this kind of vehicle by around 50 percent; they would need around 350 kg of batteries per 100 km. With the right initiatives and policies the battery-electric technology should be technically capable of covering most of the long haul truck and bus market, but it would require a massive deployment of charging facilities and improved electrical infrastructure.

Supplements from biomass, hydrogen and possibly some fossil fuels will therefore probably be needed in years to come. As discussed previously, biomass and fossil fuels are less suited for the transport sector due to the low efficiency in the combustion engine. In addition, biomass is likely to be a scarce resource in the years to come and will be in demand both to replace fossil energy and petrochemical products. Biofuels should therefore only be used in the transport segments when other clean, or renewable, alternatives are unavailable.

Although we support the long-term implementation of battery electric vehicles in all transport sectors, we strongly recommend strengthening research and development of other fuels and technologies also for road transport. As discussed below, alternative fuels will probably play an important long-term role for other transport modes, and road transport applications can be an important arena to research, test and expose new technologies.

Sea and air transport

Liquid hydrogen needs four times as much storage volume as typical conventional transportation fuels. Liquid hydrogen could be an acceptable energy carrier for some maritime applications first, later on possibly for aviation purposes. This will require significant technological developments to reach acceptable cost levels. Large-scale research projects and commercial developments are ongoing, and within a 20 year period, we should be able to see the progress needed, assuming the right political decisions are made. Biofuels can be used for all transport purposes within very few years time; here the challenge is more related to limited supply, as discussed in section 2.6.3.



The Norwegian shipowner Eidesvik is involved in developing maritime applications for fuel cells. The use of fuel cells in ships can improve energy efficiency and reduce GHG-emissions significantly. Photo: Eidesvik

The previous paragraphs have argued that improved technologies are feasible for a range of transport applications. How fast, and in which market segments they will be implemented, depend not only on technology and cost developments, but also on political decisions. The transport sector is complex with large variation between the various transport modes and transport functions, and technological breakthroughs are often unpredicted. In addition, resources vary around the world, so it makes little sense to pick one technological winner and stop researching and developing alternatives. Therefore, we take a composite approach towards the future, making use of many of the technologies discussed.

As discussed above, our transport scenario is no projection, or prediction of the future. It is a demonstration of possibilities based on present knowledge and expectations. It will be a disappointment, and a surprise, if researchers and industries do not come up with technologies and approaches not covered in the Bellona scenario, technologies that will alter both assumptions and results. Nevertheless, in order to be able to establish the Bellona Scenario, targets are needed on these issues, and the inputs to the transport sector are summarized in the table below.

Table 2.3. Implementation of new fuels and technologies. All figures are percentages of number of vehicles, and all implementation is linear from the stated year up to 2050.

OECD 2050	Fossil fuels	Electricity	H2	Biofuels	Implementation
Road transport	0 %	100 %	0 %	0 %	Electricity from 2015
Sea transport	50 %	0 %	25 %	25 %	Hydrogen from 2030, biofuels from 2020
Aviation	0 %	0 %	0 %	100 %	Biofuels from 2020

NON-OECD 2050	Fossil fuels	Electricity	H2	Biofuels	Implementation
Road transport	25 %	50 %	0 %	25 %	Bio from 2010, electricity from 2015
Sea transport	50 %	0 %	25 %	25 %	Hydrogen from 2030, biofuels from 2020
Aviation	0 %	0 %	0 %	100 %	Biofuels from 2020

Even though it is very probably that hybrid and plug-in-hybrid vehicles to a large extent will be replaced by electrical vehicles before 2050, they will play an important role in increasing energy efficiencies and reducing emissions beyond what is projected in business as usual scenarios in the years to come. In addition, they will be an important platform on which to improve electricity-based transportation technologies.

With the assumptions on energy efficiencies discussed in the *energy technologies* section and the implementation tables above, energy use is calculated in the Bellona Scenario in Table 2.4 and in Table 2.5.

Table 2.4. Energy use for transportation in the Bellona Scenario, per transport mode.
All figures in TWh.

	2005	2010	2015	2020	2030	2040	2050
Road	18,600	20,200	21,900	22,000	21,500	20,500	18900
Aviation	2,900	3,400	4,000	4,500	5,600	6,700	7,800
Shipping	2,300	2,500	2,800	3,000	3,500	3,800	4,100
Rail	380	400	450	490	570	640	720
TOTAL	24,100	26,600	29,100	30,000	31,200	31,600	31,500

Table 2.5. Energy use for transportation in the Bellona Scenario, per energy carrier.
All figures in TWh.

	2005	2010	2015	2020	2030	2040	2050
Fossil fuels	23,700	26,200	28,400	27,900	23,500	16,500	7,300
Biofuels	0	0	290	660	3,800	8,200	13,900
Electricity	370	410	450	1,460	3,790	6,490	9,490
Hydrogen	0	0	0	0	0	370	830
TOTAL	24,100	26,600	29,100	30,000	31,200	31,600	31,500

Compared to the business as usual scenario in Table 2.2, energy use is reduced by one-third, and the use of renewable and clean fuels is significant in the Bellona Scenario.

2.6. Renewable Energy

Key messages

- Today, biomass and hydroelectric power are the main sources of renewable energy. Biomass and waste provide 10 percent of primary energy supply, while hydro power and other renewables provide 2 and 0.5 percent, respectively.
- New renewable energy sources like wind and solar power have tremendous growth potential. By providing the right incentives in the early stages of development, wind and solar power have the global potential to supply 6,000 TWh and 11,000 TWh annually by 2050, respectively.
- The output of bioenergy from forestry, agriculture and potentially also from aquaculture, could be increased drastically. As a *sustainable* part of a GHG mitigation strategy, the potential is more moderate. This study concludes that the bioenergy potential in 2050 is approximately 60,000 TWh per year.

Renewable energy is energy from resources which are naturally replenished - such as sunlight, wind, water, biological processes and geothermal heat. Replacing energy from fossil fuels with renewable energy will be the cornerstone of any strategy to substantially reduce greenhouse gas emissions.

While renewable energy's potential is close to limitless, our ability to transform this potential into usable forms of energy has historically been limited. We have finally reached a point in time when new technologies are available, and are being developed that cost effectively produce renewable energy.



Three energy sources: Sun, wind and biomass. Photo: © Guerito, 2005

2.6.1. Solar Power

The sun is a prerequisite for life as we know it on our planet. With the exception of geothermal energy and tidal water, solar energy is the driving force behind all other renewable energy sources.

The theoretical potential of solar energy is enormous. The amount of solar radiation which reaches the Earth's surface each year is more than 12,000 times the world's current energy consumption.

Today 1.7 billion people around the world live without basic energy services. Eighty percent of them live in rural areas. Solar power has the potential to provide electricity to consumers, as well as industry, in both rural and urban areas.

Overview

The term solar power is used synonymously with solar energy and refers to the conversion of sunlight into electricity. This can be done with photovoltaics (PV), concentrating solar power (CSP) and various other technologies.

Solar power can be delivered to the electric grid directly from large solar power stations, or from smaller grid-connected systems (often placed on rooftops or integrated into buildings). Earlier, off-grid systems had the largest market share, but after the recent European expansion, grid-connected systems have taken the lead.



Concentrating Solar Power

Source: <http://www.wired.com/science/planetearth/multimedia/2005/11/69528?slide=2&slideView=2>

Market Potential, Solar Power

From 2002 to 2006, the solar PV market grew on average 60 percent annually and global installed PV capacity is now 9 GW_p. Almost 50 percent of the global capacity is installed in the European Union ^[46].

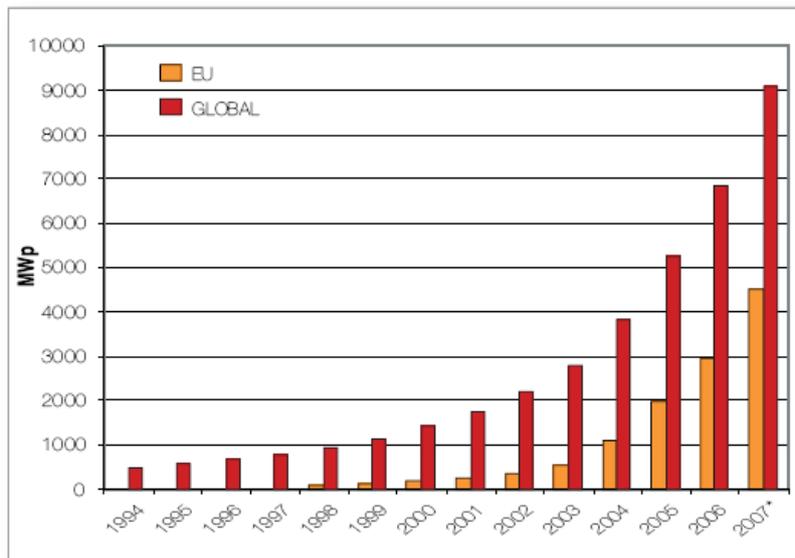


Figure 2.8. Historical development of cumulative installed global and EU PV capacity ^[47].

The solar power market is to a large extent dependent on national support mechanisms like feed-in tariffs and tax credits. Currently, electricity produced from PV is only price competitive with 5-10 percent of the electricity delivered to households in OECD countries. In the past, cost improvements in solar PV have been as high as 20-25 percent with each doubling of installed capacity ^[48], and further cost reductions are expected. By 2010, electricity produced from PV is

expected to be competitive with 50 percent of the electricity delivered to households in OECD countries ^[49].

By the end of the year 2007, solar power provided less than one thousandth of the global energy supply and the variations in expectations for the future market share of solar power are quite large.

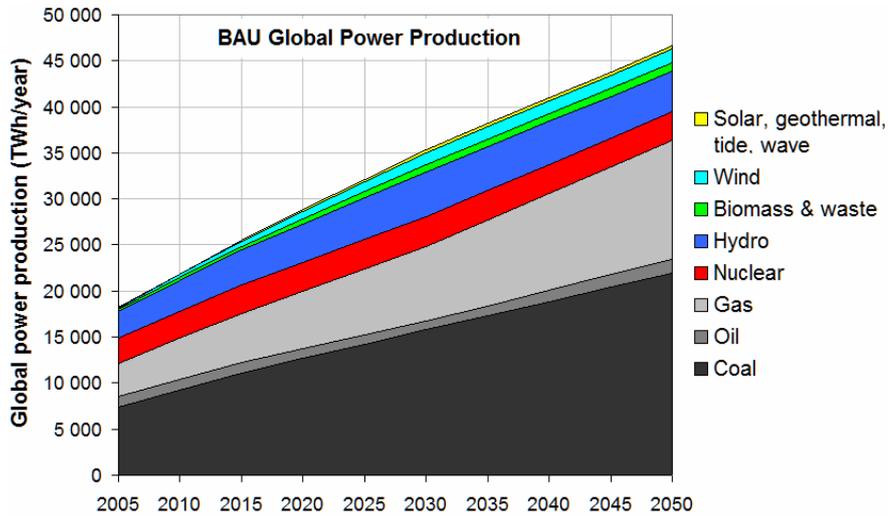


Figure 2.9. IEA's ^[5,7] business as usual scenario for power production. Solar, tide and wave power production can not be seen in the figure because they have too low production.

IEA's business as usual scenario (pictured above) describes a quite modest increase in solar power market share, while others expect the growth in solar power to be dramatic (see picture below).

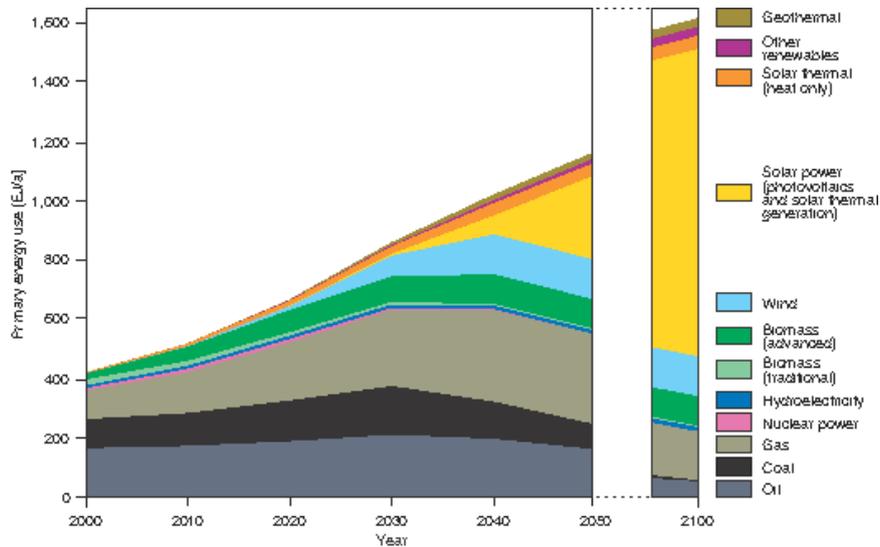


Figure 2.10. Expected growth in solar power. Source: German Advisory Council on Global Change - Berlin 2003.

The report *Solar Generation IV* was published by the European Photovoltaic Industry Association and Greenpeace in 2007. This report provides a thorough evaluation of the future market potential

for solar power, as well as the possible obstacles for the supplier side. According to the report, total installed PV capacity could be 1,272 GW_p by 2030, (i.e. 144 times larger than current installed capacity).

The market for Concentrating Solar Power is also expected to experience significant growth. The European Renewable Energy Council and Greenpeace^[8] estimate that this market will grow from 1 TWh in 2003 to 2,933 TWh in 2050.

In its “high-range case” that assumes aggressive action to prevent further global warming, McKinsey estimates a combined growth in U.S. solar PV and Concentrating Solar Power capacity from less than 1 GW today to 228 GW in 2030^[48].

Solar Power in the Bellona Scenario

As described above, the different estimates for solar energy growth potentials vary significantly. The assumptions behind the different scenarios are also quite varied, ranging from business as usual where no major political changes are assumed, to scenarios based on theoretical energy potential. Some scenarios are driven by cost assumptions and others by assumptions for production capacity.

Solar power growth will depend on continued technological development and learning rate improvements - to bring efficiency rates up and costs down. Installations of PV cells and modules around the world have been growing at an average rate of more than 35 percent since 1998^[50]. Already by 2010, electricity produced from PV is expected to be competitive with 50 percent of the electricity delivered to households in OECD countries^[49]. The market for solar power is enormous and when prices reach parity with other electricity sources, the demand for solar power is expected to dramatically accelerate.

Bellona has used the “Advanced Scenario” from *Solar Generation IV – 2007*^[50] as the basis for expected PV growth from 2008 to 2030. This scenario assumes that continuing and additional market support mechanisms will result in economies of scale that will further reduce PV prices to levels where solar power is competitive with other electricity sources.

After 2030, Bellona assumes very limited growth in solar production capacity (see production capacity graph below). By 2030, annual production capacity will have reached more than 170 GW per year. These production facilities will continue to deliver, resulting in continued PV market growth. The Bellona Scenario shows that global PV installations can provide 8,100 TWh per year by 2050.

Table 2.6. Future Solar Power production in the Bellona Scenario

Solar Power (TWh/year)	2010	2020	2030	2040	2050
Photovoltaics	25	300	1 800	5 100	8 100
Concentrating Solar Power	9	200	900	1 900	2 900

PV, Annual Installation Capacity

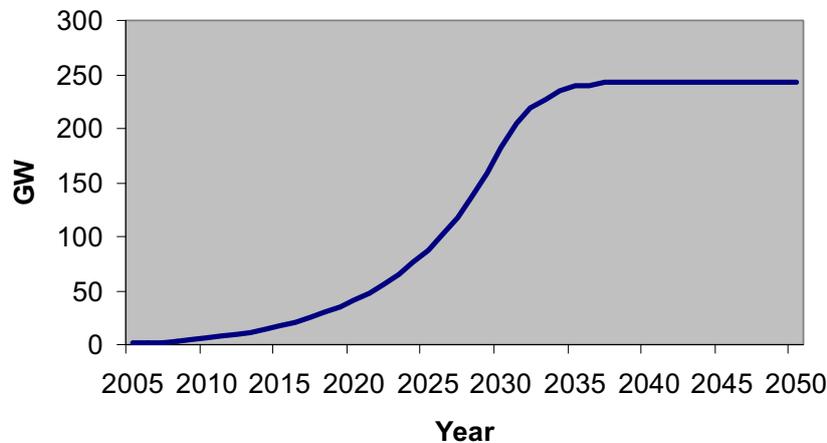


Figure 2.11. PV Production capacity growth addressed in the Bellona Scenario

Concentrating Solar Power (CSP) is expected to experience a similar, but less dramatic, cost compression. The Bellona Scenario for CSP is based on “the Alternative Scenario”, published by the European Renewable Energy Council and Greenpeace^[8].

2.6.2. Wind Power

During daytime, heat from the sun warms the Earth and warm air rises. The cold air that moves in to replace the warm air creates movement (wind). This wind-flow represents energy of enormous proportions, but only a small amount can be utilised for wind energy production.

Overview

Wind power is the conversion of wind energy into more useful forms (such as electricity), using wind turbines. Traditional windmills used the wind energy directly to crush grain or pump water. Today, wind power is produced in large-scale wind farms connected to electrical grids, as well as in individual turbines that provide electricity to isolated locations.

The amount of electricity produced, varies with wind conditions. This intermittency limits wind power potential requiring that wind is combined with other energy sources. However, if one establishes a system of wind parks at different locations, the risk of little or no wind is reduced by geographic diversification.



A wind turbine consists of a tower, blades, and a nacelle containing the generator, gears and control system. The wind puts the blades in motion in the same way that an airplane wing gives lift to the plane. Energy is transferred from the turbine via the drive shaft to the generator inside the nacelle. The generator transforms the kinetic energy to electric energy, which is in turn transferred to the grid via a transformer. Photo: Photo: stock.xchng.

Market Potential

Total installed capacity for wind power was 94 GW in 2007. Wind energy is now increasing more than any other power technology in Europe, and wind represented 40 percent of total new power in 2007, according to the European Wind Energy Association.

GLOBAL CUMULATIVE INSTALLED CAPACITY 1996-2007

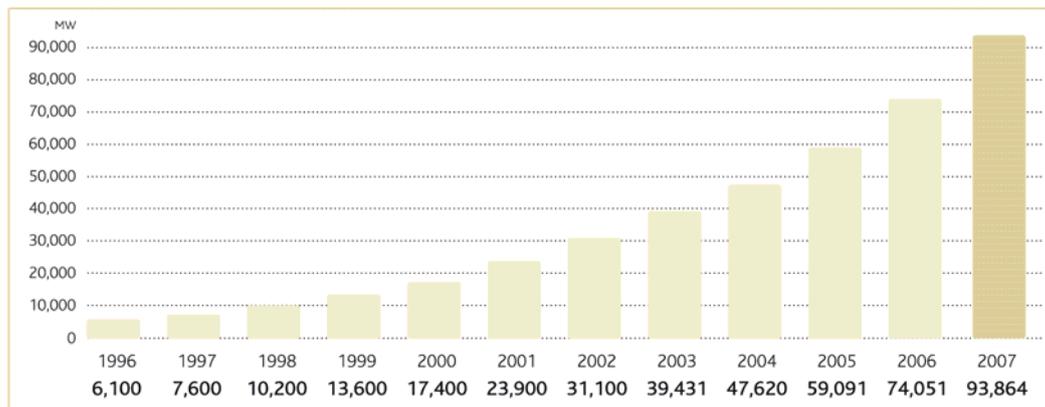


Figure 2.12. Total installed capacity for wind power 1996-2007 ^[51]

On January 23rd, 2008, the EU proposed binding targets for renewable energy for all its member states. If this proposal is adopted as law, the EU is committed to produce 20 percent of its energy consumption from renewable sources by 2020. The EU has also committed to increase this percentage up to 30 percent if other major states (e.g. the U.S.), make similar commitments. For 20 percent of the EU's energy consumption to be based on renewable sources, the power sector will have to increase its share of renewable energy to 34 percent. Most of this increase is expected to come from increased use of biomass and wind power. The EU estimates that wind will provide

approximately 540 TWh of electricity in 2020 ^[52] compared to approximately 83 TWh in 2005. The EU expects a lot of this growth to come from off-shore wind. Off-shore wind is still in an early stage but has enormous potential. A study on the potential for off-shore wind power on the Norwegian continental shelf ^[53] concluded the physical wind power potential to be 14,000 TWh per year. This is equivalent to four times the annual power generation in Europe. The Danish energy company Dong Energy is currently in the process of building a 230 MW off-shore wind park off the Danish coast. This will be the world's largest off-shore wind park to date, with 98 windmills ranging from 98 to 100 meters in height ^[54].

The Greenpeace/EREC report published in January 2007, provides an “alternative scenario” with significant growth in wind power ^[8]. Most of the capacity growth is expected before 2030. It is interesting to note that the actual growth that has occurred since this scenario was made has been much larger than expected. The expected cumulative capacity in 2010 of 108 GW will be reached in 2008.

The Global Wind Energy Council, (GWEC) estimates that global installed wind capacity will increase from 94 GW in 2007 to 240 GW by the end of 2012 ^[51].

In McKinsey's “high-range case”, that assumes aggressive action to prevent further global warming ^[48], it is estimated that U.S. wind capacity could increase from 10 GW in 2005 to 164 GW by 2030, based on an abatement cost of less than USD 50 per tonne of CO₂. This estimate includes on-shore wind only and does not assume that off-shore wind will become competitive.

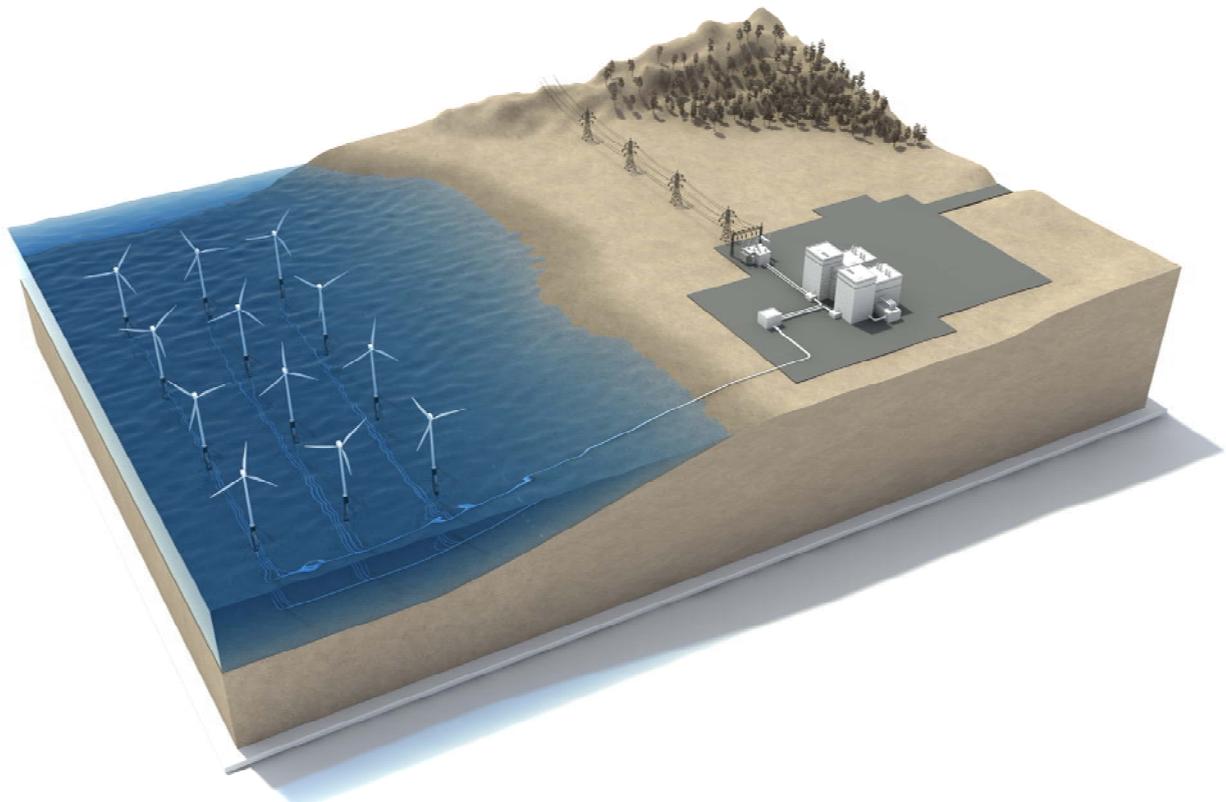


Illustration of offshore wind power. Source: Prosjektlab.

Wind Power in the Bellona Scenario

Wind power is a more mature technology than solar power and has experienced a tremendous growth the last decade. The Bellona Scenario is based on GWEC's market forecast for 2008-2012^[51]. GWEC has collected data from more than 70 countries and expects historical growth rates to continue - resulting in a global installed capacity of 240 GW by the end of 2012. Bellona assumes that capacity growth will slow down after 2012.

Table 2.7. Average growth in installation capacity for wind power 2013-2050

	2013-2020	2021-2030	2031-2040	2041-2050
Average Growth in Installation Capacity	8 %	4 %	3 %	1 %

This capacity growth will result in the following cumulative installed capacities:

Table 2.8. Total installed capacity 2010-2050

	2010	2020	2030	2040	2050
Total Installed Capacity (GW)	170	670	1 400	2 300	3 000

For comparison, McKinsey's "high-range case", which assumes aggressive action to prevent global warming but limits abatement costs to USD 50 per tonne of CO₂, shows installed wind capacity in the U.S. increasing from 10 GW in 2005 to 164 GW in 2030^[48]. This increase does not include off-shore wind. A similar increase on the world level would lead to an on-shore installed capacity of approximately 1,000 GW in 2030. The Bellona Scenario assumes that the off-shore wind market will start growing around 2015-2020 and reach significant capacity by 2030. This is consistent with EU expectations. In its "Renewable Energy Road Map"^[55], the EU commission predicts that off-shore wind will represent more than a third of installed wind capacity in Europe by 2020.

