Energy Efficiency (2011) 4:409–433
DOI 10.1007/s12053-010-9098-y

Energy [R]evolution 2010—a sustainable world energy outlook

Sven Teske · Thomas Pregger · Sonja Simon · Tobias Naegler · Wina Graus · Christine Lins

Received: 29 June 2010 / Accepted: 18 October 2010 / Published online: 6 November 2010

Abstract The Energy [R]evolution 2010 scenario is an update of the Energy [R]evolution scenarios published in 2007 and 2008. It takes up recent trends in global energy demand and production and analyses to which extent this affects chances for achieving climate protection targets. The main target is to reduce global CO_2 emissions to 3.7 Gt/a in 2050, thus limiting global average temperature increase to below 2°C and preventing dangerous anthropogenic interference with the climate system. A ten-region energy system model is used for simulating global energy supply strategies. A review of sector and region specific energy efficiency measures resulted in the specification of a global energy demand scenario incorporating strong energy efficiency measures. The corresponding supply scenario has been developed in an iterative process in close cooperation with stakeholders and regional counterparts from academia, NGOs and the renewable energy industry. The Energy [R]evolution scenario shows that renewable energy can provide more than 80% of the world's energy needs by 2050. Developing countries can virtually stabilise their CO_2 emissions by 2025 and reduce afterwards, whilst at the same time increasing energy consumption due to economic growth. OECD countries will be able to reduce their emissions by up to 90% by 2050. However, without a comprehensive energy efficiency implementation strategy across all sectors, the renewable energy development alone will not be enough to make these drastic emissions cuts.

Keywords Global demand projection · Energy efficiency · Efficiency standard · Global energy scenario · CO_2 reduction · Renewable energy

S. Teske (✉)
Greenpeace International,
Ottho Heldringstraat 5,
1066 AZ Amsterdam, The Netherlands
e-mail: sven.teske@greenpeace.de

W. Graus
Energy & Resources, Department of Innovation and Environmental Sciences, University of Utrecht,
Utrecht, The Netherlands

T. Pregger · S. Simon · T. Naegler
Department of Systems Analysis and Technology Assessment, German Aerospace Center (DLR),
Institute of Technical Thermodynamics,
Pfaffenwaldring 38–40,
70565 Stuttgart, Germany

C. Lins
European Renewable Energy Council,
63–65, rue d'Arlon,
1040 Brussels, Belgium

S. Teske
Große Elbstrasse 39,
22767 Hamburg, Germany

Background to Energy [R]evolution scenarios

Nearly 2 years after publishing the first two editions Energy [R]evolution scenario in 2007 and 2008

(Greenpeace/EREC 2007; Krewitt et al. 2007), the latest Energy [R]evolution 2010 scenario picks up recent trends in global energy systems and analyses to which extent they affect chances for achieving the overall target: transforming our unsustainable global energy supply system into a system which complies with climate protection targets, and at the same time offers solutions for secure access to affordable energy services in all world regions. The Energy [R]evolution scenario aims to illustrate the feasibility of reducing global CO_2 emissions to 10 Gt per year in 2050, with an advanced scenario that goes as far as reduces to 3.7 Gt per year in 2050.

Methods

The Energy [R]evolution scenarios were jointly commissioned by Greenpeace and the European Renewable Energy Council from the Institute of Technical Thermodynamics, part of the German Aerospace Center (DLR). The supply scenarios were calculated using the MESAP/PlaNet simulation model adopted in the previous editions of Energy[R]evolution studies published in 2007 and 2008. Detailed analyses carried out during preparation of the 2008 Energy [R]evolution study were also used as input for the 2010 edition. These studies comprise in particular the analysis of global energy demand from Ecofys Netherlands (Graus and Blomen 2008) and the study on global sustainable biomass potentials from the German Biomass Research Center (Seidenberger et al. 2008), see the "Estimates of the potential of renewable energy sources" section below. The future development pathway for car technologies is based on a special report produced in 2008 by the Institute of Vehicle Concepts, DLR for Greenpeace International (Schmid 2008).

The MESAP/PlaNet model

The simulation model PlaNet of the energy and environmental planning package MESAP (2008) has been created for long-term strategic planning on a national, regional or local level. PlaNet consists of two independent modules: a flow calculation module, balancing the flows of commodities of an energy demand and supply model, a cost calculation module for the calculation of the corresponding macroeconomical costs. Energy system analyses with PlaNet are carried out in two sequential steps: first the energy and material flows are determined; then based on the results of the flow calculation, the costs of this energy system are calculated.

The PlaNet flow calculation uses a set of linear equations, which can be solved sequentially. In a simulation model, the user specifies the activities or drivers of demand represented as quantities of a commodity, for example the population or the GDP. With the help of intensities (ratios between flows) like electricity consumption per person, the demand for energy services or the final energy demand can be determined. If a commodity is produced by more than one process, market shares for these processes have to be specified. The market shares define the output of a process. The input into this process will be calculated with process efficiency. This schematic allows the integrated calculation of energy flows from primary energy sources to demand drivers. The cost calculations are based on the results of the flow calculation. The estimates of the future development of population, GDP and energy intensities used in this study are presented in detail below ("Key drivers for energy demand" section).

A ten-region global energy system model implemented in the MESAP/PlaNet environment (MESAP 2008) is used for simulating global energy supply strategies. The ten regions correspond to the world regions as specified by the IEA's World Energy Outlook 2009 (Africa, China, India, Latin America, Middle East, OECD Europe, OECD North America, OECD Pacific, Other Developing Asia, Transition Economies) (IEA 2009a). Model calibration for the base year 2007 is based on IEA energy statistics (IEA 2009b, c).

The scenarios

Three scenarios up to the year 2050 are outlined in this research: a Reference scenario, a basic Energy [R]evolution scenario with a target to reduce energy related CO_2 emissions by 50%, from their 1990 levels, and an advanced Energy [R]evolution version which envisages a fall of more than 80% in CO_2 by 2050.

The Reference scenario is based on the reference scenario in the International Energy Agency's 2009 World Energy Outlook (IEA 2009a). This only takes existing international energy and environmental policies into account. The Reference scenario does not consider additional policies to reduce greenhouse gas emissions. As the IEA's projection only covers a time horizon up to 2030, it has been extended by extrapolating its key macroeconomic and energy indicators forward to 2050. Long-term projections of economic developments are only indicative and are used to project future development of the global energy demand and are by no means forecasts. The Reference scenario provides a baseline for comparison with both Energy [R]evolution scenarios. Compared to the previous (2007) IEA projections (IEA 2007), WEO 2009 assumes a slightly lower average annual growth rate of world Gross Domestic Product (GDP; 3.1%, instead of 3.6% over the period 2007–2030). At the same time, it expects global final energy consumption in 2030 to be 6% lower than in the WEO 2007 report. China and India are expected to grow faster than other regions, followed by the Other Developing Asia group of countries, Africa and the Transition Economies (mainly the former Soviet Union). The OECD share of global purchasing power parity (PPP) adjusted GDP is expected decrease from 55% in 2007 to 29% by 2050.

The Energy [R]evolution scenario has a key target of 50% renewables of the final energy consumption by 2050. A second objective is the global phasing out of nuclear energy. To achieve these goals, the scenario is characterised by significant efforts to fully exploit the large potential for energy efficiency. At the same time, all cost-effective sustainable renewable energy[1] sources are used for heat and electricity generation, as well as the production of bio fuels. The general framework parameters for population and GDP growth remain unchanged from the Reference scenario.

The Advanced Energy [R]evolution scenario takes a much more radical approach and aims to reduce global energy related CO_2 emissions by more than 80% in 2050, based on 1990 levels, to increase the likelihood of limiting warming to less than a +2° increase of the global average temperature. In order to achieve this even more ambitious reduction of CO_2 emissions, the advanced scenario assumes much shorter lifetimes for coal-fired power plants—20 years instead of 40 years. The shorter lifetime for coal power plants enables a larger deployment of renewable energy sources and the annual growth rates of renewable energy sources, especially solar photovoltaic, wind and concentrating solar power plants, have therefore been increased.