Integrating renewable sources like wind and solar power into the existing power system will require major expansion and upgrading of the existing transmission and distribution grids. Governments will have to plan for these new sources of electricity as well as make the regulatory changes needed to encourage renewable energy sources.

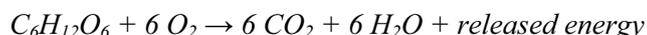
2.6.3. Bioenergy

The term "bioenergy" refers to the utilization of biomass for energy purposes. Essentially, bioenergy is solar energy captured by the photosynthesis, where sunlight, CO₂ and nutrients are converted to various combinations of carbon, hydrogen and oxygen.

Chemical reaction of the photosynthesis:



Chemical reaction of biomass combustion:



The two equations above show that although biomass combustion releases CO₂, biomass can be regarded as carbon neutral, since the amount of CO₂ released is equivalent to amount of CO₂ captured through photosynthesis.

The history of utilization of biomass for energy purposes is as long as the history of mankind. Since the invention of controlled fire, combustion of biomass for heating and cooking has dominated human energy consumption. In rural areas of developing countries, the use of biomass for heating and cooking is still the dominating source of energy. While fossil fuels, together with more advanced renewable and nuclear energy sources have been the driving force of industrialization, bioenergy still contributes significantly to the global supply of primary energy.

According to IEA ^[5], bioenergy (including waste) accounted for approximately 10 percent of the world primary energy supply, or 14,000 TWh in 2004. The traditional biomass use of wood and manure for heating and cooking dominates, and accounts for approximately 11,000 TWh. The use of biomass varies between regions, and its share of primary energy is typically inversely proportional with GDP per capita and energy consumption per capita. The biomass contribution to primary energy supply is almost 50 percent in Africa, and only 3 percent in OECD countries.

Bioenergy potential

Biomass has been subject to numerous studies in terms of regional and global energy potential, resulting in a wide range of estimates. A review of 17 studies performed by Berndes *et.al.* ^[56] revealed a range in bioenergy potential from 100 EJ per year to 400 EJ per year (27,800 – 111,000 TWh) in 2050. This corresponds to approximately 10 – 40 percent of expected global primary energy demand in 2050.

Sustainability and GHG mitigation challenges

Although bioenergy by definition is renewable energy, its usefulness in a GHG mitigation strategy depends on number of factors. Assessments of energy input and GHG emissions throughout the value chain have shown large variations, ranging from negative net impact compared to fossil fuels for palm oil ^[57], and maize ^[58] to net GHG reductions of up 80-90 percent for sugarcane from Brazil. Factors determining the mitigation performance of bioenergy are:

- Direct emissions, particularly of N₂O from agricultural production.
- Indirect emissions from land-use change (For example, deforestation to provide arable land).
- Released soil carbon due to forestry or agricultural methods.
- Direct emissions of CO₂ from the production, transportation and processing of biomass.
- Reduced biomass carbon sequestration in long-rotation forests.

Bioenergy is also subject to severe concerns in terms of general sustainability, some of which are shared with agriculture and forestry in general, and some more specific:

- Deforestation
- Biodiversity
- Arable land scarcity
- Influence on food prices

- Acute fresh water scarcity
- Long-term phosphorus scarcity (Current reserves last 120 years with current consumption, total reserve base lasts 300 years – and no substitutes exist ^[59].)

Competition with food production

Biofuels compete with food production for agricultural feedstock, and since the increase in biofuel production has occurred at a time of rising food prices, biofuels have been blamed for causing starvation among the poorest people of the world. This criticism is to some extent relevant, as biofuels are the latest arrivals in the food market, and subject to political control. However, the picture is more complex. Soaring food prices are caused by increasing demand, increasing production costs and regional draughts, and further strengthened by financial speculation. Currently, 14 million hectares (or 1 percent of arable land) are used for the production of biofuels, yielding 1 percent of global transportation fuels ^[5]. In comparison, coffee production uses 11 million hectares and cotton 33 million hectares of land. Large areas are also used for alcohol and tobacco production.

Although soaring food prices create an acute crisis for the poor in urban areas that must be dealt with, higher food prices often create a better livelihood for poor farmers, and enable increased agricultural production. Particularly in Africa, agricultural yields have been far below their potential due to artificially low world market prices, caused by production and export subsidies in the OECD countries.

If we wish to maximize world access to food, we could shift our food production down the food chain. In raising livestock that are fed "human food", a large share of energy is lost along the way because farm animals use energy to move, maintain life functions and body heat, reproduce, etc. The amount of food available to the world's population would consequently be greater if we turned feed resources like grains directly into food for humans. The land used to produce feed for farm animals can be used to produce food for humans to a much greater degree than today. The human need for protein can largely be met by soya and other lentils instead of meats.

To summarize, substantial areas of land could in principle be utilized for energy purposes without jeopardizing food supply.

Balancing forest bioenergy with carbon sequestration

In 1998, the global average Gross Annual Increment (GAI) of total growing stock was 3.4 m³ per hectares per year, while the average harvest rate was 0.5 m³ per hectares per year, with significant regional variations. In other words, we harvest less than the growth in forests on average, but some forests are overexploited. Indeed, disregarding regional differences, the harvest of biomass for energy purposes can be performed without reducing the standing biomass. However, using bioenergy in a GHG mitigation strategy must compete with carbon sequestration in forests. Although the removal of biomass does not reduce *standing biomass*, it may reduce the *growth* in standing biomass, and hence the amount of carbon stored. Particularly in long-rotation forests, short term carbon neutrality is challenging to maintain, as the combustion of an old tree releases carbon captured over many decades. Forest management must ensure that the removal of old trees enables the growth of new, faster growing trees. If forest management seeks to optimize the balance between carbon sequestration and biomass harvest, the optimal logging cycle may be prolonged, resulting in lower biomass output.

Challenges related to GHG-mitigation and general sustainability call for a careful approach. In the following review of bioenergy potential, we apply conservative estimates for wood supply, considering the severe ecological constraints, in order to maintain sustainability.

Bioenergy sources

Forests

Forest biomass sources include forest roundwood, forestry residues and plantation forests. The potential energy supply from forests is large in theory. But in practice, this potential is limited by sustainability constraints, such as biodiversity and the conflicting potential for carbon sequestration, by economic constraints such as cost and demand for wood as feedstock for paper and materials, and by technical and institutional constraints.

Forest bioenergy potential

A number of studies have been conducted to estimate the potential for bioenergy from forests when relevant constraints are applied. Smeets and Faaij^[60] present a comprehensive bottom-up estimate of the available supply of biomass for modern energy purposes in 2050 after the demand for industrial roundwood (paper, etc.) and traditional woodfuel has been met.

Forest wood and plantations

The theoretical potential for modern bioenergy from forest wood and plantations based on medium demand and medium plantation scenarios was calculated to be 20,000 TWh per year. When technical, economic and ecological constraints were applied, the potential available supply is reduced to minus 2,220 TWh per year, i.e. the supply is less than the demand.

There are strong arguments for applying a lower scenario for industrial roundwood demand. Most of the scenarios from literature date back to 1996-2000, at which time the expansion of digital media was not fully understood. The future growth in media consumption in emerging economies may to a larger extent be covered by internet. Although current demand for roundwood is increasing, policy measures to increase paper recycling and further market penetration of digital media such as e-books, e-learning, e-administration, e-banking, print on demand etc, may reduce long-term paper demand. The same applies for the demand for traditional woodfuel. Assuming widespread introduction of more efficient renewable energy sources (including small-scale solar and wind, algae or more efficient fuelwood combustion) in rural developing areas, and urbanization, makes lower demand scenarios likely.

Applying the low, instead of medium, scenarios for industrial roundwood (from 8000 TWh to 6,000 TWh) and woodfuel demand (from 7,000 TWh to 5,550 TWh) releases 2,000 and 1,400 TWh for modern bioenergy purposes, respectively, resulting in a surplus of 1,100 TWh per year, available for the substitution of fossil fuels. The contribution from traditional woodfuel to primary energy supply should, however, be included in an estimate of the total contribution from wood to primary energy supply in 2050. Summarizing the above estimates, the contribution by forest wood and plantations to global primary energy supply in 2050 is estimated at 6,700 TWh per year.

Forestry residues

As forests and plantations are harvested for roundwood, residues from both logging and processing become available. Smeets and Faaij^[60] estimated the potential for biomass utilization from residues to be 28 EJ per year, or 7,800 TWh.

Agriculture

Energy rich agricultural feedstocks such as sugarcane, corn, wheat and rape seed can be utilized for energy purposes. Transport fuel applications are particularly interesting, as these feedstocks can easily be adapted into existing fuel infrastructure and vehicles. Production of ethanol and biodiesel from agriculture, often named “first generation biofuels”, has increased rapidly, motivated by historically high oil prices and political incentives ^[11].

Energy crops on agriculture land

Although competition with food production limits the potential for dedicated energy crops on agricultural land, the above discussion shows that significant bioenergy production from energy crops is possible without threatening food security for the poor. The potential is virtually impossible to estimate accurately, but if one assumes that 2.5 percent of arable land is utilized for sugarcane biofuels in 2050, this would yield about 1,700 TWh per year.

Resources available for bioenergy purposes are not limited to existing food grain production. A review of literature performed by the IPCC ^[11] identifies significant potentials for bioenergy feedstock which are briefly described below.

Residues

Agricultural residues can to some extent be used for energy production. The availability depends on the requirement for re-use of residues for maintaining soil fertility, and the competition from other applications. The IPCC ^[11] estimates that the potential lies between 4,200 – 19,400 TWh per year. As increased organic content of soils also could be a strategy for enhancing carbon sequestration, a conservative approach is advised.

Dung

Dung from livestock can be utilized as feedstock for energy, both as traditional bioenergy for heating and cooking, and in modern applications such as biogas. According to the IPCC ^[11], the potential could be 1,400 TWh – 15,300 TWh per year.

Dedicated energy crops on abandoned land

Large areas of land are abandoned because of low profitability, etc. Higher energy prices and policy incentives may provide an opportunity for putting these areas back into production. The IPCC ^[1] cites different estimates of the potential, varying between 22 – 411 EJ per year (6,100 – 114,000 TWh per year).

Marginal and degraded land

Although production costs on marginal and degraded land are expected to be higher as yield is lower, the potential for bioenergy is substantial. The IPCC ^[11] estimates 16,700 – 41,700 TWh per year. It should be noted, however, that other estimates go far beyond this potential. For instance, Smeets ^[61] estimated that 60,000 – 350,000 TWh per year could be produced from surplus land. But, as the land-use change effect on carbon sequestration of increasing arable land is not fully understood, Bellona feels most comfortable applying conservative estimates.

The fast growing *Jatropha* is a very promising crop, in addition to algae, for bioenergy production. The *Jatropha* trees are multi-purpose crops able to grow under severe conditions. They are often planted in areas affected by desertification, and can be used to stop soil degradation. As such, *Jatropha* farms for energy production can be located in areas where food crops normally do not grow, c.f. picture below.



Jatropha plantation. Source: Asia Cleantech (<http://asiacleantech.wordpress.com/>)

New bioenergy sources

Microalgae biomass energy

Algae energy production has been below the radar in the energy debate until recently. The potential for bioenergy from algae are theoretically abundant, and potentially more sustainable than both agriculture and forestry.

Algae have traditionally been used as a food source, as fertilizers, in the production of agar, bioplastics, dyes and colorants, in feedstock, for nutritional purposes, for pharmaceutical purposes, and in pollution control. Algae are now also used in the production of biomass, biofuel and hydrogen.

Algae are some of the fastest growing species and can easily be reprocessed into biofuel. The production potential has been reported to be as high as 11 litres per m² per year^[62]. Sun, water, nutrients and CO₂ are the only elements necessary for algae growth, even on a large-scale basis.

It has been estimated that the US requirements for transport fuel could be covered by microalgae production grown in photobioreactors on an area equivalent to 3 percent of US crop area. However, as soil quality is irrelevant for enclosed algae production, marginal land, which is not suitable for agriculture, could be utilized. The utilization of algae energy is limited by costs, know-how and adequate production equipment. Today, the cost of biodiesel from this kind of microalgae production is approximately 9 times higher than conventional diesel at oil prices of USD 100 per barrel^[63]. However, it seems more than likely that technological development and economies of scale, combined with carbon pricing on fossil fuels, will close the price gap.

The realizable potential for algae energy production is impossible to estimate, as the concept is rather immature. However, theoretical calculations can be made. Assuming an output of 5 litres per m² per year, less than half of the highest reported yields, 30,000 TWh could be produced on a land area equivalent to Texas (700,000 km²).

Sustainability of algae biomass production

Algae biomass can be produced in more or less enclosed systems, thus allowing for water and nutrient recycling and reduced GHG-emissions. Production in industrial enclosed system allows for the utilization of land areas not suitable for agriculture, thus avoiding conflicts with food production.

GHG emissions from biofuel production

The GHG mitigation effect of replacing fossil fuels with biofuels has been questioned. Crutzen *et.al.*^[58] argues that the released N₂O from soil resulting from the use of N-fertilizers more than outweighs the CO₂ savings from the substituted fossil fuels, in the case of bioethanol from maize. This analysis has been criticized for using the wrong assumptions, simplifying calculations and using worst-case examples. Smeets^[64] argues that parts of the emissions associated with biofuels should be accounted for by the byproducts, *i.e.* if the byproduct animal feed replaces conventional animal feed, the related GHG emissions should be linked to the animal feed, and not the biofuel. Furthermore, a crop such as sugarcane has a very low associated N₂O emission. Life cycle assessments have shown that the GHG mitigation effect of sugarcane lies in the area of 50 – 90 percent reduction compared to oil. For simplicity, we assume 70 percent as the average mitigation effect of biofuels.

Summary of bioenergy potential

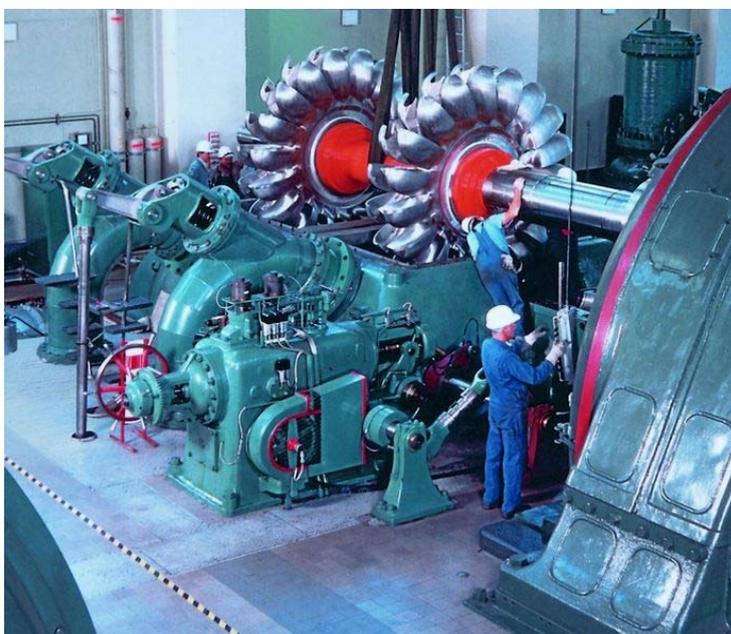
Based on the analysis above, the bioenergy potential is summarized in the table below. Although our conclusions are based on the lower range in estimates from literature, the uncertainty about this potential must be emphasized, especially with regard to the conflict discussed above with the potential for carbon sequestration in forests and soil.

Table 2.9. Summary of bioenergy potential, 2050

Bioenergy	bioenergy potential 2050 (TWh)
Traditional use of woodfuel	5,600
Modern bioenergy from forest and plantations	1,100
Forestry residues	7,800
Crop biofuel (2.5 percent of arable land)	1,700
Agricultural residues	4,200
Dung	1,400 - 15,300
Energy crops on abandoned land	6,100
Energy crops on marginal and degraded land	16,700
Algae	0 - 5,000
Sum	44,600 – 63,500

2.6.4. Hydro Power

Hydropower or hydraulic power is the force or energy of moving water. Hydro power is a mature technology that been used to generate electricity since 1870.



Pelton turbine, Copyright: Voith Siemens Hydro Power Generation.

Overview

By letting water flow through turbines on its way to the sea, we harness the kinetic energy of the moving water to produce electricity. Compared to wind farms and solar power plants, hydroelectric power plants have a very predictable load factor due to large water storage reservoirs that can be dispatched to generate power when needed. Hydroelectric plants can be easily regulated to follow variations in power demand.

Market Potential

In 2005, about 13 percent of global final energy consumption came from renewable energy sources, with 10 percent from traditional biomass^[7]. Large hydropower (producers with installed capacity larger than 10 MW) was the next largest renewable source, providing 3 percent of final energy consumption and approximately 15 percent of the world's electricity production^[65].

Globally, large hydropower grew at an average of 3 percent per year during the five-year period 2002-2006, while small hydropower had a growth rate of approximately 6 percent^[65].

On a global scale, it has been calculated that the total hydropower potential that is technically feasible to exploit is approximately 14,000 TWh per year. Of this, 8,000 TWh per year is considered economically viable^[66]. In its BAU Scenario, the IEA predicts that electricity provided by hydropower will grow from 2,900 TWh per year in 2005 to 4,800 TWh per year in 2030.

Hydro Power in the Bellona Scenario

Hydroelectric power has been used for a long time and is a very mature technology. The future potential for hydro power in the Bellona Scenario is based on IEA's predictions for future hydro power production in the BAU Scenario:

Table 2.10. IEAs business as usual scenario for hydro power production

	2010	2020	2030	2040	2050
Annual Electricity Production (TWh)	3,360	4,150	4,840	4,840	4,840

Bellona assumes that most of this growth will be materialized through modernization and expansion of existing hydro power systems. Some growth is also expected for small scale systems that will become competitive with rising power costs. It is also assumed that environmental considerations are factored into new projects developments.

2.6.5. Other Energies: Geothermal, Wave, Tidal and Salt

In addition to the renewable energy sources mentioned above, which represent the largest and the fastest growing technologies, there are several other emerging technologies such as geothermal energy, wave, tidal and salt power.

Geothermal Energy

Geothermal energy is heat energy from the earth's centre. This is a substantial energy resource. It originates from heat energy stored in the earth's core and mantle. This energy is continually renewed by the splitting of radioactive elements in the earth's crust. Total installed geothermal capacity was 9 GW in 2005 ^[67].

Tidal/Wave Energy

Tidal differences are due to gravitational forces from the sun and the moon. The sea level will rise or fall depending on which part of the earth is facing the moon. Waves are created by this phenomenon.

The largest wave energy potential is in the Atlantic and the Pacific Ocean between 40° and 65° latitude. In these areas, the energy potential is approximately 50 to 100 kW per meter width of the wave summit (wave front). Close to land, energy density diminishes because the waves are hindered by islands and the mainland ^[68].



Picture: Pelamis Wave Energy Machine.

Salt Energy

Salt energy is based on the chemical phenomenon that saline solutions attract fresh water from their surroundings. This is called osmotic power. Even though the phenomenon has been known for hundreds of years and the potential where rivers meet oceans is large, little has been done to develop technologies for this energy source. The Norwegian company Statkraft owns the most advanced salt energy project in the world. Statkraft hopes to have developed an effective salt technology by 2015^[68].

Other Energies in the Bellona Scenario

For other renewable energy sources the Bellona Scenario is based on a combination of Greenpeace/ERECs “Alternative Scenario”^[8] (for geothermal) and IEA’s business as usual scenario (tidal, wave, salt, etc.).

Table 2.11. Other Energies: Annual electricity production 2010-2050

	2010	2020	2030	2040	2050
Annual Electricity Production (TWh)	110	210	370	620	850

Bellona considers these estimates to be extremely conservative but given that tidal, wave and salt are in early stages of development, it is very difficult to accurately project their future impact. The IPCC’s *Fourth Assessment Report* includes tidal and wave energy in key mitigation technologies that are projected to be commercialized before 2030. The global potential for salt energy is estimated to be in the order of 1,600-1,700 TWh, equal to China’s entire electricity demand in 2002^[69].

If the global community follows the IPCC’s advice and facilitates the development of renewable energies on a large-scale, it is quite likely that one or more of these early stage technologies will be a major producer of global renewable energy by 2050.

2.7. Land-use Change

Key messages

Avoided deforestation, establishing new forests and improved forest management can reduce emissions and increase carbon sequestration by 10 GtCO₂ per year by 2050, or 12 percent of BAU emissions. Important positive environmental side effects will also be achieved.

In the context of climate policy, the term *land-use change* refers to changes in land use that either result in CO₂ emissions, or result in increased carbon sequestration.

Globally, vegetation and soils store an amount of carbon equivalent to 7,500 GtCO₂, and 60 percent of this amount is locked up in forest ecosystems^[4]. CO₂ is absorbed from the atmosphere via photosynthesis, and released by natural degradation of biomass, and by anthropogenic land-use changes.

Generally, boreal forest areas in North America, Europe and Russia absorb more CO₂ than they release, while the situation is the opposite in the tropical and subtropical forests in South and Central America, Sub-Saharan Africa and South and East Asia, due to deforestation and unsustainable logging practices. The net global flux of CO₂ from forests to the atmosphere is positive, *i.e.* CO₂ release is higher than CO₂ absorption. According to the IPCC^[11], land use, land-use change and forestry accounts for approximately 8 GtCO₂ net emissions per year, or 17 percent of total anthropogenic emissions. Deforestation accounts for most of these emissions, but the estimates are uncertain, and vary between 2.2 and 9.9 GtCO₂ per year^[4].

The case for a halt in deforestation

Land-use change, and in particular deforestation, is the second largest source of anthropogenic GHG emissions after fossil fuel for energy purposes. But the case for a halt in deforestation is not limited to global warming. Tropical forests, the main victim of deforestation globally, provide a wide range of ecosystem services, such as biodiversity, freshwater, food, and wood as well as livelihood for humans. As 150,000 km² of tropical forests are destructed annually, these ecosystem services disappear with them. Furthermore, deforestation is irreversible, as reforestation measures are unable to copy the complex and diverse ecosystem of tropical forests.

While other measures to reduce GHG emissions have negative side effects, such as demands on land use for renewable power production, curbing deforestation comes with both social and environmental benefits. In fact, the need for protection of the world's tropical forests should be

on the top of the agenda even without its GHG mitigation potential. This calls for a higher cost acceptance for forest conservation compared with other GHG mitigation measures.

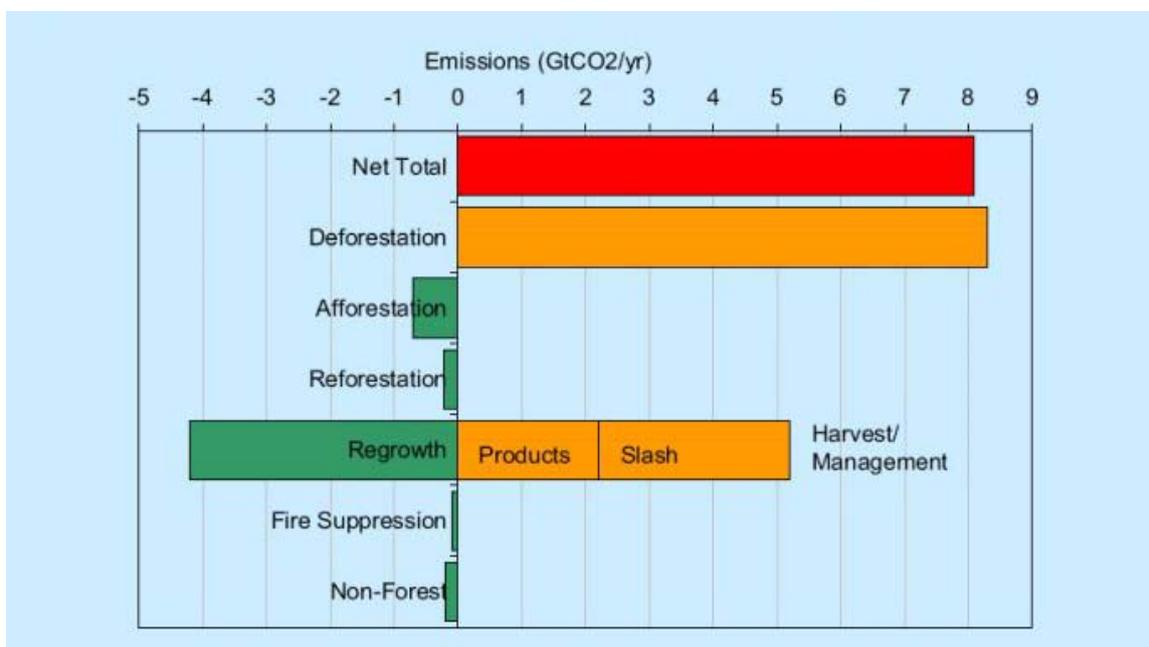


Figure 2.13. Source of emissions from global land-use change 2000. Source: Copied from Stern ^[4].

Economics of deforestation

The main driver behind deforestation is conversion to agricultural land. According to the review by Stern ^[4], observations show that the rate of deforestation is directly influenced by price fluctuation on food commodities. The cost of curbing deforestation is therefore linked to the value of land for agricultural purposes. The net present value of the return on land provided by deforestation varies from USD 2 per hectare for pastoral use, to over USD 1,000 for soya production. A study referred to by Stern, estimates that the return on land provided by deforestation in 8 countries, responsible for 70 percent of land-use GHG emissions, is USD 5 billion annually, excluding value added throughout the value chains. The value of the carbon sequestration on one hectare containing 500 tonnes CO₂ is USD 25,000, assuming a carbon price of USD 50. Although estimates are uncertain, these numbers indicate that CO₂ emissions from deforestation could be achieved at a relatively low cost. ^[4]

A paper published by Sohngen and Beach ^[70] also suggests a large potential. The figure below shows the GHG mitigation potential due to avoided deforestation in four regions at different carbon prices. At USD 27 per ton CO₂ (USD 100 per tonne C), deforestation is almost stopped, resulting in a global annual emission reductions of almost 6 GtCO₂.

The IPCC ^[11] is more conservative in its estimates, assuming an emission reduction of 4 GtCO₂ per year in 2030 at a price below USD 100, based on top-down modeling. Based on regional bottom up estimates, the GHG mitigation potential is even lower.

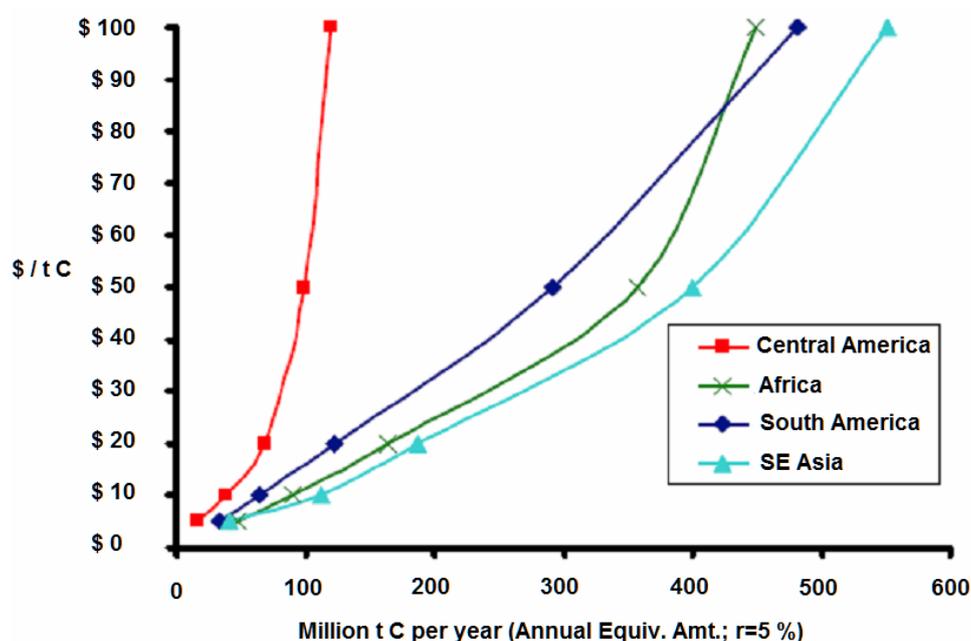


Figure 2.14. Abatement cost curves for avoided deforestation: Estimates are the gain in carbon sequestration relative to the baseline from reduced deforestation measured as the annual equivalent amount of gains from 2005–2055 (Figure based on Sohngen and Beach^[70])

Barriers and policy measures

Reducing deforestation requires no technological advances. As Norwegian Prime Minister Jens Stoltenberg put it in his annual address to the nation, “*The technology is known. Everybody knows how to not cut down trees*”. However, achieving results may still prove difficult, because of social and institutional barriers. The IPCC^[11] lists three main obstacles to preservation of tropical forests.

1. Profitability incentives work against conservation and sustainable forest management.
2. Many drivers of deforestation lie outside of the forest sector, especially in agricultural policy and markets.
3. Limited regulatory and institutional capacity and insufficient resources within governments.

The first obstacle can be overpowered if carbon emissions from deforestation are given a price, but this is difficult, as surveillance of forests is insufficient, leakage rates and baselines are uncertain and property rights are often not clearly defined. Conservation of forest may therefore depend on a wide range of policy measures, ranging from carbon market incentives, to funds to help governments develop management frameworks and surveillance systems, to establishment of clearly defined property rights.

Afforestation

In addition to deforestation, growing new forests can also reduce CO₂ emissions by sequestration. The IPCC^[11] estimates a potential, based on a review of top-down modelling results, of up to 4 GtCO₂ per year in 2030 at carbon prices up to USD 100 per tonne CO₂. As in the case for avoided deforestation, regional bottom up estimates are more conservative.

Afforestation require large up-front investments, but the benefits accumulate over decades, and the net present value of investments are therefore considerably reduced. Various methods to improve afforestation on land formerly covered by forest (reforestation) in tropical and subtropical areas generally provide GHG mitigation and positive ecological side effects. In boreal areas (like Canada and Russia) however, afforestation may have a less beneficial effect, because it may result in reduced albedo, or reflection, and thereby reduced local cooling^[71,72]. However, excluding these areas reduces the potential less than 50 percent.

Agroforestry, the combined use of agricultural and forestry methods in growing biomass, as a method for afforestation has significant potential for both GHG mitigation and economic output. A study of forestry options in Brazil, China, India, Indonesia, Mexico, the Philippines, and Tanzania, indicates a potential of 1.7 GtCO₂ per year in agroforestry^[73]. Half of this potential could be achieved at a negative cost within 2030, the other half at a cost below USD 30 per tonne CO₂.

Forest management

The amount of stored carbon in forests can be increased as result of altered forest management and forestry practices. Measures to increase carbon sequestration through forest management include harvest methods that maintain forest cover, reducing loss of dead organic matter, reducing loss of soil carbon, avoiding slash burning, planting trees after harvest, and prolonged rotation (permitting forests to grow older before harvesting).

The IPCC^[11] estimates a global GHG mitigation potential through alternations in forest management practice, based on a review of top-down modelling results, to 5.8 GtCO₂ per year in 2030 at carbon prices up to USD 100 per tonne CO₂.

Conclusion on GHG mitigation potential from forests

Estimates on global potentials for GHG mitigation from land-use change are extremely uncertain. The IPCC^[11] discusses the large differences between bottom up estimates and global modelling results, and concludes with a conservative estimate of 1,270 to 4,230 MtCO₂ per year in 2030, at carbon prices up to USD 100 per tonne CO₂. This may be too conservative, as the review of global forest modelling resulted in an estimated potential of 13,775 MtCO₂ per year at the same price. Both Stern and other literature put strong arguments behind higher potential estimates than the IPCC. Furthermore, as land-use change GHG mitigation measures often have positive environmental side effects, higher costs than USD 100 per ton CO₂ should be accepted under an ambitious climate and environmental regime. Acknowledging the high uncertainty, we conclude that land-use change GHG mitigation can contribute with a reduction of 4 GtCO₂ per year in 2030 and 10 GtCO₂ per year in 2050.

2.8. Non-CO₂ GHG Emissions

Key messages

- Today, the post-consumer waste sector contributes to less than 5 percent of global GHG emissions. Through adoption of readily available technologies, such as CH₄ landfill recovery, wastewater management and waste reduction, emissions can be reduced by more than 90 percent in 2050.
- Agriculture GHG emissions contribute to approximately 14 percent of global GHG emissions. Emissions are expected to increase to 8.3 GtCO₂ in 2030. At a carbon price up to USD 100 per ton CO₂ the mitigation potential is 4.3 GtCO₂-eq per year.

Non-CO₂ GHG include methane (CH₄), nitrous oxide (N₂O), Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs), and sulphur hexafluoride (SF₆). There are considerable emissions of these non-CO₂ GHGs in the sectors for industry, agriculture and waste. Strategies to reduce industrial non-CO₂ GHG emissions are covered by Section 2.3, while low emission strategies for waste and agriculture are given below.

2.8.1. Post Consumer Waste

The major GHG emissions from the waste sector are methane (CH₄) from landfill, followed by CH₄ from wastewater and N₂O emissions^[1]. Incineration of fossil fuel carbon also contributes to minor emissions. It is important to keep in mind that there are high uncertainties in global estimates of GHG emissions from waste due to national, regional and even local differences in definitions, data collection and statistical analysis.

Post-consumer waste is a significant renewable energy resource that can be utilized through incineration and industrial co-combustion, landfill gas exploitation and the use of anaerobic digester biogas. Because it is regularly collected at public costs, waste has an advantage compared to many other biomass resources. Worldwide, proven energy-from-waste technologies dispose of approximately 140 million tonnes of waste per year.

The heating value of mixed municipal waste is in the range of 6-14 MJ per kg^[74,75]. Currently, the approximately 140 million tonnes of municipal waste which are processed worldwide annually are equivalent to more than 330 TWh per year assuming an average heating value of 9 GJ per ton.

Global emission trends

The waste sector contributes to less than 5 percent of global GHG emissions. However, because of the lack of standardization for national waste statistics emission data are uncertain. Quantifying global trends requires annual national data on waste production and management practices. GHG emissions from landfill, like CH₄, continue for decades after disposal, thus the estimation of emission trends require models that include temporal trends.

The IPCC report ^[1] looks at two different studies (US EPA, 2006 ^[76] and Monni *et. al*, 2006 ^[77]) when estimating emissions and trends. According to Monni *et. al*, total emissions have historically increased and will continue to do so. In developed countries there will be a stabilization of CH₄ emissions due to increased landfill, CH₄ recovery, reduction in the amount of biodegradable waste in landfills by the year 2020, and decreased waste generation as a result of local waste management decisions. On the other hand, rapid increases in population and urbanization in developing countries will boost overall GHG emissions from waste. CH₄ from wastewater is expected to increase almost 50 percent between 1990 and 2020 in a business as usual scenario.

CH₄ from landfill has historically been the most significant source of GHG emissions from the waste sector. Growth in emissions is decreasing because of increased landfill recovery through flaring and utilization of landfill gas even in old landfills. In the EU over the last 20 years there have also been reduced rates of land filling due to increased incineration (in some places with energy recovery) and achieved recycling rates. Because of this initiative GHG emissions from the EU by 2010 are expected to decrease by more than 50 percent compared to emissions in 1990 ^[78].

For developing countries, rates of methane emissions are expected to increase but incentives such as CDM¹⁰ can accelerate rates of landfill recovery and use in parallel with improved land filling practices.

CH₄, and N₂O emissions from wastewater and human sewage are relatively small in developed countries. In developing countries these emissions are generally higher due to rapid growth in population and increased urbanization.

A summary of GHG emissions from landfills and wastewater is given in Table 2.12

¹⁰ Clean Development Mechanism: An emission reduction strategy under the Kyoto Protocol.

Table 2.12. Global trends for GHG emissions from waste using (a) 1996 and (b) 2006 IPCC inventory guidelines, extrapolations, and projections (data are reported in million ton CO₂ equivalents, rounded). Source: IPCC-report page 596^[1].

Source	1990	1995	2000	2005	2010	2015	2020	2030	2050
Landfill CH ₄ ^a	760	770	730	750	760	790	820		
Landfill CH ₄ ^b	340	400	450	520	640	800	1,000	1,500	2,900
Landfill CH ₄ (average a & b)	550	585	590	635	700	795	910		
Wastewater CH ₄ ^a	450	490	520	590	600	630	670		
Wastewater N ₂ O ^a	80	90	90	100	100	100	100		
Incineration CO ₂ ^b	40	40	50	50	60	60	60	70	80
Total GHG emissions	1,120	1,205	1,250	1,345	1,460	1,585	1,740		

Notes: Emissions estimates and projections as follows:

a; Based on reported emissions from national inventories and national communications, and (for non-reporting countries) on 1996 inventory guidelines and extrapolations^[76].

b; Based on 2006 inventory guidelines and BAU projection^[77].

Total includes landfill CH₄ (average), wastewater CH₄, wastewater N₂O and incineration CO₂.

Uncertainties can range from 10-30 percent for countries with good annual data to more than twofold for countries without annual data.

GHG mitigation technologies

There are a wide range of mature technologies to reduce GHG emissions from waste. These technologies include landfill gas recovery, post-consumer recycling, composting of specific waste fractions and processes that reduce GHG generation compared to landfilling. The choice of technology will depend on global, national, regional and local initiatives for both waste management and GHG emissions.

Landfill CH₄ technologies

The most important measure to decrease emissions from landfill is the implementation of an active gas extraction system. Field studies have shown that more than 90 percent recovery can be achieved^[79]. Another way of controlling CH₄ emissions is oxidation in cover soils. Further measures to reduce CH₄ emissions from landfilling are installation of geomembrane composite covers, design and installation of secondary perimeter gas extraction systems for additional gas recovery and implementation of bioreactors.

Wastewater, human sewage CH₄, and N₂O

There are a wide range of accessible technologies for wastewater management, collection treatment, re-use and disposal ranging from natural purification processes to energy intensive advanced technologies. There is a lack of systematic studies analyzing the global potential and costs of reduction in GHG emissions from wastewater.

Waste reduction, re-use and recycling

Quantifying the potential of GHG reduction from waste reduction, re-use and recycling requires use of Life-cycle-analysis (LCA) tools. Recycling contributes to reduced GHG emissions by reducing the use of virgin materials and thereby lowering the energy demand in production. A more efficient use of materials will also contribute to waste minimization.

Material efficiency can happen in several stages in the lifecycle of a product such as substitution of materials, more effective design, recycling of products and materials, use of materials from other products with lower quality requirements. These efforts are essential for products with high energy intensity.

Scenarios

Monni *et. al.* ^[77] and Delhotal *et. al.* ^[80] have developed baseline scenarios and mitigation scenarios for 2020 and 2030 respectively. Both conclude that substantial emission reduction can be achieved at a low or even negative cost. According to Monni *et. al.* more than 90 percent reduction in GHG emissions from landfilled waste can be reach at a cost level of USD 100 per ton of CO₂-eq by using thermal processes for waste to energy.

Table 2.13. Economic reduction potential for CH₄ emissions from landfilled waste by level of marginal abatement costs (from estimates by Monni *et al.* ^[77]).

Region	USD/tCO ₂ -eq				
	0	10	20	50	100
OECD	48 %	86 %	89 %	94 %	95 %
EIT*	31 %	80 %	93 %	99 %	100 %
Non-OECD	32 %	38 %	50 %	77 %	88 %
Global	35 %	53 %	63 %	83 %	91 %

* EIT: Economies in transition

2.8.2. Agriculture

Agriculture GHG emissions are estimated to be in the range of 5.1 to 6.1 GtCO₂-eq per year, and account for approximately 11- 13.5 percent of global GHG emissions, excluding CO₂ emissions from machinery, etc, that are counted under the transport, buildings and industry sector. CH₄ emissions from livestock and manure account for 5 percent, and N₂O from agricultural soils accounts for 6 percent of global GHG-emissions. Emissions have increased by 17 percent between 1990 and 2005 and they are expected to increase further, to 8.3 GtCO₂ in 2030.

Measures to reduce GHG emissions

There are no technological “quick fixes” that can reduce GHG emissions, but various changes and adjustments in agricultural practices can still contribute to significant reductions. Direct emissions of N₂O can be reduced, and carbon sequestration by photosynthesis can be improved. The following practices are capable of reducing GHG emissions in the agricultural sector:

- Restoration of cultivated organic soils
- Improved cropland management, including agronomy, tillage/residue management, nutrient management, and water management
- Improving grazing land management
- Restoration of degraded lands (erosion control, organic amendments, nutrient amendments)
- Rice management

- Livestock management
- Land-use change and agroforestry
- Manure management

The potential of the different emission reduction strategies are presented in Figure 2.15, and the total agricultural GHG mitigation potential can be summarised as follows:

- At carbon prices up to USD 50 per tonne CO₂, Smiths et al (2007) ^[81] estimated the GHG mitigation potential to be 2.5 GtCO₂-eq per year in 2030.
- At a carbon price up USD 100 per tonne CO₂ the mitigation potential is 4.3 GtCO₂-eq per year in 2030.

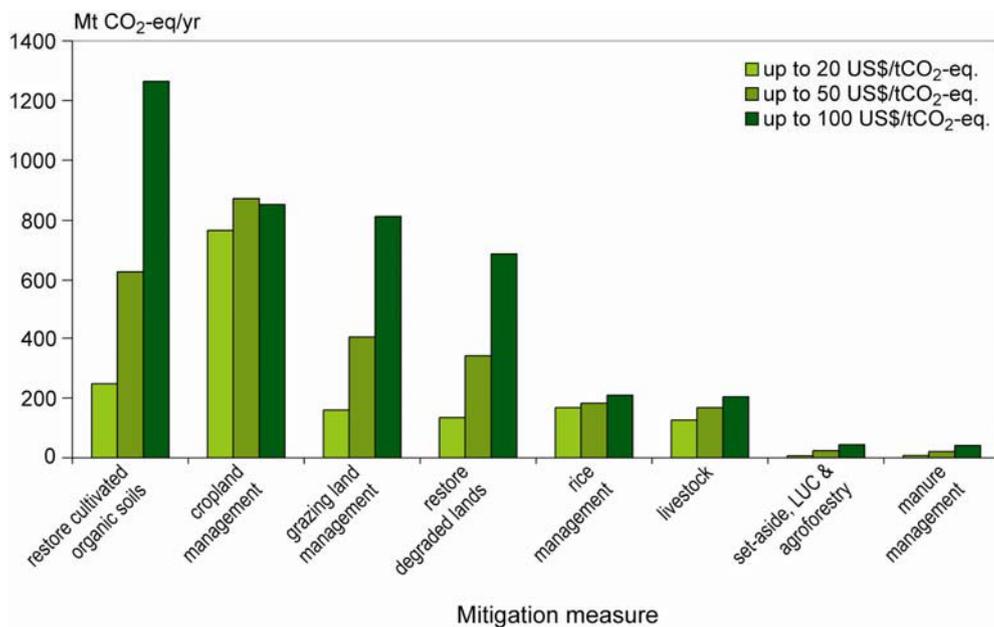


Figure 2.15. CO₂ reduction potential in agriculture at different carbon prices. Copied from the IPCC ^[1].

2.9. Carbon Capture and Storage

Key messages

- Carbon capture and storage (CCS) has the potential to significantly reduce CO₂ emissions from fossil fuel power plants and large industrial sources. As such, CCS can be the bridge to the future renewable energy society.
- CCS can be commercially available from 2020.
- 90 percent of CO₂ from fossil fuel power plants can be captured and safely stored underground.

2.9.1. How CCS Works

CO₂ Capture and Storage (CCS) is a technology with the potential to reduce GHG emissions while allowing continued use of fossil fuel ^[5,7,11,12,17,82,83,84]. The CO₂ arising from combustion of fossil fuel is captured, transported, and finally safely stored in an underground geological formation ^[85]. The different processes involved in CCS are presented in Figure 2.16.

CO₂ capture technologies are often classified as post-combustion, pre-combustion or oxyfuel CO₂ capture ^[85,86]. In post-combustion CO₂ capture the CO₂ is separated from other flue gas components by absorption. In pre-combustion CO₂ capture, the carbon in the fuel is separated prior to combustion. In the oxyfuel process the combustion is performed with pure oxygen instead of air, leading to a flue gas consisting of only CO₂ and steam, which can easily be separated.

Captured CO₂ is transported in pipelines or by ship to a storage site. CO₂ can be safely stored in underground geological formations called aquifers, in depleted oil and gas fields, or in deep unmineable coal beds.

2.9.2. The CCS Potential

There are no large-scale projects worldwide for capture, transport and storage of CO₂, but several demonstration projects are planned ^[87]. If the right regulatory framework and economic incentives are established, a large number of full-scale CCS projects could be commissioned within the next decade.

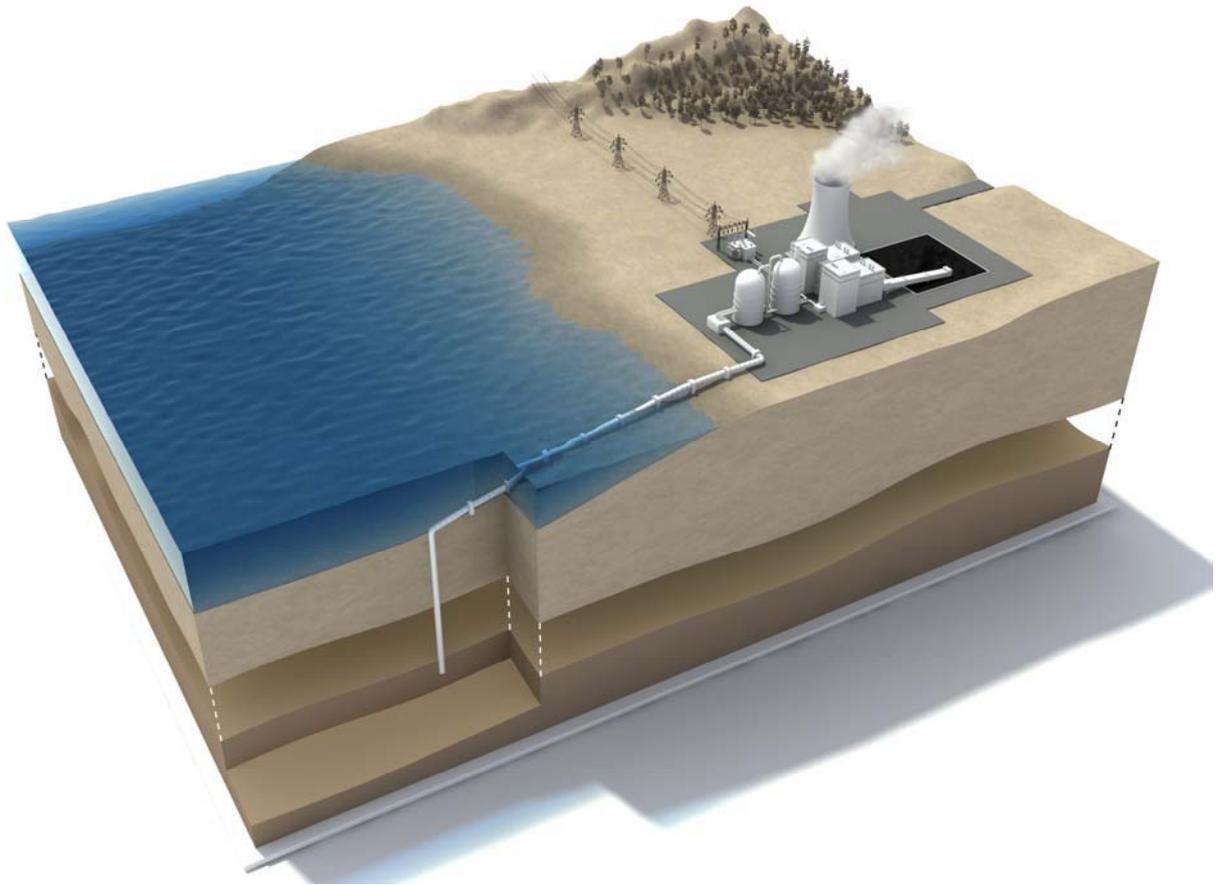


Figure 2.16. A schematic presentation of CO₂ capture and storage (CCS). CO₂ is captured from the flue gas from a fossil fuel power plant. The captured CO₂ is transported by pipeline to a storage location where CO₂ is injected for safe storage. Typically, CO₂ will be stored more than 800 meters below the ground. Source: Prosjektlab.

The International Energy Agency (IEA)

Many scenarios for future energy demand and CO₂ emissions do not take into consideration the full potential for CCS. One such example are the widely cited scenarios from the IEA World Energy Outlook studies ^[7,13]. CCS is said to be one of the most promising emission reduction technologies, but the full potential for CCS is not addressed in the scenarios IEA puts forward as its most important scenarios. In the IEA World Energy Outlook 2007 study ^[7] the so-called Reference Scenario and Alternative Policy Scenario are said to be the most realistic predictions, but these scenarios do not incorporate any GHG emission reduction at all, which is a clear indication that these scenarios are conservative and do not address the full potential of low emission technologies like CCS.

In 2006, the IEA published The Energy Technology Perspective report ^[5] where different emission reduction technologies were analysed. In this report the emission reduction potentials were determined by the impact of a wide range of policies and measures aimed at overcoming barriers for adoption of new technologies that can reduce GHG emissions. The IEA concludes that up to 7.5 GtCO₂ can be captured and stored annually on a global level by 2050. This is consistent with a report from the Massachusetts Institute of Technology that concluded that capture and storage of 4 to 8 GtCO₂ annually could be possible by 2050 ^[82].

The Batelle Memorial Institute

A report from the Batelle Memorial Institute ^[83] suggests that a total accumulation of 100 GtCO₂ could be captured and stored globally by mid-century in a scenario to stabilize the CO₂ concentration in the atmosphere at 550 ppm.

According to a more recent study from the Batelle Memorial Institute ^[84] there are 8,100 large CO₂ point sources globally that can adopt the CCS technology. The emissions from these sources are more than 15 GtCO₂ annually, and if CCS is introduced to all these sources with an 85 percent CO₂ capture rate, close to 13 GtCO₂ can be captured and stored annually.

The Bellona CCS Study 2007

In most scenarios from the literature, the potential for CCS is limited because of the significant economic and political barriers delaying the deployment of new technologies. However, the full CCS potential, assuming that there are only minor political and economic barriers to wide implementation of CCS, is documented in a Bellona study published last year ^[88]. This study assumes much stronger policies and economic incentives favouring implementation of CCS than the latest IEA scenarios.