The advanced scenario also uses the general framework parameters of population and economic growth, as well as most of the energy efficiency roadmap from the basic Energy [R]evolution (E[R]) scenario. In the transport sector, however, the advanced E[R] scenario has a final energy demand 15% to 20% lower in 2050 compared to the basic E[R] scenario. This is due to a combination of increased use of public transport and a faster uptake of efficient combustion vehicles and—after 2025—a larger share of electric vehicles. Within the heating sector, there is a faster expansion of combined heat and power generation (CHP) in the industry sector, more electricity for process heat and a faster growth of solar and geothermal heating systems. Combined with a larger share of electric drives in the transport sector, this results in a higher overall demand for power. Even so, the overall global electricity demand in the advanced Energy [R]evolution scenario is still lower than in the Reference scenario. In the advanced scenario, the latest market development projections of the renewable industry have been calculated for all sectors. More electric and hydrogen vehicles, combined with the faster implementation of smart grids and expanding super grids (about 10 years ahead of the basic E[R] scenario) allows a higher share of fluctuating renewable power generation (photovoltaic and wind). The threshold of a 40% proportion of renewables in global primary energy supply is therefore passed just after 2030 (also 10 years ahead of the basic E[R] scenario). By contrast, the quantity of biomass used for energy purposes and large hydro

[1] *Definition Renewable energy*: The authors define Renewable energy (RE) as any form of energy from geophysical or biological sources that is replenished by natural processes at a rate that equals or exceeds its rate of use. As long as the rate of extraction of this energy does not exceed the natural energy flow rate, then the resource can be utilized for the indefinite future and can be considered as "renewable". Not all energy classified as "renewable" is necessarily "endless"; for example, it is possible to utilize biomass at a greater rate than it can grow. By contrast, the rate of utilization of direct solar energy has no bearing on the rate at which it reaches the earth. Most forms of RE produce little or no CO_2 emissions, which make them import resources for addressing the mitigation of climate change. A life-cycle assessment of the entire production chain is from great importance to ensure the source is truly sustainable. For a RE resource to be *sustainable*, it must be inexhaustible and must not damage the environment, socially acceptable and climate friendly.

power remain approximately the same in both Energy [R]evolution scenarios, for sustainability reasons.

Both the basic and the advanced Energy [R] evolution scenarios have been developed in a back-casting process.[2] The CO_2 emission target has been defined on the basis of the IPCC 4th assessment report, category 1 scenario (IPCC 2007) to restrict the increase in global mean temperatures under +2°C with a required CO_2 reduction of −85% to −50% by 2050. Therefore, the main target is to reduce global CO_2 emissions to 10 Gt/a by 2050 in the basic Energy [R]evolution scenario and 3.7 Gt/a in the advanced Energy [R]evolution scenario, thus limiting global average temperature increase well below 2°C and preventing dangerous anthropogenic interference with the climate system (Hansen et al. 2008, see also the United Nations Framework Convention on Climate Change, Article 2, UNFCCC 1992). As the authors do not consider nuclear energy as an option that supports the transition towards a sustainable energy supply system, a second constraint is the phasing out of nuclear power plants until 2050.

Energy demand projections

In order to estimate the global and regional energy efficiency potential, the Dutch institute Ecofys developed energy demand scenarios for the Greenpeace Energy [R]evolution analysis in 2008 (Graus and Blomen 2008). These scenarios cover energy demand over the period 2005 to 2050 for ten world regions. Two low energy demand scenarios for energy efficiency improvements have been defined. The first is based on the best technical energy efficiency potentials and is called "Technical". The second energy efficiency scenario is based on more moderate energy savings, taking into account implementation constraints in terms of costs and other barriers and is called "Revolution". The technical potential is defined as the energy use that can be reduced by implementing established technical measures, in comparison to the level of energy use in a reference scenario, where current trends continue and no large changes take place in the production and consumption structure of the economy. The technical potential scenario assumes that measures can be implemented after 2010 and that equipment or installations are replaced at the end of their lifetime by state-of-the-art equipment. However, the Revolution scenario assumes that only a fraction of the technical energy efficiency potential can be implemented. This approach takes into account barriers for implementing technical measures for energy efficiency improvements, such as costs. Energy demand in both the basic and the advanced Energy [R]evolution scenarios is based on this second, more conservative "Revolution" scenario. The main results of the "Revolution" scenario are summarised below.

For the 2010 update of the Energy [R]evolution scenario, including the advanced version, the Graus and Blomen (2008) analysis has been reconfigured using the latest IEA statistics from World Energy Outlook 2009 (IEA 2009a). The WEO 2009 edition has a lower global final energy demand in 2030 in comparison to the 2007 edition; 438 EJ in comparison to 478 EJ (including non-energy use). The difference is mainly caused by lower GDP growth rates due to the recent financial and economic crisis, leading to a 14% lower global GDP in 2030 in comparison to the 2007 edition. In addition, an increased share of electric vehicles in the advanced scenario results in a lower final energy demand required to meet the same level of transport activity.

Key drivers for energy demand

Population development

One important underlying factor in energy scenario building is future population development. Population growth affects the size and composition of energy demand, directly and through its impact on economic growth and development. World Energy Outlook 2009 uses the United Nations Development Programme (UNPD 2009) projections for population development. For this study, the most recent population projections from UNDP up to 2050 in the medium variant are applied. Based on UNDP's 2009 assessment, the world's population is expected to grow by 0.86% per year on average over the period 2007 to 2050, from 6.7 billion people in 2007 to more than 9.1 billion by 2050. Population growth will slow over the projection period, from an average 1.2% per

[2] *Definition of Backcasting:* Backcasting starts with defining a desirable future and then works backwards to identify potentials, policies and programmes that will connect the future to the present. The fundamental question of backcasting asks: "if we want to attain a certain goal, what actions must be taken and what development pathways could be followed to get there?"

year during between 2007 and 2010 to 0.4% per year between 2040 and 2050. The population of the developing regions will continue to grow most rapidly. The Transition Economies will face a continuous decline, followed after a short while by the OECD Pacific countries. OECD Europe and OECD North America are expected to maintain their population, with a peak in around 2020/2030 and a slight decline afterwards. The share of the population living in today's non-OECD countries will increase from the current 82% to 85% in 2050. China's contribution to world population will drop from 20% today to 16% in 2050. Africa will remain the region with the highest growth rate, leading to a share of 22% of world population in 2050. Satisfying the energy needs of a growing population in the developing regions of the world in an environmentally friendly manner is a key challenge for achieving a global sustainable energy supply.

Economic growth

Economic productivity is a key driver for energy demand. Since 1971, each 1% increase in global GDP has been accompanied by a 0.6% increase in primary energy (Graus and Blomen 2008) consumption. The decoupling of energy demand and GDP growth is therefore a prerequisite for reducing demand in the future, if a continuing growth of GDP is to be achieved. Most global energy/economic/environmental models constructed in the past have relied on market exchange rates to place countries in a common currency for estimation and calibration. This approach has been the subject of considerable discussion in recent years, and the alternative of PPP (Nordhaus 2005) exchange rates has been proposed. Purchasing power parities compare the costs in different currencies of a fixed basket of traded and non-traded goods and services and yield a widely based measure of the standard of living. This is important in analysing the main drivers of energy demand or for comparing energy intensities among countries. Although PPP assessments are still relatively imprecise compared to statistics based on national income and product trade and national price indexes, they are considered to provide a better basis for global scenario development. In this study, we relied on PPP adjusted GDP estimates from the World Energy Outlook 2009 (IEA 2009a). However, as WEO 2009 only covers the time period up to 2030, the projections for 2030–2050 are based on our own estimates.

Energy-intensity decrease

An increase in economic activity and a growing population does not necessarily have to result in an equivalent increase in energy demand. There is still a large potential for exploiting energy efficiency measures. The energy intensity of an economy in this study is defined as final energy use per unit of gross domestic product. Under the Reference scenario, we assume that energy intensity will be reduced by 1.25% on average per year, leading to a reduction in final energy demand per unit of GDP of about 15% between 2007 and 2020. This value compares well with the reduction of the energy intensity of EU-25 between 1990 and 2004 (see below). In comparison, the total energy consumption in the EU-25 grew at an annual rate of just over 0.8% over the period from 1990 to 2004, while GDP grew at an average annual rate of 2.1% during the same period (EEA 2010). As a result, total energy intensity in the EU-25 fell at an average rate of −1.2% per year (a total decrease of −16% between 1990 and 2004). Despite this relative decoupling, total energy consumption has increased by 12.0% overall in the period 1990–2004. Energy intensity declined over 1990–2000 (and continuously during 1996–2000) but has remained broadly stable since then. For the entire simulation period (2007 to 2050), an average annual decrease of the energy intensity of 1.25% results in a total reduction of 56% in these 53 years. Although the current energy intensity is very different from region to region, our study implicitly assumes that all regions will be able to reduce energy intensity to Japan's level of 2007 within the next 30 years.

Under the advanced Energy [R]evolution scenario, it is assumed that active policy and technical support for energy efficiency measures will lead to an even higher reduction in energy intensity of almost 73% between 2007 and 2050. The advanced Energy [R]evolution scenario follows the same efficiency pathway, apart from in the transport sector, where a further reduction of 17% due to less vehicle use and lifestyle changes has been assumed. The increased share of electric vehicles in this scenario, with greater efficiency of electric drives, leads to a further decrease in final energy use. The energy intensity in an economy tends to decrease over time as a result of a number of factors, e.g.

- Autonomous energy efficiency improvement. These energy efficiency improvements occur because due to technological developments each new generation of capital goods is likely to be more energy efficient than the one before. This is mainly caused by (temporary) increases in energy prices from which economic actors try to save on energy, e.g. by investing in energy efficiency measures or changing their behaviour.
- Policy-led energy efficiency means economic actors change their behaviour and invest in more energy efficient technologies.
- Structural changes in the economy can reduce the energy over GDP ratio, e.g. a shift in the economy away from energy-intensive industrial activities to services related activities.