The conclusion from the Bellona study ^[88] is that the accumulated global CCS potential is 236 GtCO₂ captured and stored by 2050. This corresponds to 16 GtCO₂ captured and stored annually by 2050 and 33 percent reduction in global CO₂ emissions in 2050 compared to emissions today. The calculation of this potential is based on the following assumptions:

- Only a few large-scale CCS projects have been commissioned so far, and it will take some years until CCS can contribute to large reductions in global CO₂ emissions. The EU Commission is aiming for commercialisation of CCS technologies by 2020 ^[89]. Several CCS projects have been announced with commissioning in the period 2009 to 2016 ^[17]. For simplicity, it was assumed that CCS will start to contribute to CO₂ emission reductions in OECD countries in 2015.
- Available technologies can capture 85 to 95 percent of the CO₂ processed in a capture plant ^[85]. However, energy is required to capture, transport and inject CO₂, and CCS can therefore reduce CO₂ emissions to the atmosphere from large point-sources by approximately 80 to 90 percent ^[85]. It was assumed that all fossil fuel power plants installed in OECD countries will be equipped with CCS technology by 2050, and, as a conservative approach, it was assumed that 80 percent of CO₂ produced in the power production sector will be captured and stored in OECD countries by 2050.
- CCS can also contribute to CO₂ emission reduction in the transport sector. If vehicles running on hydrogen are widely used, the hydrogen should be produced in large plants with CCS.
- CO₂ capture applies mainly to large stationary point sources, including fossil fuel power plants and large industrial single point emissions like refineries, cement plants, chemical plants and steel mills. Implementing CCS for smaller industrial CO₂ sources is impractical and too expensive. According to IEA, global emissions from the industry sector were 5.2 GtCO₂ in 2005 ^[7]. The IPCC has identified 2,552 industrial CO₂ sources such as refineries, cement production, iron and steel industry, and petrochemical plants which emit more than 0.1 MtCO₂ annually ^[85]. The total CO₂ emissions from these sources are

2.8 GtCO₂ annually, which represents more than half of the global CO₂ emissions from the industry sector in 2002. It was therefore assumed that CCS can reduce CO₂ emissions from the industrial sector in OECD countries by 50 percent within 2050.

- The rich countries have to take a leading role in deploying strategies for reducing the CO₂ emissions. CCS deployment is therefore assumed to develop faster in OECD countries than non-OECD countries. CO₂ capture in non-OECD countries was therefore assumed to reach $\frac{3}{4}$ (i.e. 75 percent) of the level in OECD countries by 2050.

2.9.3. Carbon Negative - Combining Biomass and CCS

The carbon negative concept aims at removing CO₂ from the atmosphere and goes further in this respect than any other of the GHG reduction strategies. The concept relies on a combination of CCS and large-scale biomass production for energy purposes.

Biomass is carbon neutral as the CO₂ emitted during its combustion is balanced by the uptake of CO₂ in the photosynthesis process during biomass growth. By combining large-scale biomass power plants with CCS, the physical storage of CO₂ will ensure that CO₂ is actually removed from the atmosphere. A carbon negative plant relies on the following principles:

- A large-scale plantation for production of fast-growing crops suitable for biofuel and biopower production.
- Availability of low-value land, like deserts, so the plantation can be located in an area which ensures a sustainable bioenergy production that does not conflict with food and water production, or biodiversity.
- A supply of CO₂ in order for the biomass to grow, such as that which can be supplied by the flue gas from a power plant in the vicinity.
- A CO₂ capture plant to treat the residual CO₂ not taken up by the biomass, and a suitable storage location for safe storage of the CO₂ that is separated.

A schematic presentation of the carbon negative concept is given in Figure 2.17. The green areas close to the power plant represent a biomass plantation, and if carbon negative power is based on algae, the fast growing algae can be produced in photobioreactors as shown in Figure 2.18.

There should be a market for both small and large-scale carbon negative plants. Small plants delivering power and biofuel in the range 10-50 MW can be established to supply small societies with energy. Located in low value areas, the energy produced can contribute to sustainable industrial development, establishment of new industry and the creation of new jobs.

The technical potential for CO₂ emission reduction through the carbon negative concept is promising. However, the extent of the potential is not yet documented in published literature. The theoretical potential for carbon negative is limited by environmental, political and economic barriers, but if the right economic incentives are implemented, a large share of the global power production can be supplied by large biomass power plants with CCS. Furthermore, the potential for carbon negative depends on the potential for biomass for energy purposes, which is discussed in Section 2.6.3.

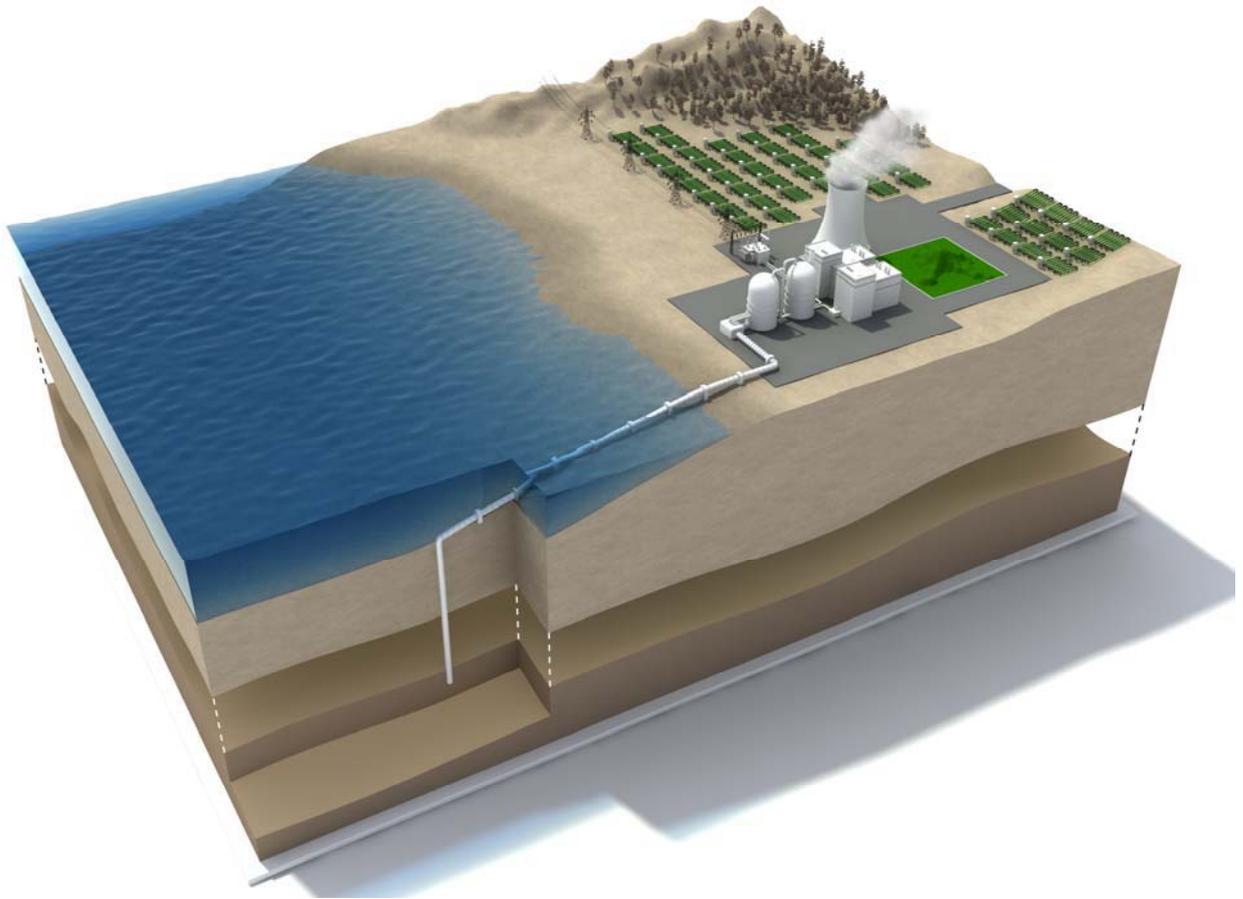


Figure 2.17. A schematic presentation of the carbon negative concept. The green areas represent a biomass plantation. The power plant is fuelled with biomass. CO₂ from the flue gas is separated and transported to a safe storage location. The flue gas can also be used to supply the biomass plantation with CO₂. Source: Prosjektlab.

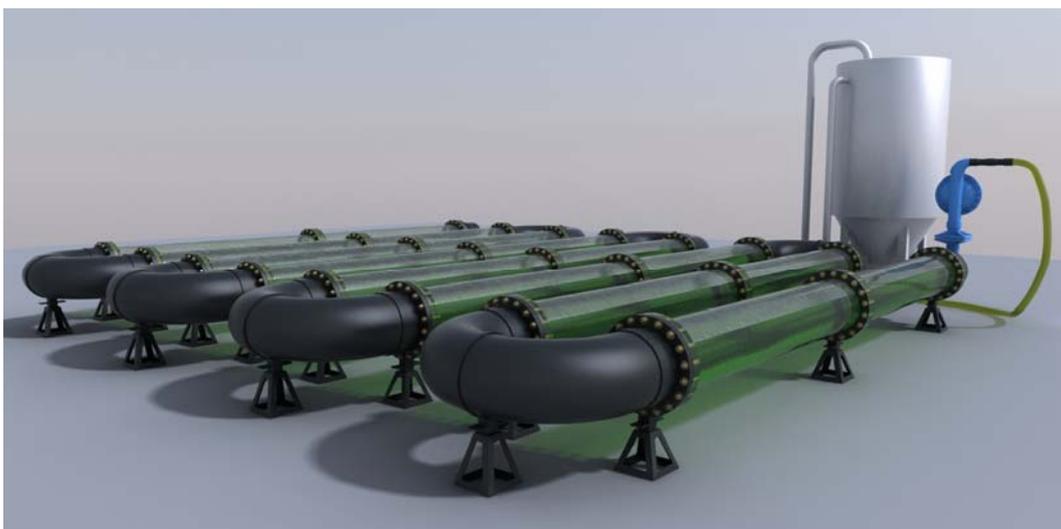


Figure 2.18. Photobioreactor for algae production. Source: Prosjektlab.

2.9.4. Safe Storage of CO₂

The technology for CO₂ storage has been in use since the 1970s. Information and experience gained from these storage projects proves that CO₂ can be safely injected and stored at well-characterized and properly managed sites for very long periods of time (*i.e.* hundreds to thousands of years). The offshore gas field Sleipner, in the middle of the North Sea, has been injecting 1 MtCO₂ per year since 1996. This is a commercial scale project, which is a good example of safe CO₂ storage in deep saline aquifers ^[90].

At present there are no technical barriers that hinder full-scale implementation of geological storage of CO₂. What is needed to realize this technology is the establishment of an internationally agreed upon regulatory framework that can govern its deployment.

Possible storage sites

Geological storage of CO₂ can be undertaken in a variety of geological settings in sedimentary basins, including depleted oil and gas fields, deep coal seams and saline formations. Other geological formations which may serve as storage sites include caverns, basalt and organic-rich shales. In general, geological storage sites should have: (1) adequate capacity and injectivity, (2) a satisfactory sealing caprock that prevents gas from escaping to the surface, and (3) a sufficiently stable geological environment.

The storage formation should be capped by extensive confining units (such as shale, salt or anhydrite beds) to ensure that CO₂ does not escape into overlying, shallower rock units and ultimately to the surface. Adequate porosity and thickness (for storage capacity) and permeability (for injectivity) are other critical parameters.

Estimates of global storage capacity indicate that 675 - 900 GtCO₂ can be stored in oil and gas fields, 3 - 200 GtCO₂ in unmineable coal seams and 1,000 - 10,000 GtCO₂ in deep saline formations ^[85]. This means that the storage capacity for CO₂ in geological formations is much higher than the global annual energy related CO₂ emissions, which were close to 27 GtCO₂ in 2005 ^[7].

Storage mechanisms

At depths below about 800 – 1,000 meters, CO₂ has a liquid-like density that provides the potential for underground storage in the porous spaces of sedimentary rocks. CO₂ can be trapped underground by various storage mechanisms, such as:

1. Trapping below an impermeable, confining layer or caprock (Structural and stratigraphic trapping);
2. The CO₂ is retained or adhered on the surfaces of the porous spaces of the storage formation so that it becomes immobile (Residual CO₂ trapping);
3. Dissolved in the fluids contained in the porous spaces of the formation (Solubility trapping); and
4. Trapping by reacting with the minerals in the storage formation and caprock to produce carbonate minerals (Mineral trapping).

CO₂ becomes less mobile over time as a result of multiple trapping mechanisms, further lowering the prospect of leakage, which builds the confidence in geological security of carbon dioxide storage.

Site characterization and monitoring

Site characterization is a prerequisite to safe geological storage of CO₂. Site characterization means evaluation of the storage site in terms of its potential storage suitability, capacity and security for injecting CO₂. Documentation of the characteristics of any particular storage site will rely on data that have been obtained directly from the reservoir.

Performance prediction of a site can be made using models that are available to predict what happens when CO₂ is injected underground. Monitoring is needed to demonstrate that CO₂ remains contained in the intended storage formations. This is currently the principal method for assuring that the CO₂ remains stored and that performance predictions can be verified.

Status for CO₂ storage

The success of CCS as a greenhouse gas mitigation strategy depends on the regulatory framework established to govern its deployment^[91]. Efforts are underway in the development of national and international rules and regulations for CCS projects^[92,93,94].

A consistent effort to address the major unresolved regulatory issues related to CCS, such as long-term stewardship of the stored CO₂, clarification of whether CO₂ is defined as industrial or hazardous waste, access and property rights, intellectual property rights, liability issues, and monitoring and verification requirements, is needed for rapid implementation of the technology.

2.10. Nuclear Energy

Key messages

- Today, 15 percent of worldwide power production comes from nuclear energy.
- Bellona does not consider nuclear energy as an appropriate tool to combat global warming due to the fact that there is no safe method for handling nuclear waste; there is a risk that nuclear know-how can be used for military programs; and there are dramatic consequences if a nuclear accident occurs.

Nuclear power production does not lead to any direct GHG emissions, and substituting fossil fuel power plants with nuclear power has therefore been suggested as a viable GHG mitigation option. But expansion of nuclear power is linked to challenges with handling of nuclear waste, nuclear accidents, costs, public opposition and the risk associated with nuclear proliferation.

2.10.1. The Potential for Nuclear Power Production

In the most optimistic scenario from IEA, the TECH Plus Scenario ^[5], a substantial deployment of nuclear energy is assumed. Nuclear energy will supply 22 percent of global electricity demand in 2050 in this scenario. This implies a three-fold increase in nuclear capacity from 2003-level by 2050. Although this assumes a major growth, because current nuclear capacity will have to be replaced by 2050 because of an aging fleet, this will only contribute to 7.2 percent of the total emission reductions in 2050 in IEAs scenario.

Questions have been raised if a larger share of nuclear power production is realistic, because the growth of nuclear energy is limited by technical, economic and security issues. These issues come in addition to public opposition and lack of implementation of long-term solutions for long-lived radioactive waste.

2.10.2. Risks Associated with Nuclear Power

There are several serious drawbacks related to nuclear energy production that must be considered if nuclear energy is to be considered as a strategy to combat global warming. Each year the current 439 nuclear reactors worldwide, produce about 12,000 tonnes of long-lived radioactive waste, adding to the waste legacy of some 220,000 tonnes in the form of spent nuclear fuel. This waste will remain radioactive for several hundred thousand years, and must be handled in a way

that does not imply restrictions on future generations. The best available technology today to handle this waste is repositories in deep (500-1,000 meter) and geologically stable formations.

Of the 31 countries relying on nuclear power, only Sweden, Finland and the USA have produced concrete plans for a deep geological repository for this type of waste. The other countries store their long-lived radioactive waste in a variety of temporary storages, that need constant monitoring and control, thus long-term radioactive waste storage is still an unresolved issue in these countries.

Even though it is unquestionably that a modern nuclear power plant is safer than the reactors developed in the 1950s and 1960s, these reactors still have unresolved safety issues. These issues are related to the consequences of loss of cooling of the reactor, and the potential meltdown of the nuclear core.. Even though the probability for an accident is low, the consequences are so serious that the low probability does not outweigh the consequences. Another issue is the risk of terror attack which have been elevated since 9.11 2001.

Nuclear power still faces serious problems with regards to public perception. After fifty years of commercial operation this energy source still meets opposition from the public. According to a survey conducted by the Gallup Organization in 2007, the European public is still strongly opposed to the use of nuclear power and respondents who are worried about climate change are even more fiercely opposed. 61 percent of the European public thinks that the nuclear share should be decreased.

According to head of the International Atomic Energy Agency (IAEA), Mohamed El Baradei, export controls have failed, allowing a black market for nuclear material to develop, a market that is also available to terrorist groups. To date, there have been numerous episodes where attempts were made to smuggle radioactive materials. Whereas the IAEA has to succeed each and every time, terrorist organizations only need to be successful once, in order to obtain radioactive materials.

An expansion of nuclear power to new countries will increase the risk that new countries could be tempted to use their nuclear know-how for military programs. As of today, the IAEA does not have the necessary resources and authority to prevent current nuclear countries from developing clandestine nuclear programs like we have seen in North-Korea, Iran and Syria to name a few recent examples.

3. The Bellona Scenario

The Bellona Scenario describes an ambitious but necessary approach to reduce global GHG emissions. The scenario is calculated based on the technological emission reduction potentials discussed in Section 2. An overview of input data to the Bellona Scenario and the calculation algorithm are given in Section 3, while a more detailed description is given in Appendix 1. Resulting energy demand and GHG emissions are presented in Section 4.

3.1. How to Calculate the Bellona Scenario

The Bellona Scenario has a different approach than most GHG emission models found in the literature. Most models ^[5,6,7,8,9,13,14] do not necessarily aim at meeting the IPCC recommendation but instead aim at describing the possible emission reduction within a limited cost per ton of CO₂ avoided, or at analysing the effect of political regulations. In contrast, the Bellona Scenario aims at analysing the issue from a different angle as it primarily focuses on describing the optimal technological path for considerable reductions in global GHG emissions by 2050. The Bellona Scenario has also the particularity of addressing all greenhouse gasses, and not just CO₂ emissions.

3.1.1. Key Components in the Calculation Method

Since the greatest portion of global CO₂ emissions is related to energy production, the Bellona Scenario includes calculations of primary energy demand and power production in addition to GHG emissions.

The model is divided into different categories of GHG emissions. This separation into categories is performed in order to demonstrate the difference in emission reduction potential in the different energy-related sectors and to demonstrate the difference in emissions from CO₂ and other greenhouse gasses. The different sectors in the Bellona Scenario are as follows:

- Power production
- Fuel transformation¹¹
- Industry
- Transport
- Residential, services & agriculture
- Land-use change
- Non-CO₂ GHG emissions

¹¹ Fuel transformation includes refineries, coal and gas transformation and liquefaction, energy use and loss by gas works, energy used in coal mines, energy used in oil and gas extraction, and energy used for electricity and heat production.

3.1.2. Algorithm

The GHG emissions are calculated as reductions in GHG emissions compared to a business as usual (BAU) scenario. Therefore, a BAU Scenario must be established before future GHG emissions can be calculated.

The Bellona Scenario is calculated in Microsoft Excel spreadsheets, and brief overviews of how the calculations are performed are given below. A more detailed description of the calculation algorithm is given in Appendix 1.

Overview of the algorithm behind the Bellona Scenario:

- Establishment of the business as usual (BAU) Scenario:
 - BAU data is established for 2005, 2015, 2020, 2030, and 2050:
 - Calculate the primary energy demand and CO₂ emissions from the energy and process-related categories (power production; fuel transformation; transport; industry; and residential, services & agriculture). Power production is also calculated.
 - Calculate CO₂ emissions from land-use change.
 - Calculate emissions of non-CO₂ GHG emissions.
- Calculation of the Bellona Scenario
 - The calculations are performed for 2015, 2020, 2030, and 2050:
 - BAU data is adjusted for possible lifestyle changes.
 - Calculate how the emission reduction potentials of the technologies addressed in Section 2 will influence energy demand, power production, and GHG emissions in all categories. The emission reduction potential is calculated as reduced emissions compared to the BAU Scenario.
 - Energy demand and GHG emissions from different categories are summarised to obtain total energy demand and GHG emissions.

3.2. The BAU Scenario

The BAU Scenario in this study is mainly based on the Reference Scenario in the IEA World Energy Outlook 2007 (WEO2007) ^[7] for primary energy demand, power production, and energy and industry-related CO₂ emissions. However complementary reference studies were used to cover some aspects that the WEO2007 failed to address.

For data regarding energy demand and energy-related CO₂ emissions in 2050, the BAU is based on the Baseline Scenario in the IEA Energy Technology Perspective 2006 ^[5] as analyses in WEO2007 are limited to the period from today until 2030.

For categories used in the Bellona Scenario but not specified in the WEO2007, the Bellona BAU Scenario is based on extrapolation of data from different IEA reports ^[7,13,14].

GHG emissions from land-use change and non-CO₂ GHG emissions are not within the scope of the WEO2007. For the issue related to GHG emissions which are not CO₂ emissions and the issue

related to land-use change, the BAU Scenario in this study is based on IPCC [6] and The World Resources Institute [10].

More details regarding the construction of the BAU Scenario are included in Appendix 1. The global GHG emissions in the BAU Scenario are given in Figure 3.1.

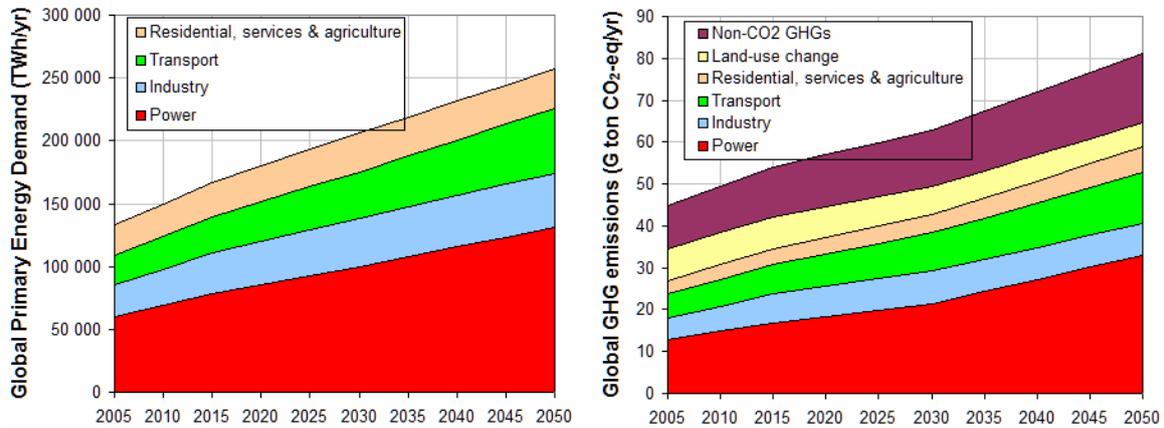


Figure 3.1. Global primary energy demand and GHG emissions in the business as usual Scenario.

3.3. Input to the Bellona Scenario

The GHG emission reduction potentials that are implemented in the Bellona Scenario are discussed briefly below. More details on how the emission reduction potentials are implemented in the Bellona Scenario are given in Appendix 1.

3.3.1. Lifestyle Change

In addition to the deployment of low emission technologies, emission reduction can also be achieved by lifestyle changes. The BAU Scenario is in itself a lifestyle change as it indicates close to a doubling in global energy demand by 2050. It is possible to alter this lifestyle change and thereby reduce the growth in energy demand and resulting GHG emissions through reduced consumption and improved availability and use of low carbon products and solutions.

The BAU Scenario in this study is based on rather conservative estimates from the IEA. This scenario shows a 10 percent higher energy demand in 2050 than in the business as usual scenario established in the Ecofys report [22]. This suggests that there is a potential for energy demand reduction for example through lifestyle changes. While it is extremely difficult to estimate the potential of emission reduction through lifestyle changes, it is assumed that the energy demand in the Bellona Scenario can be reduced by 1 percent in 2015 and 10 percent in 2050, due to lifestyle changes, compared to the BAU Scenario.

The direct effects of lifestyle changes on GHG emissions are supplemented by important secondary effects. If public awareness about technologies to combat global warming is heightened, then there will be increased pressure on decision makers to put global warming

higher on the agenda and to facilitate the lifestyle changes that are needed. This could result in improved infrastructures, reorientation of public spending, changed taxes and regulations etc.

3.3.2. Energy Efficiency in the Power Sector

There is a large potential for energy efficiency in the power sector. In OECD countries the efficiency of coal power plants can be increased from an average of 37 percent today to 50 percent in 2050. Natural gas power plants can increase their efficiency from 50 percent today to 63 percent in 2050. These assumptions are based on the EU Technology Platform for Zero Emission Fossil Fuelled Power plants which aims at steam power plants with efficiency over 50 percent and gas turbine plants with efficiency over 63 percent within the next decades ^[17].

The efficiency of fossil fuel power plants in non-OECD countries is assumed 5 percent points lower than in OECD countries.

Bio mass power production will have lower energy efficiency than coal power plants as indicated in Section 2.2. In the Bellona Scenario it is assumed that the efficiency of biomass power production will increase from 26 percent today to 40 percent in 2050.

3.3.3. Efficiency in the Industry Sector

The potential for energy efficiency has been studied by Ecofys ^[22], and in their so-called Ambitious Scenario it is concluded that enhanced energy efficiency can reduce global energy demand, for all sectors, by 47 percent in 2050 compared to a business as usual scenario. A breakdown of this efficiency potential for different sectors indicates that energy demand in the industry sector can be reduced by 37 percent in 2050 compared to a BAU Scenario.

Most of the industrial energy efficiency potentials described in Section 2.3 are addressed by Ecofys ^[22]. The energy efficiency potential for the industry sector in the Bellona Scenario is therefore based on the Ambitious Scenario from the Ecofys study ^[22].

The aim of the Bellona Scenario is not necessarily to utilise the data from the most optimistic literature, but rather to try and present an ambitious yet realistic approach. Even though the Bellona Scenario is based on the most ambitious scenario from Ecofys, this is not the most optimistic scenario found in the literature. The Ecofys report is conservative compared to the IPCC ^[1], which concludes that the overall energy saving potential by 2020 is 36 percent with a carbon price as high as 100 USD. This is a more optimistic prediction than the Ecofys Ambitious Scenario which concludes that enhanced energy efficiency can reduce the overall energy demand for all sectors by 22 percent in 2020. Furthermore, The Ecofys report, and thereby the Bellona Scenario, is consistent with the ambitious EU target of reducing energy consumption by 20 percent by 2020 ^[33].

The Ecofys report indicates some regional differences in the energy efficiency potential for industry. These regional differences are addressed in the Bellona Scenario as shown in Table 3.1.

Table 3.1. Summary of the energy efficiency potential for industry implemented in the Bellona Scenario.

Area	Energy efficiency potential (% reduction in energy demand compared to business as usual)	
	2020	2050
OECD Europe	17	35
USA	18	40
Other OECD countries	18	38
China	17	36
India	15	34
Other non-OECD countries	16	35

3.3.4. Efficiency in the Residential, Services and Agriculture Sector

The energy efficiency potential in the Bellona Scenario for the residential, services & agriculture sector is, just like the industry sector, based on the Ecofys Ambitious Scenario ^[22].

The Ecofys Ambitious Scenario concludes that global final energy demand for all sectors can be reduced by 47 percent in 2050 compared to a business as usual Scenario. A breakdown of this efficiency potential indicates that in the sector for residential, services & agriculture, the energy demand can be reduced by 52 percent in 2050 compared to a business as usual scenario.

The Ecofys report indicates some regional differences in the energy efficiency potential. These regional differences are addressed in the Bellona Scenario as shown in Table 3.2.

Table 3.2. Summary of the energy efficiency potential for residential, services, and agriculture implemented in the Bellona Scenario.

Area	Energy efficiency potential (% reduction in energy demand compared to business as usual)	
	2020	2050
OECD Europe	23	49
USA	25	56
Other OECD countries	25	54
China	24	51
India	21	47
Other non-OECD countries	23	49

3.3.5. Emission Reduction in the Transport Sector

Emission reduction strategies in the Bellona Scenario for the transport sector include introduction of electrical vehicles, biofuel, and ships with fuel cells running on hydrogen. Input data for the Bellona Scenario are market share of the different energy sources and energy carriers.

There is a large potential for electrical vehicles, biofuel and fuel cells, as shown in Section 2.5. However, the market share of each of the energy sources and energy carriers in the transport sector in 2050 is extremely difficult to predict today, because it depends to a great degree on what kind of regulations and incentives that will be implemented in the years to come to reduce GHG emissions from transportation.

Based on the potentials for biofuel, electrical vehicles and fuel cells given in Section 2.5, the development in the transport sector implemented in the Bellona Scenario is summarised below:

- **Road transport in OECD:** The share of electrical vehicles increases linearly from 0 percent in 2015 to 100 percent in 2050.
- **Road transport in non-OECD:** The share of electrical vehicles increases linearly from 0 percent in 2015 to 50 percent in 2050. The share of biofuel increases linearly from 0 percent in 2010 to 25 percent in 2050. The last 25 percent in 2050 will be fossil fuel.
- **Aviation (OECD and non-OECD):** Share of aviation based on biofuel increases linearly from 0 percent in 2020 to 100 percent in 2050.
- **Sea transport (OECD and non-OECD):** Share of sea transport based on fuel cells and hydrogen increases linearly from 0 percent in 2030 to 25 percent in 2050. Similarly, the share of biofuel for sea transport increases linearly from 0 percent in 2020 to 25 percent in 2050. The last 50 percent in 2050 will be fossil fuel.
- **Rail (OECD and non-OECD):** Share of rail based on electricity is assumed 100 percent from 2015.

The strategies mentioned above indicate that fossil fuel will be phased out from road transport in OECD by 2050. In non-OECD countries, 25 percent of the road transport will still be based on fossil fuel in 2050. Fossil fuel will also be phased out from aviation by 2050, while ship transport will still have a 50 percent share of fossil fuel in 2050.

Introduction of electrical vehicles represents a large efficiency potential. Fossil fuel based light and heavy duty vehicles have an average efficiency of 24 percent, while electrical vehicles can have an efficiency of 65 percent. This energy efficiency potential from replacing fossil fuel vehicles by electrical vehicles is addressed by the Bellona Scenario.

3.3.6. Bioenergy Potential

The bioenergy potential is analysed in Section 2.6.3 where it is indicated that the global bioenergy potential is within the range 44,600 to 63,500 TWh by 2050. If the majority of global GHG emissions are to be reduced, the full potential for biomass must be addressed, and in the Bellona Scenario a bioenergy potential of 60,000 TWh is addressed.. However, it is an absolute prerequisite that all bioenergy production is based on a *sustainable* biomass production. Biomass for energy purposes must not conflict with food and water security, biodiversity or soil structure integrity.

In the Bellona Scenario biomass is used for power production, heating, and biofuel production. By 2050 it is assumed that biomass contributes to production of 11,000 TWh electricity on a global scale, which is close to 30 percent of global power production in 2050. Furthermore, 80

percent of fossil fuel in the sector for residential, services & agriculture is assumed to be replaced by bioenergy within 2050.

As discussed in Section 3.3.5, biofuel will also be used for road transport and aviation. Bioenergy in the sectors for industry and fuel transformation is assumed to be identical to the BAU Scenario in the Bellona Scenario.

The total global primary energy demand based on biomass in the Bellona Scenario for 2050 is summarised in Table 3.3.

Table 3.3. Summary of the global primary bioenergy demand in 2050 in the Bellona Scenario.

Application	Global primary bioenergy demand in 2050 (TWh/yr)
Bio power production	31,700
Biofuel	13,900
Biomass for heating in the sector for residential, buildings & agriculture	11,500
Bioenergy in the sectors for industry and fuel transformation	2,700
Sum	59,800

As discussed in Section 2.6.3, bioenergy will lead to release of soil carbon due to forestry and agricultural. Furthermore, there will be direct emissions of CO₂ from the production, transportation and processing of biomass. In the Bellona Scenario it is therefore assumed a 30 percent GHG penalty from bioenergy, which means that when a primary CO₂ emissions reduction of 1 tonnes CO₂ is achieved by replacing fossil fuel with bioenergy, 0.3 tonnes CO₂-eq are released because of transportation of biomass and release of soil carbon, etc.

3.3.7. Renewable Power Production

The potential for renewable power production is analysed in Section 2.6 based on a bottom-up approach, and the global power production implemented in the Bellona Scenario for 2050 is summarized in Table 3.5. Furthermore, the power efficiency of the renewable energy sources in the Bellona Scenario is set equal to the efficiency given by the BAU Scenario.

Table 3.4. *Global power production from renewable sources addressed by the Bellona Scenario.*

Energy Source	Power prd. 2050 (TWh)
Hydro	4,800
Biomass & waste	11,000
Solar	11,000
Wind	6,100
Geothermal	700
Tidal, wave and Salt	100
Sum renewable power production	33,700
Total power production	37,400

The Bellona Scenario predicts a much higher renewable power production than the BAU Scenario. The increased renewable power production in the Bellona Scenario is mainly due to more power generated from solar, wind, and bio and waste. The hydro power in the Bellona Scenario is mainly based on BAU data.

Table 3.5 shows that by 2050 about 90 percent of the global power production will be based on renewable sources, according to the Bellona Scenario. The remaining 10 percent of power production will be provided by fossil fuels as nuclear energy is assumed to be phased out by 2050.

The Bellona Scenario addresses only slightly higher geothermal, tide, wave, and salt power production than BAU. The aim of the Bellona Scenario is to address a realistic and sustainable power production without too much intermittent power. Furthermore, replacing fossil fuel with renewable energy must be carried out at an ambitious, but not unrealistically high rate. A conservative wave and geothermal potential is therefore depicted. However, with the right incentives and regulations the power generated from geothermal and wave energy can be significantly higher than envisioned by the Bellona Scenario.

Prerequisites for renewable power production

In order to achieve the large share of renewable power that is implemented in the Bellona Scenario there have to be a large production of new solar cells and wind turbines. As a result, the energy demand in the industry sector will increase in order to produce all the required silicon, aluminium and steel for the solar cells, wind mills, and energy infrastructure. An increased energy demand in the industry sector, equal to 5 percent of the new renewable power, is therefore assumed.

Furthermore, solar and wind power are intermittent, and with a large share of intermittent renewable energy, storage of power will become an issue. Storage of power, either by batteries, compressed air or by pumping water back to reservoirs, will induce an overall energy loss. Therefore, it is assumed that renewable power production will increase power demand by 5 percent to compensate for energy loss due to power storage.

3.3.8. CCS

The potential for CCS in the Bellona Scenario is based on the Bellona study from 2007^[88] which concluded that CCS can reduce CO₂ emissions from fossil fuelled power plants by 80 percent in OECD countries in 2050. The Bellona Scenario is a bit more ambitious than the study, because if CCS for fossil fuelled power plants is made mandatory, which is currently being discussed in the EU, all power plants can have CCS in 2050 with a capture rate of 90 percent. The first power plants with CCS are assumed commissioned in 2020.

In addition, CCS can be implemented for refineries and hydrogen production, thereby leading to a 50 percent reduction in CO₂ emissions from fuel transformation by 2050. CCS can also be implemented for other large industrial CO₂ point sources, like steel, aluminium and cement plants, thereby reducing industrial CO₂ emissions by 50 percent by 2050^[88].

Furthermore, the concept of combining biopower production with CCS is assumed to be deployed widely by 2050. Therefore, the Bellona Scenario assumes that 80 percent of power production from biomass in 2050 is produced from large biopower plants with CCS.

Industrialised countries have to take a leading role in deploying CCS, and as a result the potential for CCS in non-OECD countries is assumed to be 75 percent of the potential in OECD countries^[88]. A summary of the CCS potential implemented in the Bellona Scenario is given in Table 3.5.

Table 3.5. Summary of the CCS potential implemented in the Bellona Scenario. More details are given in Appendix 1.

Sector	Share of CO ₂ emissions where CCS is introduced in 2050	
	OECD countries	Non OECD countries
Fossil fuelled power plants	100 %	75 %
Bio power plants	80 %	60 %
Fuel transformation and industry	50 %	37.5 %

A CO₂ capture plant needs significant energy to separate CO₂ from the flue gas, and today a capture plant will require about 15 percent of the power produced by the power plant. There are many promising RD&D activities around the world to reduce this energy penalty, and the Bellona Scenario assumes that this energy penalty will be reduced to 10 percent by 2050.

The volume of CO₂ produced in power plants depends on the fuel. According to the Norwegian Pollution Control Authority^[95] coal and natural gas produce 310 and 202 grams CO₂ per kWh, respectively, if the combustion efficiency is 100 percent. The emission from burning oil depends on the type of oil, but as an average 279 gram CO₂ is emitted per kWh. The CO₂ emissions from a biopower plant strongly depend on the type of biomass. Based on literature data^[96,97] it is assumed that a biopower plant will emit on average 450 grams CO₂ per kWh at 100 percent efficiency.

3.3.9. Non-CO₂ GHG Emissions

There are considerable non-CO₂ GHG emissions from landfilled waste, industry, and agriculture. The emission reduction potential from these sectors implemented in the Bellona Scenario is briefly discussed below. More details are given in Appendix 1.

Waste

According to Monni *et.al* ^[77] more than a 90 percent reduction in GHG-emissions from landfilled waste can be achieved at a cost level of 100 USD per ton CO₂ by 2030. Bellona believes international agreements within the waste sector can contribute to reach a goal of 90 percent reduction of emissions even before 2030 and over 95 percent within 2050. Because waste in most of the world is regularly collected at public costs, it has an advantage compared to other energy resources. Therefore, efforts in this sector may occur at lower costs compared to other initiatives to reduce global GHG emissions. For developing countries, incentives such as CDM can accelerate rates of landfill recovery and occur in parallel with improved land filling practices.

Agriculture

GHG emissions from agriculture are mainly CH₄ and N₂O, and according to the World Resource Institute ^[10] the emissions from agriculture equal 13.5 percent of global GHG emissions, *i.e.* 6 GtCO₂-eq. According to Smith et al. ^[81] the mitigation potential for agriculture in 2030 is estimated to be 2.5 GtCO₂-eq with carbon prices up to 50 USD per ton CO₂. With carbon prices up to 100 USD the potential increases to 4.3 GtCO₂-eq ^[81]. In the Bellona Scenario it is assumed that the emission reduction potential from agriculture is equal to this latter potential because carbon prices can easily increase to 100 50 USD by 2030. By assuming the same emission reduction potential in 2050 and accounting for expected increase in BAU emissions, it is estimated that agricultural GHG emissions can be reduced by 55 percent by 2050.

Industry

The reduction potential for industrial non-CO₂ GHG emissions is assumed to be equal to the industrial CO₂ emission reduction potential due to efficiency strategies. Section 3.3.3 states this potential is a 37 percent reduction in industrial emissions by 2050.

3.3.10. Land-use Change

Land-use change can lead to large reductions in GHG emissions, and the IPCC ^[11] has estimated the potential to be in the range 1.3 to 13.8 GtCO₂-eq per year. The wide range of this interval indicates that there are large uncertainties of the land-use change potential. However, an ambitious approach is required to eliminate land-use change emissions and ensure a net absorption of CO₂ by 2050. As an ambitious, but realistic approach, the land-use change potential is assumed to be 10 GtCO₂-eq by 2050 in the Bellona Scenario. This means that while land-use change produces close to 8 GtCO₂-eq today, the situation in 2050 will be a net absorption of more than 2 GtCO₂-eq in 2050.

3.3.11. Nuclear Energy

Bellona does not consider nuclear energy as an appropriate strategy to combat global warming. Indeed, as discussed in Section 2.10, the potential of nuclear power as a GHG mitigation strategy is limited, new nuclear power plants are very expensive and they present significant environmental dangers that are difficult to overcome. Nuclear energy is therefore excluded as a strategy to combat global warming.

In the Bellona Scenario it is assumed that all existing nuclear power plants will be decommissioned by 2050 ^[5], and that nuclear energy is phased out by 2050.

4. Results - Energy Demand and GHG Emissions in the Bellona Scenario

4.1. Energy Demand and Power Production

Energy demand

The global energy demands in the BAU scenario as well as the Bellona Scenario are presented in Figure 4.1. The graphs in this figure show that the energy demand in 2050 is considerably lower in the Bellona Scenario, than in the BAU Scenario. This is mainly due to the energy efficiency strategies addressed in the Bellona Scenario. In addition, renewable energy sources will constitute more than half of the total energy demand in 2050 according to the Bellona Scenario, which is considerably higher than in the BAU Scenario.

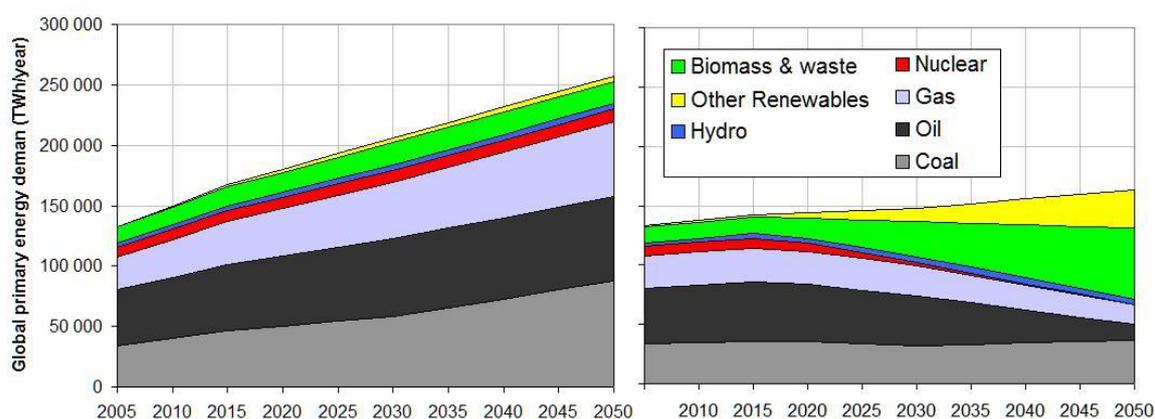


Figure 4.1. Global primary energy demand from different energy sources. Left: the BAU Scenario. Right: the Bellona Scenario.

The pie charts in Figure 4.2 show how different energy sources will contribute to the global primary energy supply. The BAU energy mix in 2050 will be quite similar to today, while in the Bellona Scenario, a large portion of fossil fuels are replaced by renewable energy sources. The pie charts also show that the share of hydro power increases only slightly due to the limited potential for new hydro power projects. Furthermore, nuclear power is phased out by 2050 in the Bellona Scenario.

Even though there is a large increase in renewable energy production in the Bellona Scenario, the world will still be dependent on fossil fuels in 2050. This is a strong indication that CCS, which permits fossil energy production with low GHG emissions, is an important strategy to reduce GHG emissions along with energy efficiency and renewable energy.

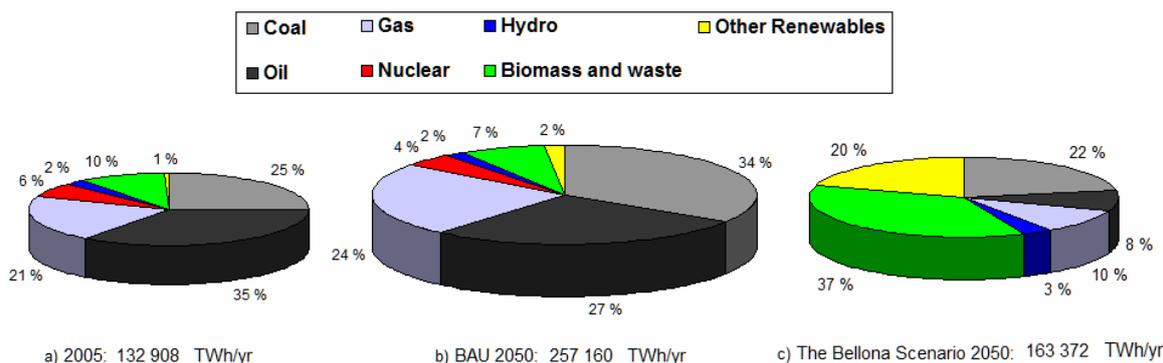


Figure 4.2. Global energy demand from different sources; (a) today, (b) the BAU Scenario in 2050, and (c) the Bellona Scenario in 2050. The area of the pie charts reflects the total primary energy demand.

The main trend in global energy demand can be summarised as follows:

- The BAU Scenario shows that:
 - The global primary energy demand will increase by 93 percent between 2005 and 2050.
 - The dependency on fossil fuel will increase from 81 to 85 percent between 2005 and 2050
 - Renewable energy will constitute only 11 percent of the global primary energy in 2050.
- The Bellona Scenario shows that:
 - The global primary energy demand will increase by 23 percent between 2005 and 2050, which represents a 36 percent lower energy demand than in the BAU Scenario.
 - The dependency on fossil fuel will decrease from 81 percent in 2005 to 40 percent in 2050.
 - Renewable energy will represent 60 percent of the energy supply in 2050.

Although the Bellona Scenario depicts an ambitious development in energy efficiency and renewable energy there are many possible clean energy technologies that are not addressed. Two examples are the large potential for solar heating of buildings and renewable energy in the industry sector. For these two strategies, the Bellona Scenario assumes similar development as the BAU Scenario. As such, the potential for more renewable energy is even greater than the Bellona Scenario depicts.

As mentioned earlier, the objective of the Bellona Scenario is to identify the prospects for clean energy development in the future that is ambitious, but also realistic. In order to make the Scenario realistic, some strategies have been addressed ambitiously, while others were addressed more conservatively. The Bellona Scenario shows that it possible to reduce energy demand and simultaneously increase the share of renewable energy. However, it is difficult to predict which low emission technologies will turn out to be most successful. The path to a sustainable energy mix in 2050 can easily turn out to be different than the one addressed by the Bellona Scenario.

Power production

The global power production in the BAU and Bellona Scenarios are shown in Figure 4.3. Power demand will increase significantly up to 2050, but the Bellona Scenario predicts a lower power demand in 2050 due to lifestyle changes and energy efficiency strategies addressed in the Bellona Scenario. Furthermore, the BAU Scenario indicates that the increased power demand will be met by increased power production from fossil fuels. In contrast, the Bellona Scenario predicts a strong increase in renewable energy production, which will allow reduced fossil power production.

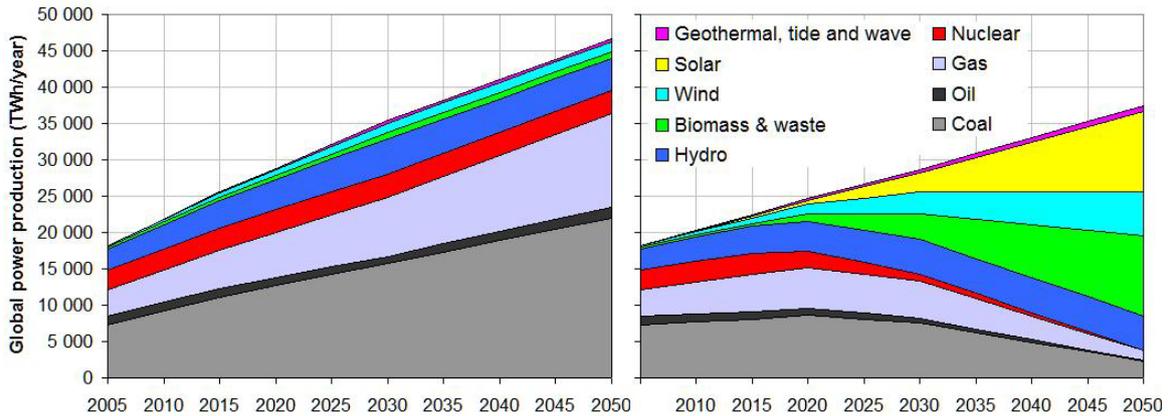


Figure 4.3. Global power production. Left: the BAU Scenario. Right: the Bellona Scenario.

The figure above shows that fossil power production will peak in 2020 in the Bellona Scenario. As a consequence, the rate of introducing new coal and gas power plants must be reduced significantly before 2020.

The energy mix for power production in 2050 for the BAU and Bellona Scenarios are compared in Figure 4.4, and the global energy demand and power production in 2050 is summarised in Table 4.1. It is seen that 90 percent of the power production in 2050 will be based on renewable sources according to the Bellona Scenario. This is a consequence of the large deployment of solar power, wind power, and large bio power plants.

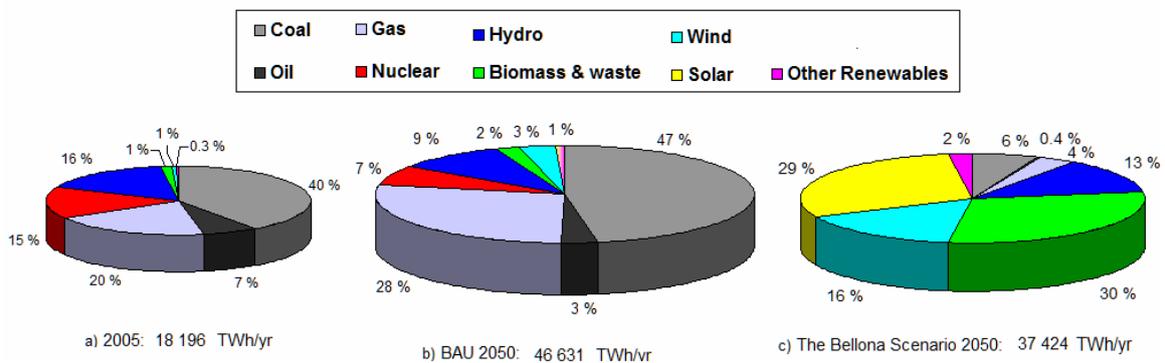


Figure 4.4. Global power production from different sources; (a) today, (b) the BAU Scenario in 2050, and (c) the Bellona Scenario in 2050. The area of the pie charts reflects the total primary energy demand.

The renewable energy production in the Bellona Scenario stems mainly from solar, wind, biomass, and hydro power. In order to ensure a realistic approach, Bellona is ambitious on the development of solar, wind and biomass power production, but more conservative on the development for wave, tidal, and geothermal power. However, it is difficult to predict the future, and wind, tidal, and geothermal power can easily contribute a much greater share of energy toward the total energy production than indicated by Figure 4.4.

Table 4.1. Primary energy demand and power production from different energy sources in 2050

Energy Source	Primary energy demand 2050 (TWh)		Power Production 2050 (TWh)	
	BAU	The Bellona Scenario	BAU	The Bellona Scenario
Coal	87,600	36,300	22,000	2,200
Oil	69,600	13,500	1,500	100
Gas	62,200	16,500	12,900	1,300
Nuclear	10,500	0	3,100	0
Hydro	4,400	4,800	4,400	4,800
Biomass & waste	18,400	59,800	900	11,000
Other renewables	4,400	32,500	1,800	17,900
Sum	257,100	163,400	46,600	37,400

4.2. GHG Emissions

The BAU Scenario predicts 81.0 GtCO₂-eq emissions globally in 2050, while the Bellona Scenario only predicts 7.1 GtCO₂-eq as shown in Table 4.2.