The energy-intensity decrease in the reference scenario results from a mix of these three factors and differs per region and per sector. For the period 2005–2030, the energy-intensity decrease is taken from the WEO 2009. For the period 2030–2040 and the period 2040–2050, the development is based on the energy intensity per region and sector in the period 2020–2030 in WEO. However, we made a correction for the change in GDP growth rate per period to avoid a situation where the energy intensity decrease in the Reference scenario is larger than the economic growth rate. For the period 2030–2040 and 2040–2050, the energy intensity decrease is calculated by the following two formulae:

$$EI_{2030-2040} = EI_{2020-2030} \times (GDP_{2030-2040}/GDP_{2020-2030})$$
$$EI_{2040-2050} = EI_{2020-2030} \times (GDP_{2040-2050}/GDP_{2020-2030})$$

where:

$EI_{2020-2030}$	Energy intensity decrease 2020–2030 in WEO (%/year)
$GDP_{2020-2030}$	GDP growth rate 2020–2030 in WEO (%/year)
$EI_{2030-2040}$	Energy intensity decrease in period 2030–2040 (%/year)
$GDP_{2030-2040}$	GDP growth rate in period 2030–2040 (%/year)
$EI_{2040-2050}$	Energy intensity decrease in period 2040–2050 (%/year)
$GDP_{2040-2050}$	GDP growth rate in period 2040–2050 (%/year)

Technical potential for energy efficiency improvement

After defining energy intensities of the Reference scenario, technical potentials for energy efficiency improvement are estimated. In this step, a list is drawn up of energy savings options taken into account per sector. After that, the technical energy savings potential is estimated per measure. The technical potentials are based on:

- Current best practice technologies
- Emerging technologies that are currently under development
- Continuous innovation in the field of energy efficiency, leading to new technologies in the future

The key assumptions for calculating technical potential are:

- Measures can be implemented after 2010
- Equipment is replaced at the end of the (economic) lifetime of equipment by state-of-the-art equipment

This study aims at calculating energy efficiency improvement by developing indicators for energy-intensity per sector and where possible by subsector.

The main energy consuming sectors are the industry and transport sectors, as well as “other sectors”, (residential sectors, services and agriculture; Graus and Blomen 2008) the subsector energy use and the selection of the measures per sector are discussed and shown in detail. Options are selected, which are expected to result in a substantial reduction of energy demand before 2050.

In the Reference scenario, total global energy demand is expected to increase from 305 EJ in 2007 to 352 EJ in 2050. The growth in the transport sector is projected to be the largest, with energy demand expected to grow from 82 EJ in 2007 to 158 EJ by 2050 (see Table 1). Demand from “other sectors” is expected to grow the least, from 124 EJ in 2007 to 198 EJ by 2050. Under the (basic) Energy [R] evolution scenario, however, growth in overall final energy demand can be limited to an increase of 12% up to 2050 in comparison to the 2007 level (341 EJ in 2050), whilst taking into account implementation

Table 1 Change in global final energy demand by 2050 in comparison to 2005 level

Sector	Energy [R]evolution		Reference	
	2007	2050	2007	2050
Industry	99 EJ	116 EJ	99 EJ	176 EJ
Transport	82 EJ	84 EJ	82 EJ	158 EJ
Buildings and others	124 EJ	142 EJ	124 EJ	198 EJ
Total	305 EJ	341 EJ	305 EJ	532 EJ

constraints in terms of costs and other barriers. The increase of the energy demand in the transport sector is very small, while in the industry and other sectors, final energy demand increases by ca. 17% (resp. 15%) between 2007 and 2050.

Figure 1 shows the potential for energy efficiency measurements for the industry, transport and other sectors in 2050 for the different world regions, i.e. the difference between the energy demand in these sectors in 2050 in the Reference scenario and the respective demand in the basic E[R] scenario, normalised to the 2005 level of total energy demand in each world region. Furthermore, the remaining total energy demand in 2050 in the basic E[R] scenario (relative to 2005 levels) is shown.

The technical savings potential up to 2050 from all the measures described in (Graus and Blomen 2008) is summarised in Table 2. Since it was not clear what assumptions the IEA WEO Reference scenario was based on, they have assumed an efficiency improvement of 1% per year. Electricity use in the "other" sector was assumed to decline at the same rate as residential use (lighting, appliances, cold appliances, computers/servers and air conditioning). They have assumed a minimum energy efficiency improvement of 1.2% in the Technical scenario and 1.1% in their Revolution scenario, including autonomous improvements. For services and agriculture, they have assumed the same percentage savings potential as for the household sector all aggregated in "other sectors". The new Reference scenario based on WEO 2009 data now includes a lower level of energy demand in the residential sector. Therefore the savings used in the new Energy [R]evolution scenarios are lower than the figures shown in Table 2. The resulting final energy demand reduction for the Energy [R]evolution scenarios compared to the Reference scenario is shown in Table 3 for each world region.

Estimates of the potential of renewable energy sources

Worldwide renewable energy resources exceed by several times current energy demand. The availability of renewable energy sources however differ between world regions (UBA 2009). The supply with energy from renewable sources in the both the basic and the advanced Energy [R]evolution scenarios is constrained by estimates of renewable energy potentials by world region and technology (REN21 (2008); Hoogwijk and Graus (2008) and UBA (2009)). Assessments of the global technical potential vary significantly up to 15,857 EJ/a (UBA 2009). This

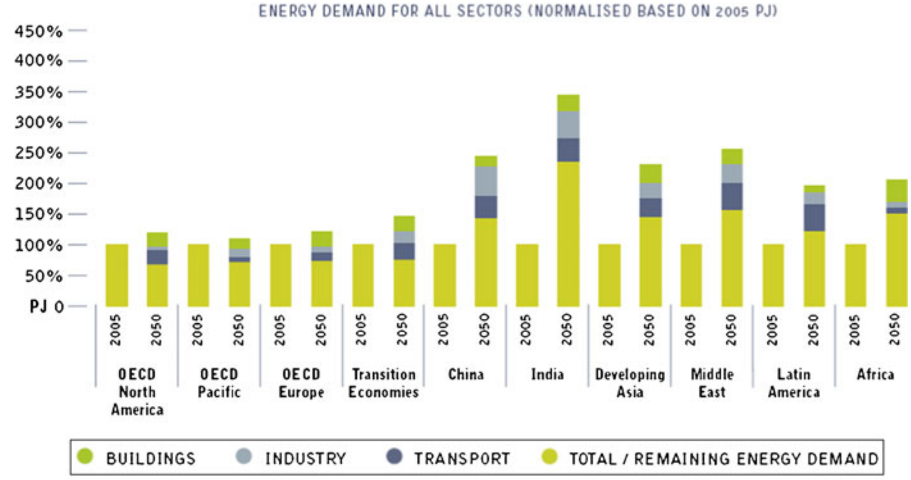

Fig. 1 Potential for energy efficiency improvements per world regions in the Energy [R]evolution scenarios by 2050: Saved energy in the industry, transport and other sectors as well as the remaining final energy demand (by 2050, relative to 2007 levels) in the basic Energy [R]evolution scenario, compared with the reference scenario

Table 2 Technical savings potential by 2050 for different types of energy use n the buildings sector

	Heating—new	Heating—retrofit	Standby	Lighting	Appliances	Cold appliances	Air conditioning	Computer/server	Other
OECD Europe	72	50	82	68	70	77	70	70	71
OECD N.-Am.	59	41		48					67
OECD Pac.	38	26		56					69
Transition Ec.	56	39		76					73
China	43			20					61
India				76					73
Other dev. Asia									
Middle East									
Latin America									
Africa									

meta study performed by the DLR, Wuppertal Institute and Ecofys, commissioned by the German Federal Environment Agency analysed ten major studies of global and regional potentials by organisations such as the United Nations Development Programme and a range of academic institutions. Each of the major renewable energy sources was assessed, with special attention paid to the effect of environmental constraints on their overall potential. The study provides data for the years 2020, 2030 and 2050. The potential for energy supply from biomass in each world region was addressed separately from the results in the UBA (2009) study (see below).

Table 3 Reduction of final energy demand in other sectors between 2005 and 2050

	Other sectors electricity	Other sectors final energy other than electricity
OECD Europe	−46%	−36%
OECD North America	−42%	−28%
OECD Pacific	−33%	−28%
Transition economies	−45%	−36%
China	−27%	−23%
India	−12%	−29%
Other developing Asia	−39%	−15%
Middle America	−36%	−15%
Latin America	−16%	−18%
Africa	−6%	−7%

Sustainable biomass potential

Bio energy is an important storable renewable energy source. However, the use of bio energy is controversial and a sustainable fuel supply chain is crucial. The limited availability of sustainable bio energy requires very efficient use especially for heating and cooling in cogeneration power plants, where overall efficiency is far higher than biomass use in the transport system (in combustion engines). As a response to the controversial discussion on the availability of biomass resources, a study on the global potential for sustainable biomass was commissioned as part of the Energy [R] evolution 2008 project (Seidenberger et al. 2008). The German Biomass Research Centre, the former Institute for Energy and Environment, compiled research into worldwide energy crop potentials in different scenarios till 2050. Additionally, scientific literature on the status quo of worldwide potential studies and the state of the art of remote sensing for investigation of biomass potentials was compiled by Seidenberger et al. (2008). As the results of the Seidenberger et al. (2008) study are not publicly available, the key results of this study are summarised in the following paragraphs:

Global potentials of biomass residues

Residues are products from forestry, agricultural waste and by-products from food production as well as waste from wood products and animals. Residues can be dry matter, e.g. wood chips as well as wet matter, e.g. animal waste. The share of each residue is a fraction of the total amount of residual biomass can vary in different regions and is mainly dependent on the population, living standards and the methods and intensity of the agricultural and forestry production in the particular region. Several studies analysing long-term residue potential in a more or less detailed way are available. A direct comparison of the studies is difficult, since the baseline assumptions are different.