Table 4.2. Global GHG emissions in the BAU and Bellona Scenarios.

Scenario	GHG emissions (GtCO ₂ -eq/year)	Change compared to BAU 2050	Change compared to BAU 2005
2005	44.9		
BAU 2050	81.0		+ 80 %
Bellona Scenario 2050	7.1	- 91 %	- 84 %

The contributions from different low emission reduction strategies to the emission reduction in the Bellona Scenario are summarised in Table 4.3. From this table it is seen that all the different emission reduction strategies contribute with significant emission reductions. In order to reduce global GHG emissions sufficiently to keep global warming below 2 °C, it is therefore essential that all the different emission reduction strategies are deployed.

Table 4.3. Emission reduction from BAU to the Bellona Scenario in 2050. All data are given as Giga tonnes CO₂-eq emission reduction compared to BAU in 2050.

Scenario (bold) and strategies (italic)		Emissions in 2050 (bold) and emission reductions in 2050 compared to BAU (italic) (GtCO ₂ -eq/year)
The BAU Scenario 2050		81.0
<i>Lifestyle change</i>		7.5
<i>Enhanced power plant efficiency</i>		2.5
<i>Efficiency in the residential, services & agricultural sector, (only CO₂ emission reduction)</i>		10.6
<i>Enhanced energy and process efficiency in industry</i>	<i>CO₂</i>	7.4
	<i>Non-CO₂</i>	1.8
<i>Efficiency strategies to reduce CH₄ and N₂O emissions in agriculture</i>		4.4
<i>Efficiency strategies to reduce non-CO₂ GHG emissions from waste handling</i>		1.8
<i>Nuclear phase out</i>		-2.3
<i>Biomass for power production and fuel transformation</i>	<i>With CCS</i>	4.4
	<i>Without CCS</i>	0.7
<i>Biomass for heating in the residential, services & agricultural sector</i>		1.5
<i>Increased renewable power production from solar, wind, hydro, wave, tidal, and geothermal sources</i>		6.0
<i>Transportation strategies; electrical vehicles, H₂ and biofuel. (Effect of renewable power for electrical vehicles is not included. Power for electrical vehicles is here assumed produced from coal power plants)</i>		0.8
<i>CCS, fossil fuelled power production</i>		5.6
<i>CCS, fuel transformation, from fossil fuelled sources</i>		2.1
<i>CCS, industrial sources</i>		1.7
<i>CCS from sources based on bioenergy</i>		9.2
<i>Land-use change</i>		8.1
The Bellona Scenario 2050		7.1

The global GHG emissions in the Bellona Scenario are reduced by 84 percent in 2050, compared to emissions in 2005. As such, the Bellona Scenario describes how global GHG emissions can be reduced sufficiently to limit global warming to 2 °C above pre-industrial level. The global GHG emissions in the Bellona Scenario are also compared to the BAU emissions in Figure 4.5 which depicts how different low emission strategies contribute to reduced global GHG emissions. Figure 4.5 shows how considerable emission cuts are achieved by energy efficiency, renewable

energy and CCS. In addition, it is seen that lifestyle changes, land-use changes, and cuts in non-CO₂ GHGs also lead to significant cuts in total GHG emissions. Furthermore, the Bellona Scenario indicates that global GHG emissions can peak before 2015.

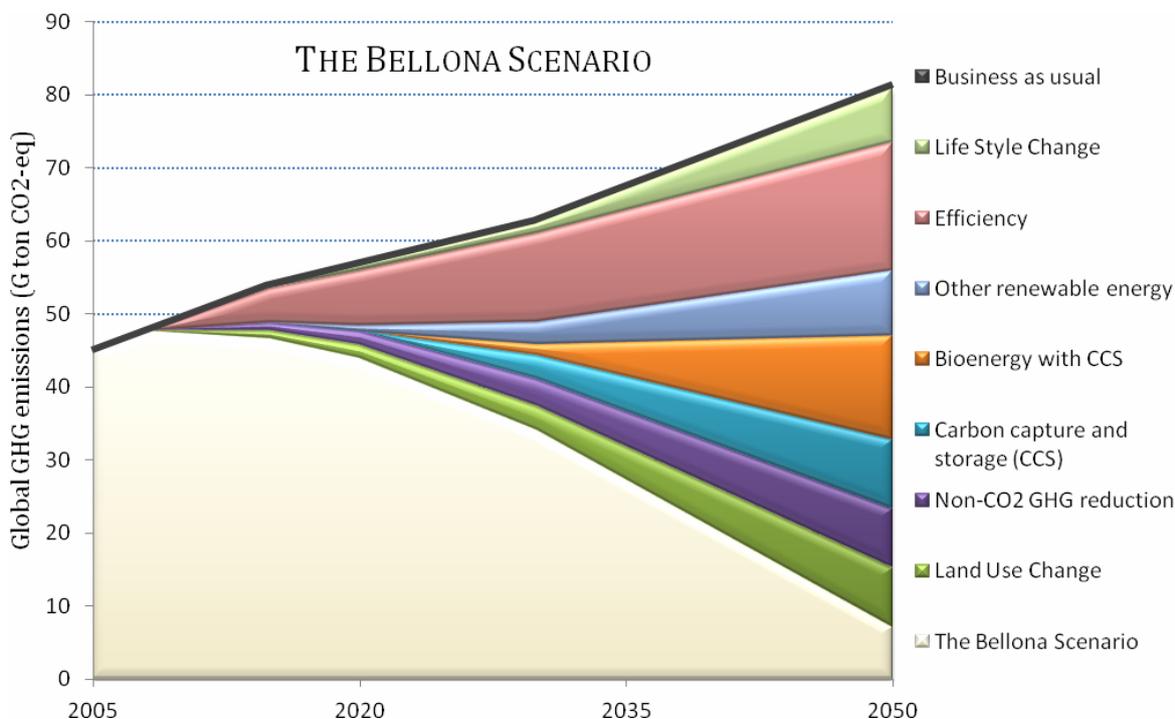


Figure 4.5. Global GHG emissions in the Bellona Scenario compared to the BAU Scenario. The upper bold black line is the BAU Scenario, and the lower bold blue line is the Bellona Scenario. The different wedges (coloured areas) indicate how much different emission reduction strategies contribute to the emission reduction from BAU to the Bellona Scenario.

The different wedges for emission reduction in Figure 4.5 constitute the strategies given below. Global GHG emission reduction in 2050 relative to BAU emissions are given in brackets.

- **Lifestyle changes (7.5 GtCO₂-eq):** Reduced primary energy demand due to lifestyle change.
- **Efficiency (17.5 GtCO₂-eq):** Energy and process efficiency in the sectors for power production, industry, transport and residential, services & agriculture. Includes only reduction in CO₂ emissions, and not the other non-CO₂ GHGs. Phase-out of nuclear power is also included here.
- **Renewables (9.7 GtCO₂-eq):** All renewable energy strategies except for bioenergy with CCS.
- **Carbon negative energy with CCS (13.6 GtCO₂-eq):** Emission reduction due to the carbon negative concept, *i.e.* large bio power plants with CCS. The wedge accounts for replacing fossil fuel with bio *and* the physical storage of CO₂ due to CCS.
- **CCS (9.4 GtCO₂-eq):** Emission reduction due to CCS on fossil fuelled power plants and large CO₂ point sources in industry and fuel transformation. The wedge only accounts for CCS for emissions from fossil fuels, *i.e.* CCS combined with biomass is not included.

- **Non-CO₂ GHG reduction (8.0 GtCO₂-eq):** Emission reduction of CH₄, N₂O, SF₆, HFC, and PFC due to emission reduction strategies in industry, agriculture and waste handling.
- **Land-use change (8.1 GtCO₂-eq):** Emission reduction due to reforestation and forest management.

Energy efficiency

The implementation of energy and process efficiency strategies in the Bellona Scenario, results in a global reduction of 28 GtCO₂-eq in 2050 compared to BAU emissions when all GHGs are addressed (and phase out of nuclear is not included). The reduction potential due to energy efficiency is presented in Figure 4.6. This figure shows that the biggest efficiency potentials are within industry, residential, services and agriculture.

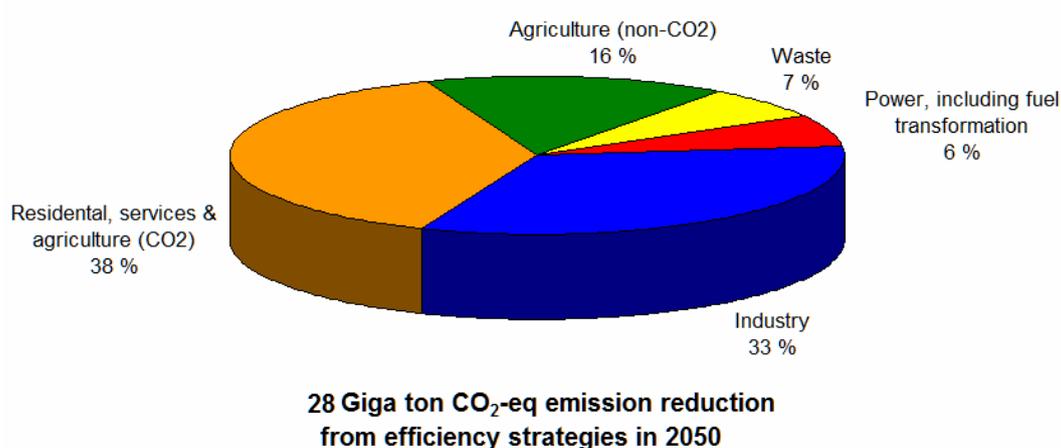


Figure 4.6. Global emission reductions due to energy and process efficiency in the Bellona Scenario are relative to the BAU Scenario in 2050. Emission reductions of all GHGs (and not just CO₂) are included.

Emission reduction strategies in the transport sector are not fully represented in the figure above. This figure only accounts for efficiency measures, and therefore the effect of renewable power production for electrical cars is not represented. This effect is included in the renewable strategies discussed below. Please also note that when efficiency measures lead to lower power demand, the resulting emission reduction is accounted in the pies for industry and residential, and not in the power production sector.

The potential for energy efficiency is larger in non-OECD countries than in OECD countries. This underlines the importance of ensuring regulations to enhance energy efficiency in developing countries in addition to developed countries.

CCS from fossil fuel and biomass sources

CCS will reduce global emissions by 19 GtCO₂ in 2050 compared to the BAU Scenario. As seen from Figure 4.7, the combination of bioenergy and CCS accounts for close to half of the CCS potential. This shows how important it is to deploy large-scale bio power plants with CCS. Up until 2030, CCS will have its largest potential for fossil fuelled power plants, but when fossil fuels become replaced by renewable sources from 2020 (*c.f.* Figure 4.3), large bio power plants

with CCS will eventually lead to larger CO₂ emission reductions than fossil fuelled power plants with CCS.

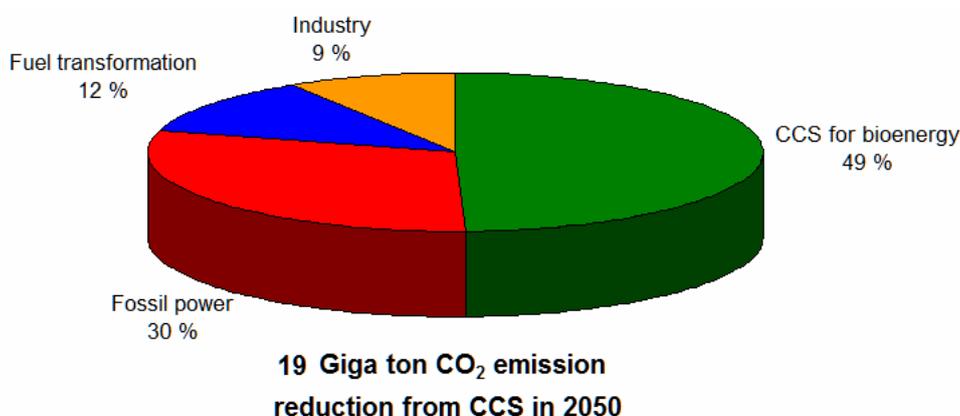


Figure 4.7. Global emission reductions due to CCS in the Bellona Scenario relative to the BAU Scenario in 2050.

CCS has its largest potential in power production, but there is also a significant potential within industry and fuel transformation, which accounts for 9 and 12 percent respectively of the CCS potential, as shown in Figure 4.7. Therefore, it is important to deploy CCS not only for power plants, but also for large industrial sources like refineries, cement plants and steel plants. The CCS potential is relatively evenly distributed in OECD and non-OECD regions, which is compelling evidence for deploying CCS in developing countries as well as developed countries.

Renewable energy (including biomass for CCS)

The increased renewable energy production in the Bellona Scenario compared to BAU results in 14 GtCO₂ less GHG emissions in the Bellona Scenario globally in 2050. As seen from Figure 4.8 power production constitutes most of this emission reduction potential, but significant emission reduction is also achieved by biofuels and biomass for heating in buildings.

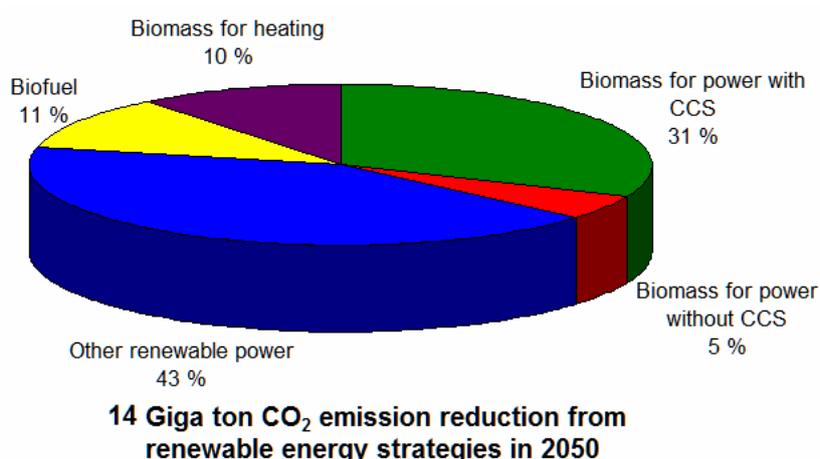


Figure 4.8. Global emission reductions due to increased renewable energy production in the Bellona Scenario relative to the BAU Scenario in 2050. Other renewable power are mainly solar and wind power.

Biomass for power and fuel transformation constitutes 36 percent of the renewable emission reduction potential, which is a result of the large potential for the carbon negative concept addressed by the Bellona Scenario. The wedge called *Other renewable power* in Figure 4.8 is mainly CO₂ emission reduction due to replacing fossil power by solar and wind power.

Emission cuts in different sectors

Global CO₂ emissions split by different sectors are shown in Figure 4.9. In this figure the CO₂ emission reductions are accounted for in the sector where they physically occur. For instance, if energy efficiency in the industry sector leads to reduced consumption of oil for heating purposes, then the emission reduction is accounted for in the industry sector. But when energy efficiency leads to lower electricity consumption, the CO₂ emission reduction is accounted for in the power sector.

Figure 4.9 shows that power production represents the largest potential in terms of GHG emissions reductions and that even negative CO₂ emissions can be expected through the introduction of the carbon negative concept. This concept relies on a combination of CCS and large-scale biomass production for energy purposes and ensures that CO₂ is actually removed from the atmosphere.

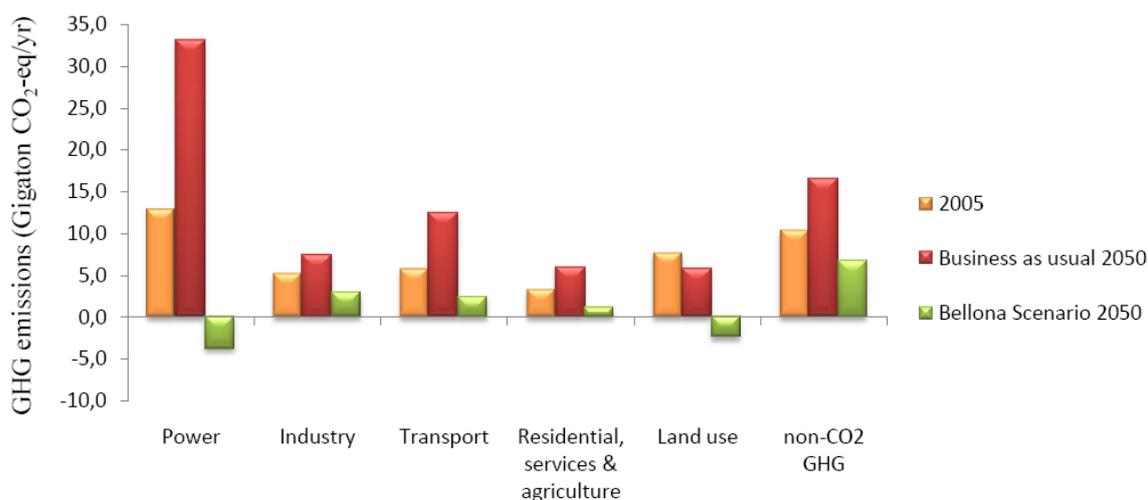


Figure 4.9. Global GHG emissions from different sectors in 2005 and 2050 according to the BAU and Bellona Scenarios. Please note that the first five sectors only include CO₂ emissions.

It is evident from Figure 4.9 that there are significant emission reduction potentials in all sectors. This underlines the importance of establishing incentives and regulations for all sectors to motivate deployment of low emission technologies.

The emission reduction in the transport sector indicated in Figure 4.9 is much higher than that reported in Table 4.3. This is because the emission reduction potential when changing from fossil fuelled vehicles to electrical vehicles depends on how the electricity is produced. The GHG emission reduction from electrical cars is much higher if the electricity is produced from renewable sources, rather than fossil fuels. In Figure 4.9 it is assumed that electricity for electrical cars comes from renewable sources, while in Table 4.3, the effect of renewable power is reported separately.

Figure 4.9 also indicates that non-CO₂ GHG emissions will comprise a larger share of total GHG emissions in 2050 than today. This is because it is more difficult to reduce non-CO₂ GHG emissions. Again, this factor demonstrates how important it is to establish strategies to reduce emissions of all GHGs, and not only CO₂.

4.3. Case Studies

Several case studies have been conducted to investigate the effect of different mitigation strategies on GHG emission reductions. A description of the different case studies is given in Table 4.4 along with the calculated reduction in global GHG emissions. The calculated GHG emissions for each of the case studies are shown in Figure 4.10.

Table 4.4. Description of the case studies.

Case no.	Case Name	Case Description	Global GHG emissions in 2050 (GtCO ₂ -eq)	Calculated reduction in global GHG emissions in 2050 compared to emissions today
0	The Bellona Scenario	The Bellona Scenario as presented in section 3	7.1	- 84 %
1	No CCS	Same as case 0, but with no CCS strategies	25.7	- 43 %
2	Nuclear energy included	Same as case 0, but without the phase out of nuclear energy	6.9	- 85 %
3	No carbon negative	Same as case 0, but without the carbon negative concept	16.3	- 64 %
4	Weak incentives for developing countries	The potential for the emission reduction strategies in non-OECD countries is half of the potential in Case 0*	25.7	- 43 %

* All input data to the Bellona Scenario is specified in Appendix 1. In Case 4, all mitigation potentials specified in this Appendix are halved for non-OECD countries.

The following conclusions can be made from the results in Table 4.4 and Figure 4.10:

- If CCS is not included in the strategy to reduce global GHG emissions it is not possible to achieve the emission reduction target established by the IPCC.
- There are only minor differences in the Bellona Scenario and Case no. 2 where nuclear energy is included. The low effect of including nuclear energy is due to the relative small share of nuclear power in the BAU Scenario and the subsequent reduced potential for CCS if nuclear plants are built to replace fossil fuel power plants.

- If the carbon negative concept is not deployed, an emission reduction greater than 50 percent is possible. However, this reduction is not as optimal as in the Bellona Scenario.
- If the incentives for deploying low emission technologies in developing countries are too weak, it will be difficult to achieve sufficient global emission reductions. This underlines the importance of ensuring strong incentives for emission reduction not only in developed countries, but also in developing countries.

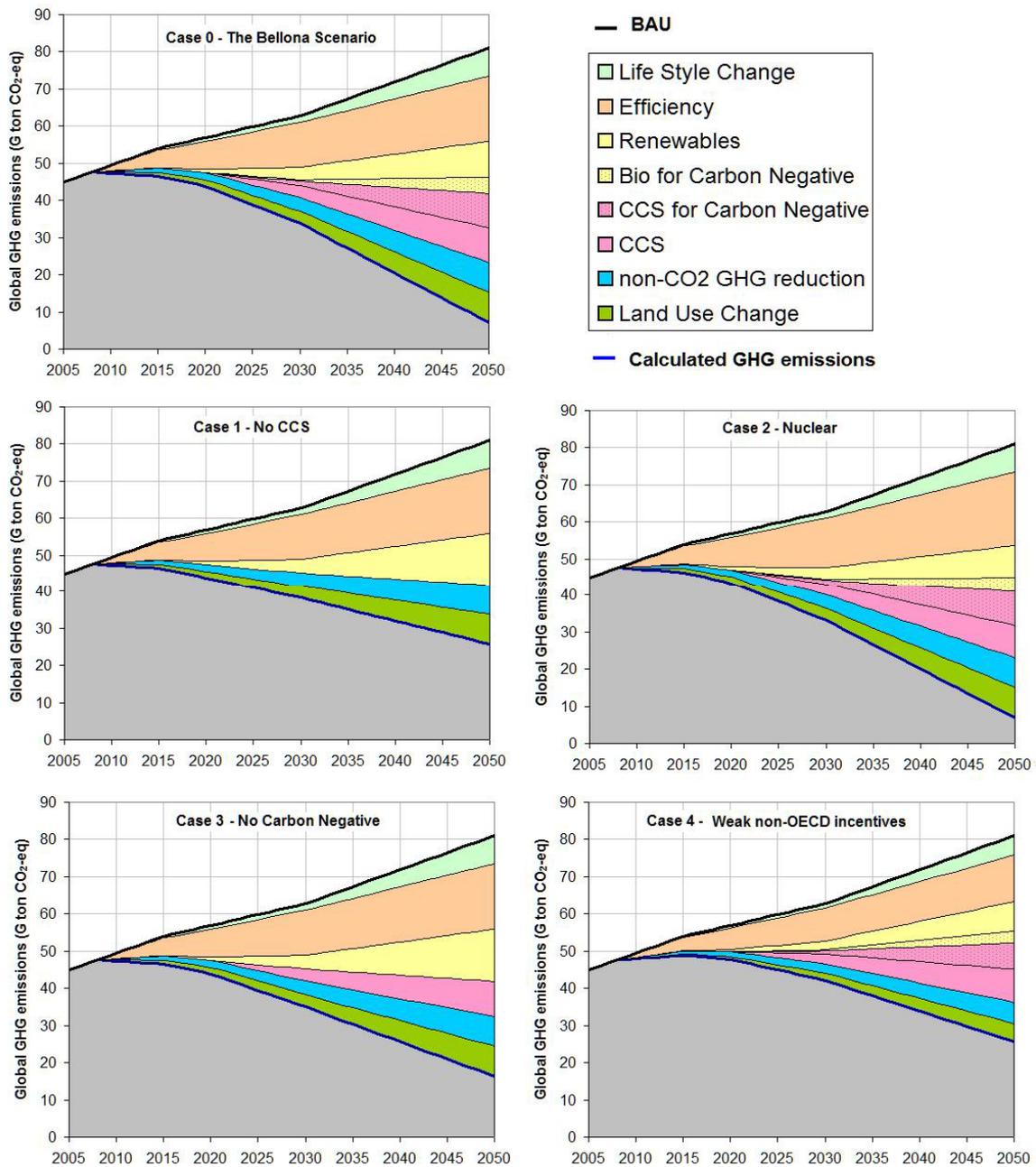


Figure 4.10. Business as usual global GHG emissions and calculated global GHG emissions for the case studies.

4.4. Implementing the Bellona Scenario

A successful deployment of the Bellona Scenario requires many technological innovations to reduce energy demand and replace fossil fuels by renewable energy. Some of the necessary technology advances are:

- Combining biopower plants with CCS to produce carbon negative power represents a large share of the emission reductions implemented in the Bellona Scenario. The technologies in this concept are known, but more technical knowledge is needed to make large-scale deployment possible. Life cycle analysis has to be performed to determine the potential for sustainable production of biomass for energy purposes. Algae are some of the fastest growing species, and are already being used for bioenergy production at several locations. Further studies are however needed to investigate the global potential and optimal method for algae production.
- Biomass for energy purposes can be used for production of power, heat, and biofuel. Further research is required to determine how to optimize a plant for co-production of power, heat, and biofuel from biomass.
- Reduced cost is a prerequisite to make CCS commercially attractive. To do this, large-scale demonstration projects are needed as soon as possible. The European Commission ^[89] has ambitions to establish a flagship program of 10-12 full-scale CCS projects in Europe. It even considers building one of the projects in China to pave the way for CCS in developing countries. Several other CCS demonstration projects are also planned, such as the FutureGen project in the USA as well as several projects in Australia.
- Demonstration programs must also be established to ensure commercialisation of technologies for renewable power, particularly within offshore wind, wave, tidal, salt, and geothermal power.
- Research is required to boost development of solar and wind power technologies. Public R&D funding should therefore be transferred from fossil fuel research activities to renewable energy R&D activities.
- Passivehouses with a minimum of energy consumption must be further developed. Even more important is the development of *plushouses* where houses and buildings not only produce their own energy, but also deliver power to the grid. One version of this concept is to cover facades by solar cells and optimising ventilation, heat recovery and insulation. For skyscrapers, wind mills can be integrated in the building to supply the building with power.
- Fuel cells have the potential to be an important technology for energy conversion. On a short timescale fuel cells will probably have a limited potential within transport and small-scale power production, but on a longer timescale, fuel cells are widely applicable for road transport and large-scale power generation. Ambitious RD&D programs are required to ensure development and commercialisation of fuel cell technology.