Following Seidenberger et al. (2008), we used results from Dessus et al. (1993) for 2020, as it is the only study with region-specific residue potentials for 2020. For 2050, biomass residuals potential is based on Smeets et al. (2007) as the authors have defined sustainability criteria in their assessment. Moreover, Smeets et al. (2007) offer a relatively high level of transparency and traceability from the methodological point of view. Nevertheless, it must be pointed out that the calculated potentials seem to be conservative and were partly converted from the original aggregation necessary for our scenario analysis, which is listed below in Table 4. Because of the lack of data, the Asian region is most problematic.

Global potentials of energy crops

Besides the utilisation of biomass from residues, the production of energy crops in agricultural production systems is of controversial. Therefore, the technical potentials of energy crops were calculated assuming that the demand for food takes priority. In a first step, different scenarios for the demand of arable land and grassland for food production were calculated for each of 133 countries.

- BAU scenario: Agricultural conditions existing at present time also apply for the future.
- Basic scenario: No forest clearing; reduced use of fallow areas for agriculture
- Sub 1 scenario: Basic scenario + ecological area expanded, followed by reduced yield level

Table 4 Residue potentials by region, based on Dessus et al. (1993) and Smeets et al. (2007)

Residue potential in EJ/yr	2020			2050		
	Dry residues (solid fuels)	Wet residues (biogas)	Total	Dry residues (solid fuels)	Wet residues (biogas)	Total
OECD Europe	6.4[b]	0.5[d]	7.0	7.0 [e]	0.5[d]	7.5
OECD North America	11.3[b]	0.5[d]	11.8	17.0 [e]	0.6[d]	17.6
OECD Pacific	2.3[b]	0.2[d]	2.5	6.0 [e]	0.2[d]	6.2
Transition economies	4.8[b]	0.3[d]	5.1	5.0 [e]	0.3[d]	5.3
China	5.6[c]	1.4[d]	7.0	6.3 [f]	1.4[d]	7.7
India	3.6[c]	1.3[d]	4.9	6.3 [f]	1.5[d]	7.8
Rest of Asia	9.3[b]	1.2[d]	10.5	6.4 [e]	1.6[d]	8.0
Latin America	5.6[b]	0.5[d]	6.1	12.0 [e]	0.6[d]	12.6
Africa[a]	1.9[b]	1.1[d]	3.0	12.3 [e]	1.5[d]	13.8
Middle East[a]	0.4[b]	0.2[d]	0.6	0.7 [e]	0.4[d]	1.1
World	51.2	7.4	58.6	79.0	8.6	87.6

[a] In both studies, the original division is "Sub-Saharan Africa" and "Middle East and North Africa", the division in "Africa" and "Middle East" is calculated on the basis of population

[b] Original data of the category "residues" in Dessus et al. (1993) plus the values of "forest residues" in Smeets et al. (2007) minus 10%

[c] "residues" of Dessus et al. (1993) plus forest residues which are calculated by the following method: On the basis of FAO data the development of forest area is estimated. With the data "forest residues" of Smeets et al. (2007) for "East Asia" and "Southeast Asia" data for China and India are calculated

[d] Potential of wet residues is assumed by the estimated factor of 1 PJ per one million people

[e] Original data of Smeets et al. (2007)

[f] Smeets et al. (2007) gives potentials for East Asia (included China) and South and Southeast Asia (included India). Following these data, the potentials for China and India are calculated on the basis of population data. 70% of the potential (9 EJ) are in India, 63% of the potential (10 EJ) are in China

– Sub 2 scenario: Basic scenario + food consumption is reduced for industrialised countries
– Sub 3 scenario: combination of Sub 1 and 2 scenarios

The needs and surpluses of agricultural areas are balanced between the countries of the groups EU-27, other European countries, North America, Central America, South America, Oceania, Asia and Africa to estimate the area available for the cultivation of energy crops in each world region. In a next step, the surpluses of agricultural area in each world region are classified as arable land and grassland. On grassland hay and grass silage are produced, on arable land fodder silage[3] and short rotation coppice[4] (SRC) are cultivated. Silage of green fodder and grass are assumed for biogas production, wood from SRC and hay from grasslands are assumed for the production of heat, electricity and synthetic fuels (BtL[5] or ethanol from lignocelluloses).[6] Country specific yield developments are taken into consideration.

As a result, the global biomass potential from energy crops in 2050 was estimated to range from 6 EJ in the Sub 1 scenario to 97 EJ in the BAU scenario (see Fig. 2). In comparison to the BAU scenario, potentials decrease clearly in the Basic and Sub 1 scenario, and the lowest potentials exist in the Sub 1 scenario. The considerable higher demand of agricultural area in the Sub 1 scenario compared to the Basic and the BAU scenario is due to an ecological orientated agriculture with less fertilizer and less pesticide and therefore lower specific yields.

In the Sub 2 scenario, considerable higher energy crop potentials can be released by changing the human food pattern, reducing meat consumption and consequently, the area necessary for fodder production. Also in the Sub 3 scenario, considerable potentials can be realized, in most cases even higher than in the BAU scenario. The most important country for the differences between the scenarios in 2050 is Brazil. In the BAU scenario, big agricultural areas are released by deforestation in Brazil, whereas in the Basic and Sub 1 scenario, this deforestation does not occur anymore. Consequently, no additional agricultural area for energy crops is available in Brazil in these two scenarios. In contrast high potentials are available in the Sub 2 scenario as a consequence of the reduced meat consumption of the Brazilian. Because of high population and low quantity of agricultural area, no area surpluses for energy crop production are available in Central America, Asia and Africa. However, the EU, North America and Australia have relatively stable potentials.

The Basic and Sub 3 scenario are of particular importance, since the Basic scenario would be the "minimum solution" for future agriculture. The Sub 3 scenario demonstrates the development of an ecological orientated agriculture. But such a development is only realistic, if the eating behaviour changes. Otherwise, the higher demand of food crops from an increasing world population cannot be compensated. The results of the calculation show that the availability of biomass resources is driven by different factors (as evident in the boundary conditions set in the different scenarios above), which do not only affect the global food situation but also the conservation of natural forests and other biospheres. So, the assessment of future biomass potentials is the starting point for the discussion about the integration of bio energy into a renewable energy system.

Global total potential for biomass for energy purposes

The total global biomass potential (energy crops and residues) in 2020 ranges from 66 EJ (Sub scenario 1) to 110 EJ (Sub scenario 2). For 2050, scenario results range from 94 EJ (Sub scenario 1) to 184 EJ (BAU scenario). Those numbers are conservative calculations and have an estimated uncertainty, especially for in 2050, of a factor of two. Reasons for this

[3] Arable land fodder silage: Fodder crops are harvested green and conserved as silage. This silage can be used for biogas production.

[4] Short rotation coppice (SRC) are fast growing tree species (e.g. willow, poplar, eucalyptus), harvested usually every 3 years. The wood chips can use for heat, electricity production and for lignocelluloses fuels.

[5] Biomass to liquid (BTL) or BMTL is a multi-step process to produce liquid biofuels from biomass.

[6] Lignocellulosic biomass refers to plant biomass that is composed of cellulose, hemicellulose and lignin. The carbohydrate polymers (cellulose and hemicelluloses) are tightly bound to the lignin. Lignocellulosic biomass can be grouped into four main categories: (1) agricultural residues (including corn stover and sugarcane bagasse), (2) dedicated energy crops, (3) wood residues (including sawmill and paper mill discards), and (4) municipal paper waste.

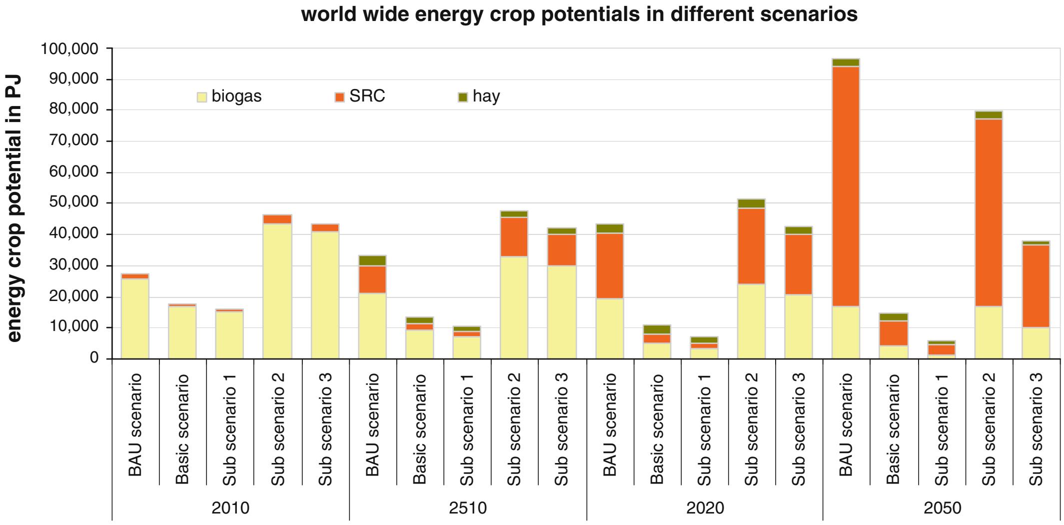

Fig. 2 World wide energy crop potentials in different scenarios in 2050 (Seidenberger et al. 2008)

uncertainty are due to the unknown consequences of climate change on agricultural production, possible changes of the worldwide political and economical dynamics, a higher yield increase as a consequence of a change in agricultural techniques and/or the faster development in plant breeding. The global potential for biomass residues is estimated to be 88 EJ in 2050 (see Table 4). With a biomass consumption of 88.7 EJ in 2050, the Energy [R]evolution scenario complies with the most stringent requirements towards sustainable biomass use.

Economic boundary conditions

To implement the Energy [R]evolution pathways, an assessment of costs and benefits for society is essential. For this study, we focused on the costs of the power sector, calculating power generation costs as well as necessary investments and fuel costs for each scenario. The main assumptions for the cost calculation are presented in the following: Assumptions for heat and transport prices require a much more detailed approach for each region, thus were not included in the economic assessment.

Fuel price projections

The recent dramatic fluctuations in global oil prices have resulted in slightly higher forward price projections for fossil fuels. Under the 2004 "high oil and gas price" scenario from the European Commission, for example, an oil price of just \$34 per barrel was assumed in 2030. More recent projections of oil prices by 2030 in the World Energy Outlook (IEA 2009a) range from $\$_{2008}$ 80/bbl in the lower prices sensitivity case and up to $\$_{2008}$ 150/bbl in the higher prices sensitivity case. The Reference scenario in WEO 2009 assumes an oil price of $\$_{2008}$ 115/bbl. Since the first Energy [R]evolution study was published in 2007, however, the actual price of oil has moved over \$100/bbl for the first time, and in July 2008 reached a record high of more than \$140/bbl. Although oil prices fell back to \$100/bbl in September 2008 and around \$80/bbl in April 2010, the projections in the IEA reference scenario might still be considered too conservative. Taking into account the growing global demand for oil, we have assumed a price development path for fossil fuels based on the IEA WEO 2009 higher prices sensitivity case extrapolated forward to 2050 (see Table 5). As the supply of natural gas is limited by the availability of pipeline infrastructure, there is no world market price. In most regions of the world, the gas price is directly tied to the price of oil. As a consequence, gas prices used in this study are assumed to increase to \$24–29/GJ by 2050. Additional price projections for biomass considered that biomass from energy crops are mainly available in the industrialised countries, especially in Europe as calculated by Seidenberger et al. (2008). Thus, biomass prices in Europe are assumed to be much higher than prices for residual biomass in the other regions.

Table 5 Fossil fuel and biomass price assumptions for the three scenarios (in US$ 2008)

	Unit	2000	2005	2007	2008	2010	2015	2020	2025	2030	2040	2050
Crude oil imports												
IEA WEO 2009 “Reference”	barrel	34.30	50.00	75.00	97.19		86.67	100	107.5	115		
USA EIA 2008 “Reference”	barrel					86.64		69.96		82.53		
USA EIA 2008 “High Price”	barrel					92.56		119.75		138.96		
Energy [R]evolution	barrel						110.56	130.00	140.00	150.00	150.00	150.00
Natural gas imports												
IEA WEO 2009 “Reference”												
United States	GJ	5.00	2.32	3.24	8.25		7.29	8.87	10.04	11.36		
Europe	GJ	3.70	4.49	6.29	10.32		10.46	12.10	13.09	14.02		
Japan LNG	GJ	6.10	4.52	6.33	12.64		11.91	13.75	14.83	15.87		
Energy [R]evolution 2010												
United States	GJ			3.24		8.70		10.70	12.40	14.38	18.10	23.73
Europe	GJ			6.29		10.89		16.56	17.99	19.29	22.00	26.03
Japan LNG	GJ			6.33		13.34		18.84	20.37	21.84	24.80	29.30
Hard coal imports												
OECD steam coal imports												
Energy [R]evolution 2010	tonne			69.45		120.59	116.15	135.41	139.50	142.70	160.00	172.30
IEA WEO 2009 “Reference”	tonne	41.22	49.61	69.45		120.59	91.05	104.16	107.12	109.4		
Biomass (solid)												
Energy [R]evolution 2010												
OECD Europe	GJ			7.4		7.7	8.2	9.2		10.0	10.3	10.5
OECD Pacific and North America	GJ			3.3		3.4	3.5	3.8		4.3	4.7	5.2
Other regions	GJ			2.7		2.8	3.2	3.5	4.0		4.6	4.9

Source 2000–2030, IEA WEO 2009 higher prices sensitivity case for crude oil, gas and steam coal; 2040–2050 and other fuels, own assumptions

Cost of CO_2 emissions

Assuming that a CO_2 emission trading system will be established across all world regions in the longer term, the cost of CO_2 allowances needs to be included in the calculation of electricity generation costs. Projections of emissions costs are even more uncertain than energy prices, however, and available studies span a broad range of future estimates. As in the previous Energy [R]evolution study, we assume CO_2 costs of \$10/tCO_2 in 2015, rising to \$50/tCO_2 by 2050. Additional CO_2 costs are applied in Kyoto Protocol Non-Annex B (developing) countries only after 2020. The cost projections for CO_2 are relatively conservative due to the fact that a global emission trading system requires a strong and ambitious mandatory framework to reduce global energy related CO_2 emissions. However, the UNFCCC conference in Copenhagen in December 2009 failed to agree on such legally binding targets, and a global emission trading scheme will require several more years of negotiations.

Projections of future investment costs for power generation

Fossil fuel power plants Although the fossil fuel power technologies in use today for coal, gas, lignite and oil are established and at an advanced stage of market development, further cost reduction potentials for conventional power technologies are assumed. The potential for cost reductions is limited, however, and will be achieved mainly through an increase in efficiency. Table 6 summarises our assumptions on the technical and economic parameters of future fossil-fuelled power plant technologies. In spite of

Table 6 Development of efficiency and investment costs for selected fossil power plant technologies

		2007	2015	2020	2030	2040	2050
Coal-fired condensing power plant	Efficiency (%)	45	46	48	50	52	53
	Investment costs ($/kW)	1,320	1,230	1,190	1,160	1,130	1,100
	Electricity generation costs including CO_2 emission costs ($CENTS/kWh)	6.6	9.0	10.8	12.5	14.2	15.7
	CO_2 Emission[a] (g/kW)	744	728	697	670	644	632
Lignite-fired condensing power plant	Efficiency (%)	41	43	44	44.5	45	45
	Investment costs ($/kW)	1,570	1,440	1,380	1,350	1,320	1,290
	Electricity generation costs including CO_2 emission costs ($CENTS/kWh)	5.9	6.5	7.5	8.4	9.3	10.3
	CO_2 Emission[a] (g/kW)	975	929	908	898	888	888
Natural gas combined cycle	Efficiency (%)	57	59	61	62	63	64
	Investment costs ($/kW)	690	675	645	610	580	550
	Electricity generation costs including CO_2 emission costs ($CENTS/kWh)	7.5	10.5	12.7	15.3	17.4	18.9
	CO_2 Emission[a] (g/kW)	354	342	330	325	320	315

Source DLR, 2010

[a] CO_2 emissions refer to power station outputs only; life-cycle emission are not considered

growing raw material prices, we assume that further technical innovation will result in a moderate reduction of future investment costs as well as improved power plant efficiencies. These improvements are, however, outweighed by the expected increase in fossil fuel prices, resulting in a significant rise in electricity generation costs.

Renewable technologies In contrast to fossil fuel power technologies, renewable energy technologies still have considerable cost reduction potentials. Table 7 summarises the assumptions for cost trends for renewable power technologies as derived from the respective extrapolated learning curves. It should be emphasised that the expected cost reduction is basically not a function of time, but of cumulative capacity, so dynamic market development is required. Most of the technologies will be able to reduce their specific investment costs between 30% and 70% of current levels by 2020 and between 20% and 60% once they have achieved full maturity (after 2040). This would continue the historical developments, where solar photovoltaic modules decreased the costs over 50% between 1990 and 2001 (EC European Commission 2005), while specific costs for wind turbine went down from US $2,700/kW to US $1,500/kW between 1982 and 2009 (Nielson et al. 2010) Reduced investment costs for renewable energy technologies lead directly to reduce heat and electricity generation costs. Electricity generation costs today are around $0.8 to $0.26 cents/kWh for the most important technologies, with the exception of photovoltaic. In the long term, costs are expected to converge at around $0.5 to $0.12 cents/kWh (including photovoltaic). These estimates depend on site-specific conditions such as the local wind regime or solar irradiation, the availability of biomass at reasonable prices or the credit granted for heat supply in the case of combined heat and power generation.