- Implementation of clean and renewable fuels and energy carriers in the transport sector will require new infrastructure and the public sector should take responsibility and prioritize research and deployment of the needed infrastructure. One example: Fast charging of batteries requires specialized charging facilities and, in some cases, improved power supply. Infrastructure for charging will probably be a prerequisite for large scale deployment of battery-electric vehicles. Furthermore, a large fleet of battery-electric vehicles can play an important role as energy buffers in a power system based on larger shares of intermittent renewable energy sources.
- Improved energy infrastructure is a prerequisite for boosting renewable energy production. Large-scale bioenergy production requires new infrastructure for production and transport of biomass. A large share of intermittent renewable power will require new advanced and intelligent grids, and supergrids for long-distance transport of large quantities of power. New solutions for buffering and storing of the increased intermittency of power must be developed. Furthermore, infrastructure for heat transport must be improved.

All the possible technological advances described above can be carried out provided that the right regulatory framework and economic incentives are established. In other words, bold political leadership is what we need to deploy the Bellona Scenario and reduce GHG emissions sufficiently to combat global warming.

5. Conclusions

Key messages

- Global warming is a tremendous challenge, but it can be tackled.
- Global GHG emissions can be reduced by up to 85 percent by 2050 compared to emissions today.
- Already known technologies and industrial practices suffice to do the job.
- Bold political leadership is required to deploy the mitigating solutions.

The IPCC has documented that global warming can lead to dramatic consequences if the average global temperature increase is not limited to 2 °C above the pre-industrial level. This necessitates reducing global greenhouse gas emissions by 85 percent by 2050 compared to emissions today. Our study shows that a portfolio of existing and emerging technologies and strategies can achieve the necessary emission reductions.

The potentials for different emission reduction strategies are established primarily from available literature. Based on such emission reduction potentials, the Bellona Scenario is created to show how a possible combination of technologies and strategies can lead to the necessary reductions in global GHG emissions.

According to the Bellona Scenario, global GHG emissions in 2050 are reduced by 84 percent compared to emissions in 2005. The global GHG emissions will be 7.1 GtCO₂-eq in 2050, which is 73.9 GtCO₂-eq lower than the BAU Scenario.

The emission reduction strategies addressed in the Bellona Scenario are summarized below. Global GHG emission reductions in 2050 relative to BAU emissions are given in brackets.

- **Lifestyle changes (7.5 GtCO₂-eq):** Reduced primary energy demand due to lifestyle change.
- **Efficiency (17.5 GtCO₂-eq):** Energy and process efficiency in the sectors for power production, industry, transport and residential, services & agriculture. Includes only reduction in CO₂ emissions, and not the other non-CO₂ GHGs. Phase-out of nuclear power is also accounted for.
- **Renewables (9.7 GtCO₂-eq):** All renewable energy strategies except for biomass for carbon negative energy.

- **Carbon negative energy (13.6 GtCO₂-eq):** Emission reduction due to CCS on power plants fuelled with biomass.
- **CCS (9.4 GtCO₂-eq):** Emission reduction due to CCS on fossil fuel power plants, point sources for fuel transformation, and industry based on fossil fuels.
- **Non-CO₂ GHG reduction (8.0 GtCO₂-eq):** Emission reduction of CH₄, N₂O, SF₆, HFC, and PFC due to emission reduction strategies in industry, agriculture and waste handling.
- **Land-use change (8.1 GtCO₂-eq):** Emission reduction due to reforestation and forest management.

The combination of strategies addressed in the Bellona Scenario is also shown in the figure below.

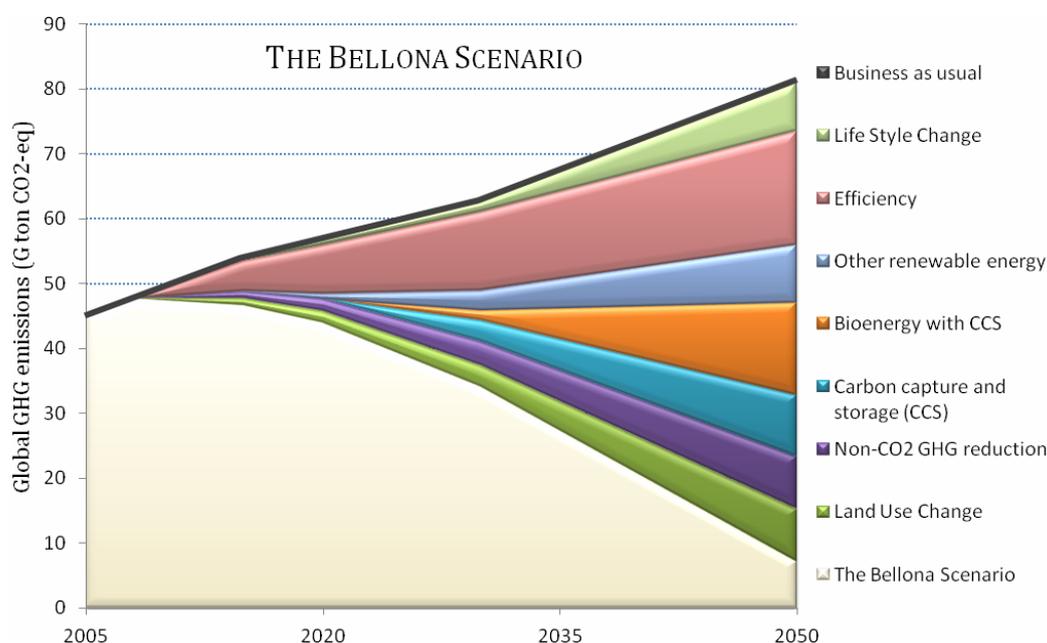


Figure 5.1. Global GHG emissions in the Bellona Scenario compared to the BAU Scenario.

The Bellona Scenario shows considerable emission reductions in all sectors, including power production, industry, transport, buildings and agriculture. This underlines the importance of deploying emission reduction strategies in all sectors.

According to the Bellona Scenario, global primary energy demand will increase by 23 percent from 2005 to 2050. However, the energy demand will be 36 percent lower than the BAU predictions for 2050. Renewable energy will be introduced at a high rate in the Bellona Scenario, and 60 percent of the global energy demand will be based on renewable sources in 2050. This is considerable higher than BAU estimates, but it also shows that the world will be dependent on fossil fuels in 2050. Furthermore, the Bellona Scenario shows that 90 percent of power production will be based on renewable sources in 2050.

Several case studies are performed to investigate how an overall strategy to reduce global GHG emissions should be designed. It is concluded that it is impossible to obtain sufficient GHG emission reduction without CCS and carbon negative. Furthermore, there are only minor changes

in the total GHG emission reduction potential if nuclear is not phased out., because if nuclear plants are built to replace fossil fuel power plants there is a subsequent reduced potential for CCS.

The case studies also show that if the incentives for deploying low emission technologies in developing countries are too weak, it will be difficult to achieve sufficient global emission reductions. This underlines the importance of ensuring strong incentives for emission reduction in developing countries.

Cost calculations have not been performed. If we really *must*, as scientific evidence tells us, reduce emissions by up to 85 percent by 2050, then the first step is to show that this indeed *is* technically and practically achievable. As such, the next logical step for future research is to perform cost calculations for deploying the Bellona Scenario.

There are technologies available to achieve sufficient GHG emission reductions. All the technological advances described in the Bellona Scenario can be carried out provided the right RD&D activities are carried out and the right regulatory framework and economic incentives are established. In other words, bold political leadership is what we need to deploy the Bellona Scenario and reduce GHG emissions sufficient to combat global warming.

Acknowledgement

This paper has been prepared as a part of Bellona's work related to the EU Technology Platform on Zero Emission Fossil Fuel Power Plants (ZEP). Bellona would like to thank The Research Council of Norway and The Norwegian Ministry of Environment who have funded portions of Bellona's activity within the ZEP.

Appendix 1. The Bellona Scenario for GHG Emission Reduction

The Bellona Scenario is briefly described in Section 3. More details on how the Bellona Scenario is calculated are described below along with a detailed presentation of all input data to the Bellona Scenario.

In this appendix, the calculation behind the Bellona Scenario is called the Bellona Model. This model constitutes of two essential parts; (i) a business as usual (BAU) Scenario for primary energy demand, power production, and GHG emissions, and (ii) an algorithm to calculate the future primary energy demand, power production, and GHG emissions based on specific input data.

Repartition per sector and geographical region

As the potential of technologies in terms of CO₂ reduction varies from one geographical area to another, the Bellona Model is built so that these geographical specificities are taken into account. A distinction is made between OECD and non-OECD countries in order to visualise the difference in emission reduction potential in developed and developing countries. Specific calculations are also performed for significant developed and developing countries or area.

The Bellona Model distinguishes the following geographical areas:

- OECD Europe
- USA
- All other OECD countries
- China
- India
- All other non-OECD countries

The model is also separated in different categories of GHG emissions within each geographical area. The separation in categories is performed to visualise the difference in emission reduction potential in different energy related sectors and to visualise the difference in emissions from CO₂ and other greenhouse gasses. The different sectors in the Bellona model are as follows:

- Power production
- Fuel transformation¹²
- Industry
- Transport
- Residential, services & agriculture
- Land-use change
- Non-CO₂ GHG emissions

¹² Fuel transformation includes refineries, coal and gas transformation and liquefaction, energy use and loss by gas works, energy used in coal mines, energy used in oil and gas extraction, and energy used for electricity and heat production.

The first six bullet points in the list above only calculate CO₂ emissions in addition to primary energy demand and power calculations. Calculation of non-CO₂ GHG emissions are only performed in the sector given in the last bullet point. The first five sectors in the list above are established to enable direct comparison with data reported by the International Energy Agency (IEA) ^[5,7,13,14] as these data are used to establish the business as usual scenario. More details on definitions of sectors are available in IEA publications ^[7,13].

The BAU Scenario in the Bellona Model

The business as usual Scenario (BAU) in the Bellona Model is an estimation of future energy demand and GHG emissions based on predictions from the literature where already implemented strategies from world leaders to shape the future are accounted for. This means that new strategies necessary to combat global warming that are not part of official politics yet are not addressed in the BAU Scenario.

The BAU Scenario implemented in the Bellona Model is to some extent a compilation and an extrapolation of data found in published literature. The challenge has been to define a BAU Scenario according to the same principles and at the same detailed level than those applying for the Bellona Model in terms of geographical area, sectors, energy sources, and time.

The BAU Scenario contains data for global primary energy demand, power production, CO₂ emissions, and non-CO₂ GHG emissions onwards to 2050 for all sectors and geographical regions specified above.

The sources used to define the BAU Scenario are described in the following.

Energy demand and power production

The energy demand and power production data are based on the Reference Scenario from the IEA World Energy Outlook 2007 (WEO2007) ^[7]. As it only reports data until 2030, the Baseline Scenario in the IEA Energy Technology Perspective 2006 (ETP2006) ^[5] is used as a supplementary source for 2050 data.

When the data of the WEO2007 and ETP2006 are not sufficiently detailed to cover all aspects of the Bellona Model, the Reference Scenario from the IEA World Energy Outlook 2004 and 2006 (WEO2004 and WEO2006) ^[13,14] are used as supplementary sources.

For instance, the WEO2007 in some cases reports only the sum of the energy demand and CO₂ emissions for several sectors without specifying data for each sector, while the WEO2004 makes a distinction between all sectors. In such cases, the BAU Scenario take into account the data regarding global energy demand reported in WEO2007 and simply split such data into different sectors based on the proportions from WEO2004. Although such extrapolations introduce uncertainties in the BAU Scenario, it is however insignificant compared to the uncertainties already embedded in a BAU predictions of future energy demand.

Energy and process related CO₂ emissions

The energy and process related CO₂ emissions data are based on WEO2007 until 2030, while data for 2050 are based on ETP2006. As the ETP2006 report does not specifies the energy and process

related CO₂ emissions for all the geographical areas defined in the Bellona Model, the BAU Scenario is based on the total global CO₂ emissions in 2050 reported by ETP2006, while CO₂ emissions in different sectors are based on growth rates in 2030 reported by WEO2007.

The WEO2007 do not include CO₂ emissions from international aviation. According to the World Resources Institute ^[10], such emissions represent 6 percent of total CO₂ emissions in the transport sector. The same figure is used for aviation in the BAU Scenario. Furthermore, the WEO2006 ^[13] indicates that CO₂ emissions from aviation will increase by 2.5 percent per year, and this annual increase is implemented in the BAU Scenario for the period from 2005 to 2050.

CO₂ emissions from land use

The World Resources Institute (WRI) ^[10] reports that global CO₂ emissions from land-use change represents 7,619 GtCO₂ per year. This figure is however uncertain due to measurements methods. IPCC has developed several scenarios regarding land-use change ^[6]. Although these scenarios are very divergent, the average trend is that global emissions should remain stable until 2015 and then decrease onwards 2050, and finally represent 75 percent of today's emissions by 2050. The BAU data relative to CO₂ emissions from land-use change used in the Bellona model are based on the WRI report for today's emissions and the IPCC reports for emission trends onwards 2050.

Non CO₂-GHG emissions

Non-CO₂ GHG emissions include methane (CH₄), nitrous oxide (N₂O), Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs), and sulphur hexafluoride (SF₆). According to the World Resources Institute (WRI) ^[10] global non-CO₂ emissions represent 23 percent of total GHG emissions.

IPCC has developed several scenarios for future development in non-CO₂ emissions ^[6]. Although, there are large variations between all these scenarios, an average trend indicates that non-CO₂ GHG emissions will increase only half as much as global CO₂ emissions onwards to 2015.

BAU data for non-CO₂ GHG emissions in the Bellona model are based on the WRI report for today's emissions and the IPCC report for emission trends onwards 2050.

Emission Reduction Strategies in the Bellona Scenario

The Bellona Model is used to calculate the Bellona Scenario based on specific input data. The input data is briefly discussed in Section 3, while all input data to the Bellona Scenario is given in the tables below.

Table A 1. Lifestyle change potential in sectors for power, fuel transformation, industry, transport, and residential, services & agriculture.

Region	Assumed energy demand reduction in the Bellona Scenario. Given as percent reduction compared to the BAU Scenario			
	2015	2020	2030	2050
Global	1 %	2 %	3 %	10 %

Table A 2. Power plant efficiency. The data is established based on the analysis in Section 3.3.2.

Power plant and region	Power plant efficiency in the Bellona Scenario			
	2015	2020	2030	2050
Coal and oil power plants – OECD	40 %	43 %	46 %	50 %
Coal and oil power plants – non-OECD	55 %	58 %	60 %	63 %
Gas power plants – OECD	35 %	38 %	41 %	45 %
Gas power plants – non-OECD	50 %	53 %	55 %	58 %
Bio power plants	30 %	32 %	35 %	40 %

Table A 3. CO₂ emissions from power production.

Power plant	CO ₂ emissions at 100 % efficiency* (g CO ₂ / kWh)
Coal power plant	310 ^[95]
Oil power plant	202 ^[95]
Gas power plant	279 ^[95]
Bio power plant	450 ^[96,97]

* In general, the CO₂ emissions reduction is calculated as percent reduction from BAU based on how much the primary energy demand from fossil sources is reduced. The numbers in the table are used to (1) calculate the ratio of emissions from coal, oil and gas, and (2) to calculate how much CO₂ that is stored from bio power plants with CCS.

Table A 4. Energy efficiency potential in the industrial sector. The energy efficiency potentials are based on the Ecofys report ^[22] as described in Section 3.3.3.

Region	Energy demand reduction in the Bellona Scenario. Given as percent reduction compared to the BAU Scenario			
	2015	2020	2030	2050
OECD Europe	12 %	17 %	29 %	35 %
USA	13 %	18 %	27 %	40 %
Other OECD	13 %	18 %	26 %	38 %
China	13 %	17 %	31 %	36 %
India	11 %	15 %	28 %	34 %
Other countries	12 %	16 %	25 %	35 %

Table A 5. Energy efficiency potential in the sector for residential, services, and agriculture. The energy efficiency potentials are based on the Ecofys report ^[22] as described in Section 3.3.4.

Region	Energy demand reduction in the Bellona Scenario. Given as percent reduction compared to the BAU Scenario			
	2015	2020	2030	2050
OECD Europe	17 %	23 %	41 %	49 %
USA	18 %	25 %	38 %	56 %
Other OECD	19 %	25 %	37 %	54 %
China	18 %	24 %	43 %	51 %
India	15 %	21 %	39 %	47 %
Other countries	16 %	23 %	35 %	49 %

Table A 6. Efficiency potential for reduction of non-CO₂ GHG emissions. The data is calculated based on the analysis in Section 3.3.9.

Region	GHG emission reduction in the Bellona Scenario. Given as percent reduction compared to the BAU Scenario			
	2015	2020	2030	2050
Global	9.1 %	15.5 %	28.5 %	54.4 %

Table A 7. Emission reduction strategies in the transport section. The data is established based on the analysis in Section 3.3.5.

Strategy and region	Share of primary energy demand for transport in the Bellona Scenario (%)								
	OECD				Non-OECD				
	2015	2020	2030	2050	2015	2020	2030	2050	
Electrical vehicles	1.6	12.2	32.9	73.9	1.6	6.9	17.2	37.7	
H ₂ Fuel cells	0	0	0	2.4	0	0	0	2.4	
Biofuel	0	0	5.8	19.0	2.4	4.7	15.0	37.1	
Fossil fuel	98.4	87.8	61.3	4.7	96.0	88.4	67.8	22.8	
Efficiency ratio - vehicles on fossil fuel vs electrical vehicles (global)*				24 % / 65 %					

* Vehicles on fossil fuel have an average efficiency of 24 percent, while electrical vehicles have an average efficiency of 65 percent.

Table A 8. Nuclear power phase out.

Region	Percent of nuclear power in the BAU Scenario that is phased out in the Bellona Scenario.			
	2015	2020	2030	2050
Global	6.8 %	21.6 %	58.1 %	100 %

Table A 9. Renewable power production. The data is established based on the analysis in Section 3.3.7.

Energy source	Share of power production (%) *			
	2015	2020	2030	2050
Hydro	BAU	BAU	BAU	11.0 %
Biomass & waste	BAU	4.2 %	12.6 %	29.4 %
Wind	2.4 %	4.7 %	9.5 %	16.3 %
Solar	0.9 %	2.1 %	9.4 %	29.4 %
Geothermal	0.7 %	0.8 %	1.4 %	1.9 %
Wave & tidal	BAU	BAU	BAU	0.3 %

- * (1) BAU indicates that the Bellona Scenario uses identical values as in the BAU Scenario.
(2) Furthermore, a test is implemented in the algorithm in the Bellona Model to ensure that BAU data is used if the data in the table above indicates lower renewable power production for the BAU Scenario. This test is performed for each geographical region.
(3) The efficiency for power production from renewable sources is in the Bellona Scenario set equal to the global average efficiency factors in the BAU Scenario.

Table A 10. Renewable energy for industry; fuel transformation; residential, services & agriculture.

Energy source and sector		Share of primary energy demand (%) *			
		2015	2020	2030	2050
Renewable energy in industry		BAU	BAU	BAU	BAU
Renewable energy for fuel transformation		BAU	BAU	BAU	BAU
Renewable energy for heating in residential, services & agriculture	Biomass & waste	BAU	11.4 %	34.3 %	80 %
	Other renewables	BAU	BAU	BAU	BAU

- * (1) BAU indicates that the Bellona Scenario uses identical values as in the BAU Scenario.
(2) Furthermore, a test is implemented in the algorithm in the Bellona Model to ensure that BAU data is used if the data in the table above indicates lower renewable power production for the BAU Scenario. This test is performed for each geographical region.

Table A 11. Other input parameters related to renewable energy. The data is established based on the analysis in Section 3.3.6 and 3.3.7.

Parameter	Value in the Bellona Scenario
Increased power demand due to need for storage of energy when large shares of intermittent power are deployed	5 % of the difference between renewable power production in the Bellona Scenario and the BAU Scenario
Increased energy demand for production of solar cells, wind turbines, bioenergy infrastructure etc.	5 % of the difference between renewable power production in the Bellona Scenario and the BAU Scenario
GHG emissions from biomass used for energy purposes	30 % of the emission reduction due to introduction of biomass for energy purposes is assumed re-emitted

Table A 12. CCS. The data is established based on the analysis in Section 3.3.8.

Input Parameter		2015	2020	2030	2050
Share of fossil fuel power production that have CCS	OECD	0 %	0 %	33 %	100 %
	Non-OECD	0 %	0 %	25 %	75 %
Share of bio power production that have CCS	OECD	0 %	0 %	26.7 %	80 %
	Non-OECD	0 %	0 %	20 %	60 %
Share of fuel transformation CO ₂ emissions where CCS is introduced	OECD	0 %	0 %	16.7 %	50 %
	Non-OECD	0 %	0 %	12.5 %	37.5 %
Share of industrial CO ₂ emissions where CCS is introduced	OECD	0 %	0 %	16.7 %	50 %
	Non-OECD	0 %	0 %	12.5 %	37.5 %
Increased energy demand due to CCS (given as percent of the power production from a power plant)		15 %	13 %	11 %	10 %
CO ₂ capture rate (Percent of produced CO ₂ that is separated in a CO ₂ capture plant)		80 %	83 %	87 %	90 %

Table A 13. Land-use change. The data is established based on the analysis in Section 3.3.10.

Parameter	Potential for global emission reduction compared to BAU (GtCO ₂ -eq / year)			
	2015	2020	2030	2050
Land-use change	1.0	1.8	3.2	8.1 *

* A reduction in GHG emissions is implemented in the BAU Scenario. The potential for 2050 is therefore equal to a reduction of 10 GtCO₂-eq compared to land-use change emissions in 2005.

Input parameters are specified for each geographical region in the Bellona Model, but the results in Section 4 are only presented at the accumulated global level. This is done because of large uncertainties in splitting global emission reduction potentials on the different geographical regions. Literature data often gave good global emission reduction potentials, but no regional

potentials. For several input parameters, the emission reduction potentials are therefore set equal in all geographical regions, as can be seen from the tables above.

Algorithm in the Bellona Model

Accounting of emissions and energy

In the Bellona model the CO₂ emissions are accounted in the sector where they physically take place. In other words, CO₂ emissions due to electricity consumption and heat in the sector of industry, transport, and residential, services & agriculture are accounted in the sector where heat and electricity are generated, *i.e.* in the power production sector.

For instance, when oil is consumed in the industry sector, the related CO₂ emissions are accounted as CO₂ emissions in the industry sector. On the contrary, when the industry sector consumes electricity, the related CO₂ emissions are accounted in the power sector as they are generated at the power plant (if it is a fossil fuel power plant) and not in the industry sector because the consumption of electricity does not lead to CO₂ emissions.

The emission reduction due to efficiency strategies is accounted in the same manner. If energy efficiency in the industry sector leads to a reduced consumption of oil for heating purposes, the emission reduction is accounted in the industry sector. But when energy efficiency leads to less electricity consumption, the CO₂ emission reduction is accounted in the power sector.

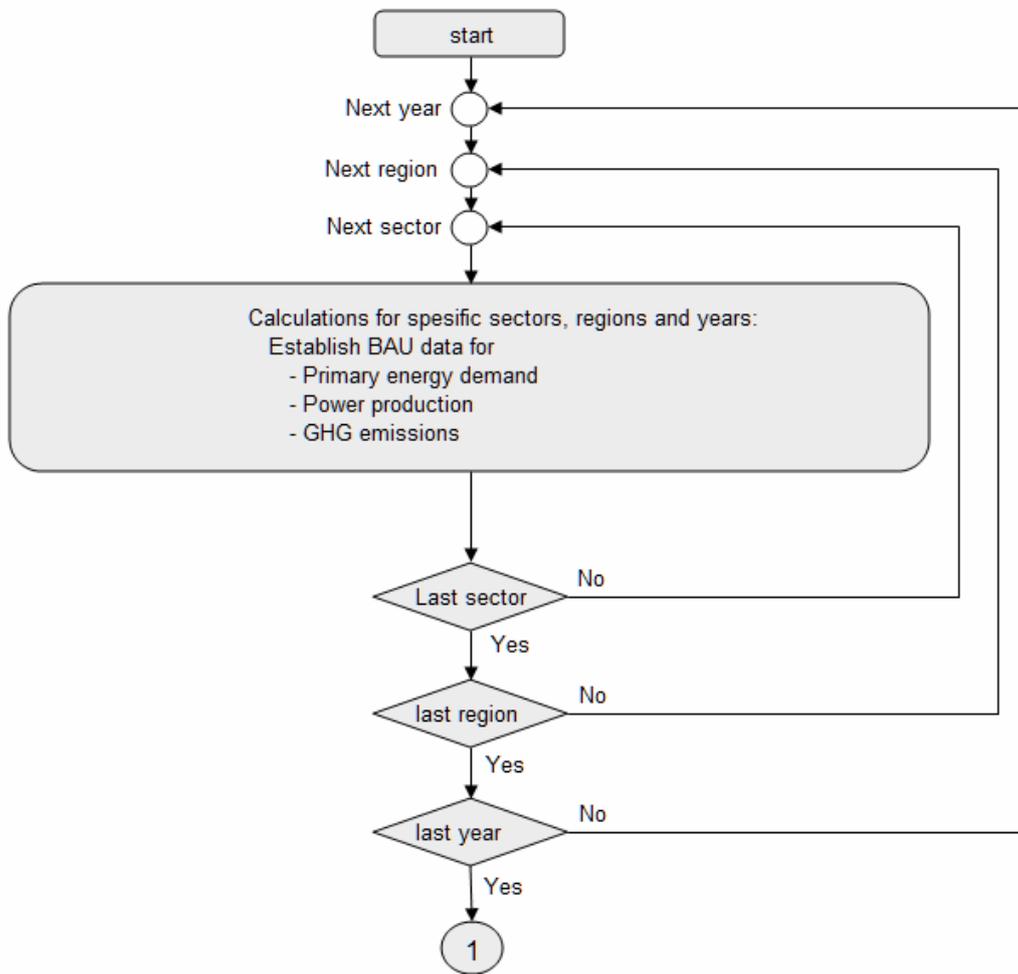
The algorithm in the Bellona Model is based on primary energy demand and not final energy consumption. As a consequence, the energy demand for production of electricity and heat are accounted in the sector where it is produced, and not in the sector where it is consumed. For instance, when industry consumes electricity, it is of course accounted as power consumption in the industry sector. But power consumption in the industry sector does not lead to increased primary energy demand in the industry sector; it will lead to increased primary energy demand in the power sector, as electricity is *produced* in the power sector.