Estimation of job effects Greenpeace engaged the Australian-based Institute for Sustainable Futures to model the employment effects of our 2009 sustainable future energy scenario compared to business as usual. The results, published in 2009 as “Working for the climate—Renewable Energy & The Green Job [R] evolution”, form the basis for the calculations in the 2010 Energy [R]evolution scenarios. The model calculates indicative numbers for jobs that would either be created or lost under both the Energy [R] evolution and Reference scenarios. This requires a series of assumptions summarised below.

- Start with the amount of electrical capacity that would be installed each year and the amount of electricity generated per year under the Reference

Table 7 Projected cost development for renewable power generation technologies, market volumes and investments

		2007	2015	2020	2030	2040	2050
Photovoltaics (pv)							
Energy [R]evolution							
Global installed capacity	GW	6	98	335	1,036	1,915	2,968
Investment costs	$/kWp	3,746	2,610	1,776	1,027	785	761
Operation and maintenance costs	$/kW/a	66	38	16	13	11	10
Advanced Energy [R]evolution							
Global installed capacity	GW	6	108	439	1,330	2,959	4,318
Investment costs	$/kWp	3,746	2,610	1,776	1,027	761	738
Operation and maintenance costs	$/kW/a	66	38	16	13	11	10
Concentrating solar power (CSP)							
Energy [R]evolution							
Global installed capacity	GW	1	25	105	324	647	1,002
Investment costs	$/kWp	7,250	5,576	5,044	4,263	4,200	4,160
Operation and maintenance costs	$/kW/a	300	250	210	180	160	155
Advanced Energy [R]evolution							
Global installed capacity	GW	1	28	225	605	1,173	1,643
Investment costs	$/kWp	7,250	5,576	5,044	4,200	4,160	4,121
Operation and maintenance costs	$/kW/a	300	250	210	180	160	155
Wind power							
Energy [R]evolution							
Global installed capacity (on + offshore)	GW	95	407	878	1,733	2,409	2,943
Investment costs—onshore	$/kWp	1,510	1,255	998	952	906	894
Operation and maintenance costs—onshore	$/kW/a	58	51	45	43	41	41
Investment costs—offshore	$/kWp	2,900	2,200	1,540	1,460	1,330	1,305
Operation and maintenance costs—offshore	$/kW/a	166	153	114	97	88	83
Advanced Energy [R]evolution							
Global installed capacity (on + offshore)	GW	95	494	1,140	2,241	3,054	3,754
Investment costs—onshore	$/kWp	1,510	1,255	998	906	894	882
Operation and maintenance costs—onshore	$/kW/a	58	51	45	43	41	41
Investment costs—offshore	$/kWp	2,900	2,200	1,540	1,460	1,330	1,305
Operation and maintenance costs—offshore	$/kW/a	166	153	114	97	88	83
Biomass							
Energy [R]evolution							
Global installed capacity—electricity only	GW	28	48	62	75	87	107
Investment costs	$/kWp	2,818	2,452	2,435	2,377	2,349	2,326
Operation and maintenance costs	$/kW/a	183	166	152	148	147	146
Global installed capacity—CHP	GW	18	67	150	261	413	545
Investment costs	$/kWp	5,250	4,255	3,722	3,250	2,996	2,846
Operation and maintenance costs	$/kW/a	404	348	271	236	218	207
Advanced Energy [R]evolution							
Global installed capacity—electricity only	GW	28	50	64	78	83	81
Investment costs	$/kWp	2,818	2,452	2,435	2,377	2,349	2,326
Operation and maintenance costs	$/kW/a	183	166	152	148	147	146
Global installed capacity—CHP	GW	18	65	150	265	418	540

Table 7 (continued)

		2007	2015	2020	2030	2040	2050
Investment costs	$/kWp	5,250	4,255	3,722	3,250	2,996	2,846
Operation and maintenance costs	$/kW/a	404	348	271	236	218	207
Geothermal							
Energy [R]evolution							
Global installed capacity—electricity only	GW	10	19	36	71	114	144
Investment costs	$/kWp	12,446	10,875	9,184	7,250	6,042	5,196
Operation and maintenance costs	$/kW/a	645	557	428	375	351	332
Global installed capacity—CHP	GW	1	3	13	37	83	134
Investment costs	$/kWp	12,688	11,117	9,425	7,492	6,283	5,438
Operation and maintenance costs	$/kW/a	647	483	351	294	256	233
Advanced Energy [R]evolution							
Global installed capacity—electricity only	GW	10	21	57	191	337	459
Investment costs	$/kWp	12,446	10,875	9,184	5,196	4,469	3,843
Operation and maintenance costs	$/kW/a	645	557	428	375	351	332
Global installed capacity—CHP	GW	0	3	13	47	132	234
Investment costs	$/kWp	12,688	11,117	9,425	7,492	6,283	5,438
Operation and maintenance costs	$/kW/a	647	483	351	294	256	233
Ocean energy							
Energy [R]evolution							
Global installed capacity	GW	0	9	29	73	168	303
Investment costs	$/kWp	7,216	3,892	2,806	2,158	1,802	1,605
Operation and maintenance costs	$/kW/a	360	207	117	89	75	66
Advanced Energy [R]evolution							
Global installed capacity	GW	0	9	58	180	425	748
Investment costs	$/kWp	7,216	3,892	2,806	1,802	1,605	1,429
Operation and maintenance costs	$/kW/a	360	207	117	89	75	66
Hydro							
Energy [R]evolution							
Global installed capacity	GW	922	1,043	1,206	1,307	1,387	1,438
Investment costs	$/kWp	2,705	2,864	2,952	3,085	3,196	3,294
Operation and maintenance costs	$/kW/a	110	115	123	128	133	137
Advanced Energy [R]evolution							
Global installed capacity	GW	922	1,111	1,212	1,316	1,406	1,451
Investment costs	$/kWp	2,705	2,864	2,952	3,085	3,196	3,294
Operation and maintenance costs	$/kW/a	110	115	123	128	133	137

(business as usual) and the two Energy [R] evolution scenarios.

- Use "employment factors" for each technology, which are the number of jobs per unit of electrical capacity (fossil as well as renewable), separated into manufacturing, construction, operation and maintenance and fuel supply.
- Take into account the "local manufacturing" and "domestic fuel production" for each region, in order to allocate the level of local jobs, and also to allocate imports to other regions.
- Multiply the electrical capacity and generation figures by the employment factors for each of the energy technologies.

- For non-OECD regions, apply a “regional job multiplier”, which adjusts the OECD employment factors for different levels of labour-intensity in different parts of the world. Regional factors are used for coal mining, so no regional adjustment is needed in this case.
- For the 2020 and 2030 calculations, reduce the employment factors by a “decline factor” for each technology; this reflects how employment falls as technology efficiencies improve.

The model used a range of inputs, including data from the International Energy Agency, US Energy Information Association, European Renewable Energy Council, European Wind Energy Association, US National Renewable Energy Laboratory, Renewable Energy Policy Project, census data from the United States, Australia and Canada and the International Labour Organisation. These calculations only take into account direct employment, for example the construction team needed to build a new wind farm. They do not cover indirect employment, for example, the extra services provided in a town to accommodate construction teams.

Key results

Energy demand and energy generation

Today, renewable energy sources account for 13% of the world’s primary energy demand. Biomass, which is mostly used in the heat sector, is the main source. The share of renewable energies for electricity generation is 18%, while their contribution to heat supply is around 24%, to a large extent accounted for by traditional uses such as collected firewood. About 80% of the primary energy supply today still comes from fossil fuels (IEA 2009b, c). Both Energy [R]evolution scenarios describe development pathways that turn the present situation into a more sustainable energy supply. The advanced version takes into account that achieving the urgently needed CO_2 reduction target might be necessary more than a decade earlier than implemented in the basic Energy [R]evolution scenario. The following summary shows the results of the advanced Energy [R]evolution scenario, which will be achieved through the following measures:

- Exploitation of existing large energy efficiency potentials will lead to an only slightly increased final energy demand in the Energy [R]evolution scenarios—from the current 305 EJ/a (2007) to 341 EJ/a in 2050, compared to 531.5 EJ/a in the Reference scenario. This dramatic reduction is a crucial prerequisite for a significant share of renewable energy sources in the overall energy supply system in the future, compensating for the phasing out of nuclear energy and reducing the consumption of fossil fuels.
- More electric drives are used in the transport sector as well as hydrogen produced by electrolysis from excess renewable electricity. Compared to the basic Energy [R]evolution scenario, they play a much bigger role in the advanced Energy [R]evolution scenario. After 2020, the final energy share of electric vehicles on the road increases to 4% and by 2050 to over 50%. More public transport systems also use electricity, as well as a greater shift in transporting freight from road to rail is implemented.
- The increased use of CHP also improves the supply system’s energy conversion efficiency, increasingly using CO_2 favourable natural gas and biomass instead of coal. However, CHP is limited by the available heat demand. In the long term, efficiency measures decrease demand for heat and also the large potential for producing heat directly from renewable energy sources limit the further expansion of CHP.
- The electricity sector will be the pioneer of renewable energy utilisation. By 2050, around 95% of electricity can be produced from renewable sources in the Energy [R]evolution scenarios. A capacity of 14,045 GW will produce 43,922 TWh/a of renewable electricity in 2050. A significant share of the fluctuating power generation from wind and solar photovoltaic will be used to supply electricity to vehicle batteries and produce hydrogen as a secondary fuel in transport and industry. Load management strategies are a precondition to reduce excess electricity generation and more balancing power is then made available.
- In the heat supply sector, the Energy [R]evolution scenarios increase contribution of renewables to 91% by 2050. Fossil fuels will be increasingly replaced by more efficient modern renewable technologies, in particular biomass, solar collectors and geothermal. Geothermal heat pumps and, in the

world's sunbelt regions, concentrating solar power, will play a growing part in industrial heat supply.

- In the transport sector, the existing large efficiency potentials will be exploited by a modal shift from road to rail and by using much lighter and smaller vehicles. As biomass is mainly committed to stationary applications, the production of bio fuels is limited by the availability of sustainable raw materials. Electric vehicles, powered by renewable energy sources, will play an increasingly important role from 2020 onwards.
- By 2050, in the Energy [R]evolution scenarios 80% of primary energy demand will be covered by renewable energy sources. Figure 3 shows the development of the energy supply mix between 2007 and 2050 in three different scenarios.

Development of CO_2 emissions

While CO_2 emissions worldwide will increase by more than 60% under the Reference scenario up to 2050, and are thus far from a sustainable development path, under the advanced Energy [R]evolution scenario, they will decrease from 28,400 million tonnes in 2007 (including international aviation and marine bunkers) to 3,700 in 2050, 82% below 1990 levels. Annual global per capita emissions will drop from 4.1 to 0.4 tonnes/capita. In spite of the phasing out of nuclear energy and a growing electricity demand, CO_2 emissions will substantially decrease in the electricity sector. In the long run, efficiency gains and the increased use of renewable electric vehicles, as well as a sharp expansion in public transport, will even reduce CO_2 emissions in the transport sector. With a share of 42% of total emissions in 2050, the transport sector will reduce significantly but remain the largest source of CO_2 emissions—followed by the industry sector and power generation.

Results of the economic assessment

Future costs for efficiency measures

Renewable energy will initially cost more to implement than existing power and heat generation. The slightly higher electricity generation costs under the advanced Energy [R]evolution scenario will be compensated for, however, by reduced demand for fuels in other sectors such as heating and transport. Assuming average costs of 3 cents/kWh for implementing energy efficiency measures, the additional cost for electricity supply under the advanced Energy [R]evolution scenario will amount to a maximum of \$31 billion/a in 2020. These additional costs, which represent society's investment in an environmentally benign, safe and economic energy supply, continue to decrease after 2020. By 2050 the annual costs of electricity supply will be \$2,700 billion/a below those in the Reference scenario.

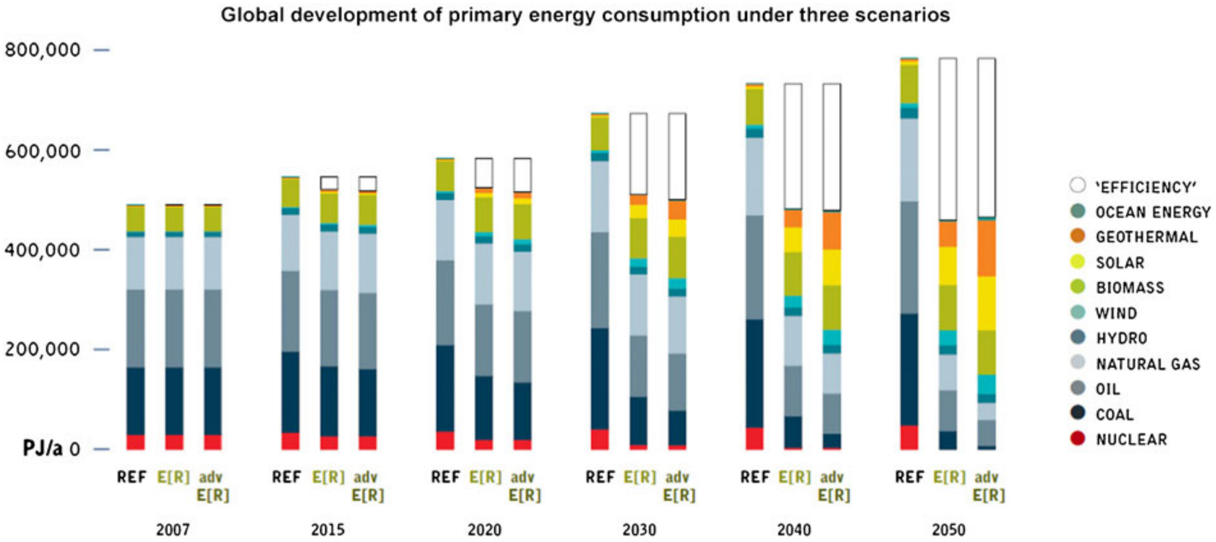

Fig. 3 Global development of primary energy consumption under three scenarios

Future investment in renewable power technologies

Global investments of $17.9 trillion would be required until 2030 in the power sector for the advanced Energy [R]evolution scenario to become reality—approximately 60% higher than in the Reference scenario ($11.2 trillion). Under the Reference version, the levels of investment in renewable energy and fossil fuels are almost equal—about $5 trillion each—up to 2030. Under the advanced scenario, however, the world shifts about 80% of investment towards renewables; by 2030, the fossil fuel share of power sector investment would be focused mainly on combined heat and power and efficient gas-fired power plants. The average annual investment in the power sector under the advanced Energy [R]evolution scenario between 2007 and 2030 would be approximately $782 billion. Compared to a total of $491 billion annually in average in the reference scenario, only $291 billion would be additional investment.

In turn, the investment in renewable technologies will lead to a significant saving of fossil fuels. Because most renewable energy has no fuel demand, the fuel cost savings in the advanced Energy [R]evolution scenario reach a total of $6.5 trillion or $282 billion per year until 2030 and a total of $41.5 trillion or an average of $964 billion per year until 2050. However, the investments are just compensated for on the long run. Over the whole projection period fuel saving will compensate for most of the renewable power investment.

The additional annual investment for the advanced Energy [R]evolution scenario is equal to 1.37% of global GDP.[7] In case a decarbonisation of the energy system does not take place, the human and financial price caused by climate change could be enormous. The report "Silent Crisis" by the Global Humanitarian Forum (GHF 2009) indicates that every year climate change leaves over 300,000 people dead, 325 million people seriously affected and economic losses of US $125 billion.

Future global direct employment

Job effects of the Energy [R]evolution scenarios were calculated in comparison to the Reference Scenario (see the "Key results" section). Worldwide, both of the Energy [R]evolution scenarios would create more direct jobs the power sector than the reference case.

- By 2015, global power supply sector jobs in the Energy [R]evolution scenario are estimated to reach about 11.1 million, 3.1 million more than in the Reference scenario. The advanced version will lead to 12.5 million jobs by 2015.
- By 2020 in the Energy [R]evolution scenario, over 6.5 million jobs in the renewables sector would be created due to a much faster uptake of renewables, three-times more than today. The advanced version will lead to about one million jobs more than the basic Energy [R]evolution.
- By 2030, the Energy [R]evolution scenario achieves about 10.6 million jobs, about two million more than the Reference scenario. Approximately two million new jobs are created between 2020 and 2030, twice as much as in the Reference case. The advanced scenario will lead to 12 million jobs, that is 8.5 million in the renewables sector alone. Without this fast growth in the renewable sector, global power jobs will be a mere 2.4 million. Thus, by implementing the Energy [R]evolution, there will be 3.2 million or over 33% more jobs by 2030 in the global power supply sector.

Shifting towards an efficient use of renewables—a sustainable global energy supply perspective

The Energy [R]evolution scenario is a "bottom-up" scenario, driven by technology development in the various sectors. This contrasts approaches implementing cost-driven top-down approaches. Around the world, however, energy modelling scenario tools are under constant development and in the future, both approaches are likely to merge into one, with detailed tools employing both a high level of technical detail and economic optimisation. The Energy [R]evolution scenario uses a "classical" bottom-up model which has been constantly further developed, and now includes calculations covering both the investment pathway in the power sector and the employment effect. For the Energy [R]evolution scenarios, feasible development pathways for renewable power markets were analysed together with EREC.