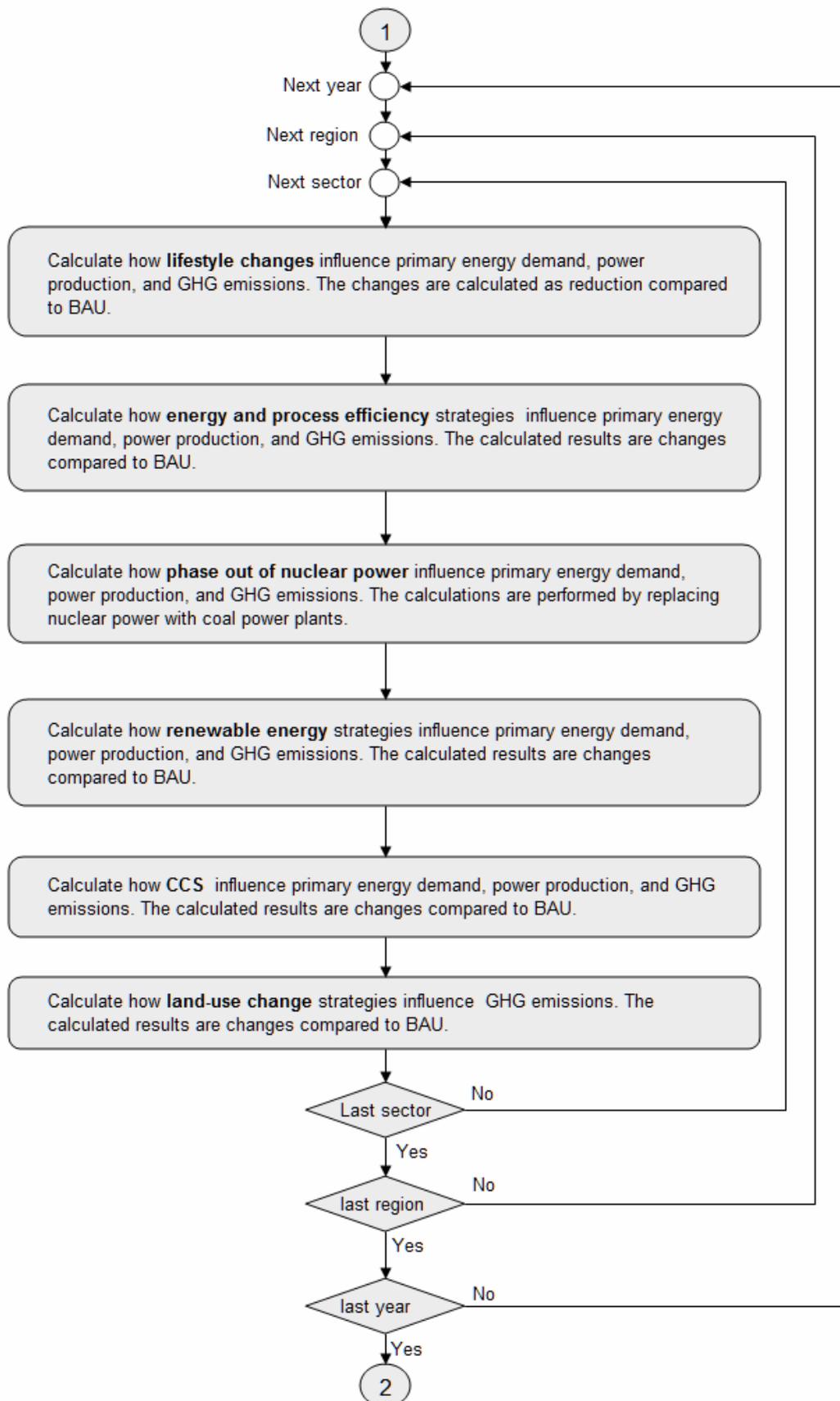
Algorithm

The Bellona Model is implemented in Microsoft Excel spreadsheets, and separate calculations are performed according to the following definitions:

1. **Regions:** Calculations are performed for six geographical regions: OECD Europe; the USA; other OECD countries; China; India; and other countries.
2. **Sectors:** Calculations are performed for the following sectors: Power generation, fuel transformation; industry; transport; residential, service & agricultural; land-use change; non-CO₂ GHG emissions.
3. **Years:** The calculations in the Bellona Model are performed for the years: 2015; 2020; 2030; and 2050. In addition, BAU data is established for 2005.

The calculations are performed according to the following algorithm.





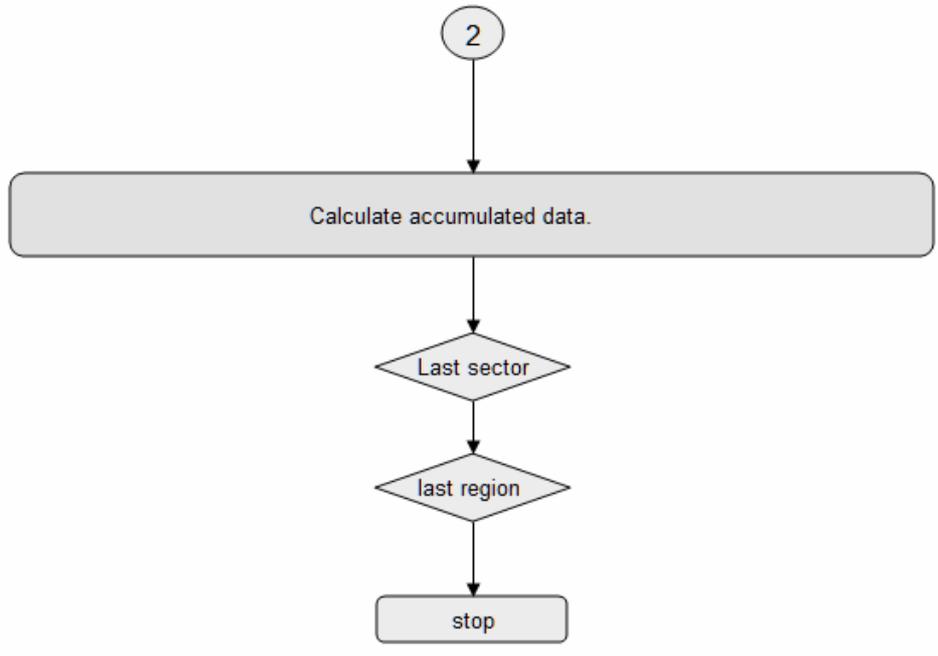


Figure 5.1. Algorithm for the Bellona Model.

References

- 1 Intergovernmental Panel on Climate Change (IPCC), Climate Change 2007. Synthesis report, IPCC Secretariat, Geneva, Switzerland, November 2007, <http://www.ipcc.ch/ipccreports/ar4-syr.htm>.
- 2 Intergovernmental Panel on Climate Change (IPCC), Climate Change 2007, Working Group II report: Impacts, Adaptation and Vulnerability, IPCC Secretariat, Geneva, Switzerland, April 2007, <http://www.ipcc.ch/ipccreports/ar4-wg2.htm>.
- 3 Climate Change Information Kit. M. Williams (ed.). Published by UNEP and UNFCCC, 2002.
- 4 N. Stern, Stern Review: The economics of Climate Change, Cambridge University Press, October 2006, http://www.hm-treasury.gov.uk/Independent_Reviews/stern_review_economics_climate_change/sternreview_index.cfm.
- 5 International Energy Agency (IEA), Energy Technology Perspectives 2006. International Energy Agency report, Paris, France, 2006.
- 6 IPCC Special Report – Emission Scenarios. Special Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, 2000, <http://www.ipcc.ch/ipccreports/sres/emission/index.htm>.
- 7 International Energy Agency (IEA), World Energy Outlook 2007, OECD and International Energy Agency report, Paris, France, 2007.
- 8 Energy [r]evolution, Report from Greenpeace and European Renewable Energy Council (EREC), January 2007, <http://www.greenpeace.org/international/press/reports/energy-r-evolutionsummary>.
- 9 R. James, et al, The Power to Reduce CO₂ Emissions, EPRI Discussion Paper, August 2007, <http://www.epri-reports.org/DiscussionPaper2007.pdf>.
- 10 K. A. Baumert, T. Herzog, J. Hershing, Navigating the numbers. Greenhouse gas data and international climate policy. World Resources Institute report, 2005, http://pdf.wri.org/navigating_numbers.pdf.
- 11 Intergovernmental Panel on Climate Change (IPCC), Climate Change 2007, Working Group III report: Mitigation of Climate Change, IPCC Secretariat, Geneva, Switzerland, May 2007, <http://www.ipcc.ch/ipccreports/ar4-wg3.htm>.
- 12 International Energy Agency (IEA), Energy Technology Perspectives 2008. International Energy Agency report, Paris, France. To be published June 2008.
- 13 International Energy Agency (IEA), World Energy Outlook 2006, OECD and International Energy Agency report, Paris, France, 2006.
- 14 International Energy Agency (IEA), World Energy Outlook 2004, OECD and International Energy Agency report, Paris, France, 2004.
- 15 Tim Jackson, Eleni Papathanasopoulou, Pete Bradley and Angela Druckman, 2007 Attributing UK Carbon Emissions To Functional Consumer Needs: Methodology And Pilot Results. Resolve Working Paper 01-07.
- 16 Elcogas, Memoria de sostenibilidad (sustainability report), 2005
- 17 The EU Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP), Strategic Research Agenda, 2006. Published online at <http://www.zero-emissionplatform.eu/website/library/index.html>.

- 18 The Naturkraft Web-site, http://www.naturkraft.no/default.asp?V_ITEM_ID=454.
- 19 U.S. Department of Energy, Energy efficiency and Renewable Energy, Web article: http://www1.eere.energy.gov/biomass/abcs_biopower.html.
- 20 Oy Alholmen Kraft AB, <http://www.alholmenskraft.com>.
- 21 World Business Council on Sustainable Development, Toward a Sustainable Cement Industry, Climate Change, 2002, <http://www.wbcsd.org>.
- 22 W. Graus, M. Harmelink, Global low energy demand scenarios 2003-2050, Ecofys report, Utrecht, The Netherlands, August 2006, http://www.energyblueprint.info/fileadmin/media/documents/Global_energy_demand_scenarios_22Augustus06.pdf?PHPSESSID=4a111dee8949efe1d441ffc3eacd71.
- 23 H. De Keulenaer, R. Belmans, E. Blaustein, D. Chapman, A. De Almeida, B. De Wachter, P. Radgen, Energy Efficient Motor Driven System, European Copper Institute 2004: http://sunbird.jrc.it/energyefficiency/pdf/HEM_lo_all%20final.pdf.
- 24 Smith, Robin, Chemical Process Design and Integration, John Wiley and Sons, 2005.
- 25 Industrial Ecology, www.ntnu.no/indecot.
- 26 D. Ürge-Vorsatz, A Novikova, Potentials and costs of carbon dioxide mitigation in the world's building, Department of environmental sciences and policy, Central European University. Published by Energy Policy, 2008.
- 27 Passivehouse "Wohnen & Arbeiten"; <http://www.passivhaus-vauban.de/idee.en.html>
- 28 The European Greenlight program; <http://www.eu-greenlight.org/What-to-do/what1.htm>
- 29 IEA 2001. Things That Go Blip <http://www.iea.org/textbase/nppdf/free/2000/blipinthenight01.pdf>
- 30 W De Groote, Potential of short-term energy efficiency and energy saving measures. E-ster bvba, 2005.
- 31 Harmelink, M.; W. Graus, K. Blok, M Voogt. Low Carbon electricity systems. Methodology and results for the EU. Ecofys. Utrecht, The Netherlands. Prepared for WWF, 2003.
- 32 K. Blok, Improving energy efficiency by five percent and more per year?, Massachusetts Institute of Technology and Yale University, 2005.
- 33 Action plan for energy efficiency, Communication from the commission 2006, directive 2006/32/EC on energy end-use efficiency and energy services.
- 34 World Business Council on Sustainable Development, Mobility 2030: Meeting the Challenges to Sustainability, 2004, <http://www.wbcsd.org/plugins/DocSearch/details.asp?type=DocDet&ObjectId=NjA5NA>.
- 35 Vattenfall, The Landscape of Global Abatement Opportunities up to 2030. Transport Sector Deep Dive, 2007, www.vattenfall.com/www/ccc/ccc/Gemeinsame_Inhalte/DOCUMENT/567263vattenfall/P0272864.pdf.
- 36 Concawe/Eucar 2007, Well-to-wheels analysis of future automotive fuels and powertrains in the european context, <http://ies.jrc.ec.europa.eu/wtw.html>.
- 37 G. Kendal. WWF. Plugged in the end of the oil age. 2008. http://assets.panda.org/downloads/plugged_in_full_report_final.pdf.
- 38 "Plug-In-Hybrids: An Environmental and Economic Performance Outlook", Report Number T061, American Council for an Energy Efficient Economy, September 2006.
- 39 International Energy Agency, Prospects for Hydrogen and Fuel Cells, 2005, p61.

- 40 M. Åhman, Primary Energy Efficiency of Alternative Powertrains in Vehicles, *Energy* **26**, 973-989. 2001.
- 41 The European Hydrogen and Fuel Cell Technology Platform (HFP), available at web: http://www.infotools.hfpeurope.org/hfp_pro/
- 42 A. E. Hammersmidt, Fuel Cell Propulsion of Submarines, Paper presented at Advanced Naval Propulsion Symposium 2006, Arlington, VA, USA, 2006, available at www2.sea.siemens.com/.../0/SiemensPresentsFuelCellattheAdvancedNavalPropulsionSymposium.pdf.
- 43 Press release from CRC solutions. Retrieved 29 April 2008. <http://www.cfc-solutions.com/en/pres/pres.htm>.
- 44 Information sheet: The Norwegian Hydrogen Platform, http://www.forskningsradet.no/servlet/Satellite?blobcol=urldata&blobheader=application%2Fpdf&blobkey=id&blobtable=MungoBlobs&blobwhere=1192364355397&cachecontrol=5%3A0%3A0+*%2F*%2F*&ssbinary=true.
- 45 International Energy Agency. Biofuels for Transport. An international perspective. 2004.
- 46 Solar Energy Technologies and Applications. Canadian Renewable Energy Network. 2007
- 47 EPIA, Global Market Outlook for Photovoltaics until 2012
- 48 Reducing the U.S. Greenhouse Gas Emissions: *How Much at What Cost?*, MCKinsey&Company/The Energy Conference Board, December 2007
- 49 Energy mix 2050, SINTEF Energy Research, 2008
- 50 Solar Generation IV, Greenpeace/EPIA, 2007
- 51 Global wind report 2007, GWEC, 2008
- 52 Ordered by European Commission, DG Trend Economic analysis of reaching a 20% share of renewable energy sources in 2020
- 53 Potensialstudie av havenergi i Norge. ENOVA, Norway 2007
- 54 Dagens Næringsliv (Norwegian newspaper), April 19th 2008
- 55 “Renewable Energy Road Map”, Communication from the commission to the council and the European Parliament, 10.1.2007
- 56 Berndes, G., Hoogwijk, M., and van den Broek, R. 2003. The contribution of biomass in the future global energy supply: a review of 17 studies. *Biomass and Bioenergy* Volume 25, Issue 1, July 2003, Pages 1-28. Elsevier.
- 57 Bringezu, S., Ramesohl, S., Arnold, K., Fishedick, M., von Geibler, J., Liedtke, C. And Schutz, H. 2007. Towards a sustainable biomass strategy. *Wuppertal papers*. No. 163. june 2007. Wuppertal institute.
- 58 Crutzen, P. J., Mosier, A. R., Smith, K. A., and Winiwarter, W. 2007. N₂O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. *Atmospheric Chemistry and Physics Discussions*, 7, 11191-11205.
- 59 USGS, 2006. Phosphate rock. *Mineral Commodity Summaries*, January 2006. U.S. Geological Survey.
- 60 Smeets, Edward M. W. and Faaij, André P. C. 2006. Bioenergy potentials from forestry in 2050. An assessment of the drivers that determine the potentials. *Climatic Change* Volume 81, Numbers 3-4 / April, 2007. Springer Netherlands.
- 61 Smeets, E.M.W. 2008. Possibilities and limitations for sustainable bioenergy production systems. Thesis. Utrecht University.

- 62 Solix Biofuels, Fort Collins, CO, USA, <http://www.solixbiofuels.com/html/company.html>.
- 63 Christi, Y. 2008. Biodiesel from microalgae beats bioethanol. *Trends in biotechnology*. Volume 26, pages 126-131. Elsevier.
- 64 Smeets, E. 2007. Interactive comment on “N₂O release from agro-biofuel production negates globalwarming reduction by replacing fossil fuels” by P. J. Crutzen et al. *Chemistry and Physics Discussions*, 7, pp4616–4619.
- 65 REN21 (2008). Global Status Report Renewables 2007. 2008
- 66 International Hydropower Association (IHA) and IEA Hydro, IEA Hydro’s web site; www.ieahydro.org/faq.htm.
- 67 IEA Geothermal Energy Annual Report 2005
- 68 Renewable energy. The Norwegian Water Resources and Energy Directorate, ENOVA, The Norwegian Research Council, Norway 2007.
- 69 Dagens Næringsliv (Norwegian newspaper), April 25th 2008
- 70 Sohngen, B., and Beach, R.H.. 2006. Avoided deforestation as a Greenhouse gas mitigation tool: Economic issues for considerations. Discussion paper.
- 71 Rypdal, Kristin. Cicero Oslo. Skog som klimatiltak. Klima 1:2007
- 72 G. Bala, K. Caldeira, M. Wickett, T.J. Phillips, D.B. Lobell, C. Delire and A. Mirin, Combined climate and carbon-cycle effects of large-scale deforestation. Proceedings of the National Academy of Science of the United States of America. Doi: 10.1073/pnas.0608998104.) 2007.
- 73 Makundi, W.R. and Sathaye, J.A. 2004. GHG Mitigation Potential and Cost in Tropical Forestry - Relative Role for Agroforestry. Environment, *Development and Sustainability*. Volume 6, Pages 235-260. Springer Netherlands.
- 74 M. Z. A. Khan and A.H. Abu-Ghararath, New approach for estimating energy content of municipal solid waste. *Journal of Environmental Engineering*, 117, 1991, pp376-380.
- 75 Reference document on the best available techniques for waste incineration (BREF), integrated pollution prevention and control. European IPPC Bureau, Seville, Spain, 602 pp, 2006. <http://eippcb.jrc.es>.
- 76 Global Anthropogenic non-CO₂ Greenhouse Gas Emissions: 1990-2020. US EPA report, Office of Atmospheric Programs, Climate Change Division, 2006. www.epa.gov/ngs/econ-inv/downloads/GlobalAnthroEmissionsReport.pdf.
- 77 S. Monni, R. Pipatti, A. Lehtilä, I. Savolainen, and S. Syri, Global climate change mitigation scenarios for solid waste management. Espoo, Technical Research Centre of Finland. VTT Publications, No. 603, pp 51, 2006.
- 78 Greenhouse gas emission trends and projections in Europe 2004. European Environment Agency (EEA) Report no5/2004, Progress EU and its member states towards achieving their Kyoto targets, Luxembourg, 2004, ISSN 1725-9177, 40 pp.
- 79 K. Spokas, J. Bogner, J. Chanton, M. Morcet, C. Aran, C. Graff, Y. Moreau-le-Golvan, N. Bureau, and I. Hebe, Methane mass balance at three landfill sites: what is the efficiency of capture by gas collection systems? *Waste Management*, **26**, 2006, pp. 516-525.
- 80 C. Delhotal, F. de la Chesnaye, A. Gardiner, J. Bates, and A. Sankovski, Estimating potential reductions of methane and nitrous oxide emissions from waste, energy and industry. *The Energy Journal*. Special Issue: Multi-Greenhouse Gas Mitigation and Climate Policy, F.C. de la Chesnaye and J. Weyant (eds), 2006.

- 81 Smith, P., D. Martino, Z. Cai, D. Gwary, H. Janzen, P. Kumar, B. McCarl, S. Ogle, F. O'Mara, C. Rice, B. Scholes, O. Sirotenko, 2007: Agriculture. In *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
http://www.mnp.nl/ipcc/pages_media/FAR4docs/final_pdfs_ar4/Chapter08.pdf.
- 82 The Future of Coal. Massachusetts Institute of Technology, 2007, <http://web.mit.edu/coal/>.
- 83 J. J. Dooley, R. T. Dahowski, C. L. Davidson, M. A. Wise, N. Gupta, S. H. Kim, E. L. Malone, Carbon Dioxide Capture and Storage. Report prepared by Battelle Memorial Institute, 2006, http://www.epa.gov/air/caaac/coaltech/2007_02_battelle.pdf.
- 84 J. A. Edmonds, M. A. Wise, J. J. Dooley, S. H. Kim, S. J. Smith, P. J. Runci, L. E. Clarke, E. L. Malone, G. M. Stokes. Global Energy Technology Strategy. Report prepared by Battelle Memorial Institute, 2007
- 85 Intergovernmental Panel on Climate Change (IPCC), Carbon Dioxide Capture and Storage, IPCC report, 2005, http://arch.rivm.nl/env/int/ipcc/pages_media/SRCCS-final/IPCCSpecialReportonCarbondioxideCaptureandStorage.htm.
- 86 Bellona Fact sheet. CO₂-capture, Bellona publication, October 2007, <http://www.bellona.org/factsheets/1191913555.13>.
- 87 A Bellona Web article on planned CCS projects will be published at www.bellona.no June 2008.
- 88 Aage Stangeland, A model for the CO₂ capture potential, *International Journal of Greenhouse Gas Control*, Vol. 1, 2007, pp 418-429, http://www.bellona.org/filearchive/fil_Stangeland_-_Bellona_Paper-Model_for_CO2_capture_potential.pdf.
- 89 Commission of the European Communities. Communication of the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Supporting Early Demonstration of Sustainable Power Generation from Fossil Fuel, 23 January 2008. http://ec.europa.eu/energy/climate_actions/doc/2008_co2_comm_en.pdf.
- 90 Solomon, S, 2006: Carbon Dioxide Storage: Geological Security and Environmental Issues - Case Study on the Sleipner Gas Field in Norway, The Bellona Foundation, Oslo, Norway, 2007, http://www.bellona.no/artikler/notat_solomon.
- 91 Solomon, S., Kristiansen, B., Stangeland, A., Torp, A.T. and Kårstad, O. 2007. A Proposal of Regulatory Framework for Carbon Dioxide Storage in Geological Formations, http://www.irgc.org/irgc/IMG/pdf/IRGC_CCS_BellonaStatoil07.pdf.
- 92 CSLF, "Considerations on Legal Issues for Carbon Dioxide Capture and Storage Projects," Report from the Legal, Regulatory and Financial Issues Task Force, 13 August 2004.
- 93 Carbon Dioxide Capture and Geological Storage, Australian Regulatory Guiding Principles. http://www.industry.gov.au/assets/documents/itrinternet/Regulatory_Guiding_Principles_for_CCS20051124145652.pdf.
- 94 Commission of the European Communities. Proposal for a directive of the European Parliament and of the Council on the geological storage of carbon dioxide and amending Council Directives 85/337/EEC, 96/61/EC, Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC and Regulation (EC) No 1013/2006. 23 January 2008. <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2008:0018:FIN:EN:PDF>.
- 95 Norwegian Pollution Control, http://www.sft.no/artikkel_40918.aspx
- 96 Danish Center for Plant Oil Technology, Note: Rape Seed Oil for Transport 1: Energy Balance and CO₂ balance, 2000, http://www.folkecenter.net/gb/rd/transport/plant_oil/9192/.

- 97 Erik Gjernes, Hans Erik Poulsen, Nicholas Kristensen, Large Scale Utilisation of Biomass in Fossil Fired Boilers, Presented at Power-Gen Europe 2007, Madrid, Spain, <http://www.bwe.dk/pdf/art-pge2007.pdf>.