Feasibility of renewable growth rates Assumed growth rates for renewable energy technology de-

[7] IMF 2009, world GDP 2009 (ppp): US$ 70.21 trillion.

ployment are important drivers (Neij 2008). Within the range of the feasible market development for the power sector, the Energy [R]evolution scenarios tabbed the enormous potential of renewable power. Table 8 shows growth rates and the global annual market volumes for new installed capacities in the power generation for the Energy [R]evolution scenarios. They are compared with the respective development of the reference scenario as derived from IEA World Energy Outlook (2009a, b, c).

Challenging the business model of today's utilities

The Energy [R]evolution scenario will also result in a dramatic change in the business model of energy companies, utilities, fuel suppliers and the manufacturers of energy technologies. Decentralised energy generation and large solar or offshore wind projects which operate in remote areas, without the need for any fuel, will have a profound impact on the way utilities operate in 2020 and beyond. While today the entire power supply value chain is broken down into clearly defined players, a global renewable power supply will inevitably change this division of roles and responsibilities. Today's value chain will significantly change with revolutionised energy mix. While today, a relatively small number of power plants owned and operated by utilities or their subsidiaries are needed to generate the required electricity, the Energy [R]evolution scenario projects a future share of around 60% to 70% of small but numerous decentralised power plants performing the same task. Ownership will therefore shift towards more private investors and away from centralised utilities. In turn, the value chain for power companies will shift towards project development, equipment manufacturing and operation and maintenance.

Future business models for a decentralised energy supply will have to take into account that power plants are distributed and in many cases in/on buildings or on land that is not owned by the utilities. Therefore, operation and maintenance will be distributed and the power plants will be controlled over long distances most likely via internet. Project development and to some extent installation of power generators will play a much larger role for a utility than it plays with relatively few but large scale power plants. Fuel supply will play a smaller role as well.

Conclusions

The Energy [R]evolution scenarios define low energy demand projections for energy efficiency improvement. The basis for the energy demand projection is a reference scenario based on IEA WEO 2007 edition (updated on the WEO 2009) and extrapolated to 2050 by GDP growth and assumptions regarding energy-intensity decrease. In the reference scenario, worldwide final energy demand increases from 305 EJ in 2007 to 531 EJ in 2050. This is an increase of 95%. The reference scenario provides the benchmark against which the Energy [R]evolution scenarios are measured.

Energy demand reductions are principally limited by the technical energy efficiency potentials, derived from a detailed analysis of individual efficiency potentials of a high variety of important energy consuming technologies. However, taking into account implementation constraints, e.g. costs and other barriers, a more sustainable energy demand path was projected than the reference scenario, but more conservative than the technical energy efficiency potential: In the basic Energy [R]evolution scenario, worldwide energy demand is reduced to 340 EJ in 2050 and to 326 EJ in the advanced Energy [R]evolution scenario. For transport, global energy demand is projected to increase from 82 PJ in 2007 to 158 EJ in 2050 in the reference scenario. In the basic Energy [R]evolution scenario, this energy demand is reduced to 83 EJ in 2050 and to 69.5 EJ in the advanced scenario. For the Energy [R]evolution scenarios, the projected energy demand reductions are vital to achieve a share of 68.9% renewable energy in the transport sector, 86.3% in the industry and 94.3% in buildings and agriculture sector. The overall global renewable energy share by 2050 could be as high as 87.1% of final energy supply.

To achieve an economically attractive growth of renewable energy sources, a balanced and timely mobilisation of all technologies is of great importance. Such mobilisation depends on technical potentials, actual costs, cost reduction potentials and technical maturity. Climate-friendly infrastructure, district heating systems, smart grids and super grids for renewable power generation, as well as more R&D into storage technologies for electricity, are all vital if this scenario is to be turned into reality.

The successful implementation of smart grids is vital for the advanced Energy [R]evolution from 2020

Table 8 Necessary renewable industry development under three different scenarios

	Energy parameter									
	Generation [TWh/a]							Annual market volume [GW/a]		
	>600 ppm IEA WEO 2008	Reference	E[R]	Advanced E[R]	Reference	E[R]	Advanced E[R]	Reference	E[R]	Advanced E[R]
2020	27,708	27,248	25,851	25,919						
2030	33,265	34,307	30,133	30,901						
2050	50,606	46,542	37,993	43,922						
PV 2020	68	108	437	594	17%	37%	42%	5	26	36
PV 2030	120	281	1,481	1,953	11%	15%	14%	18	91	124
PV 2050	213	640	4,597	6,846	10%	13%	15%	40	141	211
CSP2020	26	38	321	689	17%	49%	62%	1	5	12
CSP2030	54	121	1,447	2,734	14%	18%	17%	2	24	45
CSP2050	95	254	5,917	9,012	9%	17%	14%	4	44	66
Wind										
on + offshore 2020	887	1,009	2,168	2,849	12%	22%	26%	26	74	101
on + offshore 2030	1,260	1,536	4,539	5,872	5%	9%	8%	60	178	229
on + offshore 2050	1,736	2,516	8,474	10,841	6%	7%	7%	47	158	202
Geothermal										
For power generation										
2020	119	117	235	367	6%	14%	20%	1	2	4
2030	158	168	502	1,275	4%	9%	15%	2	7	18
2050	229	265	1,009	2,968	5%	8%	10%	2	7	21
Heat and power										
2010	2									
2020	6	6	65	66	13%	47%	47%	0	1	1
2030	9	9	192	251	5%	13%	16%	0	3	5
2050	17	19	719	1,263	9%	16%	20%	0	6	11
Bio energy										
For power generation										
2020	324	337	373	392	8%	9%	10%	3	4	4
2030	474	552	456	481	6%	2%	2%	10	8	8
2050	474	994	717	580	7%	5%	2%	6	5	4
Heat and power										
2020	272	186	739	742	2%	19%	19%	1	13	13
2030	367	287	1,402	1,424	5%	7%	8%	6	26	27
2050	613	483	3,013	2,991	6%	9%	9%	4	26	25
Ocean										
2020	6	3	53	119	15%	55%	70%	0	2	4
2030	12	11	128	420	13%	10%	15%	0	3	12
2050	28	25	678	1,943	10%	20%	19%	0	10	27
Hydro										
2020	4,164	4,027	4,029	4,059	2%	2%	2%	20	20	21
2030	4,833	4,679	4,370	4,416	2%	1%	1%	135	126	127
2050	6,027	5,963	5,056	5,108	3%	2%	2%	78	66	67

onwards because dynamic power generation from wind and solar photovoltaic in combination with a network of decentralised cogeneration power plants and centralised offshore wind farms require a different infrastructure and operation of the network, in comparison to the current system. It is also important to highlight that in the advanced Energy [R]evolution scenario the majority of remaining coal power plants—which will be replaced 20 years before the end of their technical lifetime—are in China and India. This means that in practice, all coal power plants built between 2005 and 2020 will be replaced by renewable energy sources from 2040 onwards. To support the building of capacity in developing countries, significant new public financing, especially from industrialised countries, will be needed. It is vital that specific funding mechanisms such as the "Greenhouse Development Rights"[8] and "Feed-in tariff" schemes are developed under the international climate negotiations that can assist the transfer of financial support to climate change mitigation, including technology transfer.

The authors of Energy [R]evolution scenarios conclude that the required up scaling of the renewable energy market is not the main barrier to achieve a global renewable energy share greater than 80% or even close to 100% by 2050.

However, the implementation of technical efficiency standards to achieve the required energy efficiency pathway as well as the restructuring of the required infrastructure such as efficient smart grids and district heating networks seem to be much bigger challenge. Long-term energy policies with clear framework for infrastructure investments are needed to move towards a renewable energy system. The renewable industry can only maintain double digit annual growth rates for the coming years if the needed infrastructure will be implemented by 2020. Besides the technical challenges of grid integration from large shares of wind and solar photovoltaic generation, a different business model is required to build and operate decentralised energy generation systems instead of centralised power plants with maintenance workers dispersed over an entire region rather than only on power plant side. Demand side management becomes an important factor to avoid large storage capacities and to use fluctuating wind and solar PV power generation as efficient as possible.

Specific policy designs for implementation

In order to implement a more efficient and largely decentralised energy supply, all policies both for the supply as well as for the demand sector must ensure consistency. Being efficient must involved financial benefits and long-term security is needed to change and/or expand the infrastructure. Efficiency standards for buildings for example reduce the overall heat demand and could conflict with the expansion of district heating networks. The implantation of smart and super grids requires an integrated long-term energy plan as well as specific technical standards. The authors favour ever improving efficiency standards such as the Japanese "Top-Runner" model over static models.

Successful support mechanisms such as the German "Renewable Energy Act" provide security for investments for the supply side. A guaranteed and priority access to the grid is essential for renewable energy projects, especially large scale such as offshore wind.

Acknowledgment The authors would like to thank the many partners who provided helpful input during scenario development: DLR, Institute of Vehicle Concepts, Stuttgart, Germany, Dr. Stephan Schmid; Ecofys BV, Utrecht, The Netherlands, Eliane Blomen; Institute for Sustainable Futures (ISF), University of Technology, Sydney, Australia, Jay Rutovitz and Alison Atherton (Employment calculations)

[8] Greenhouse Development Rights: The Greenhouse Development Rights (GDR) framework has been developed from EcoEquity, School of Public Policy and the Georgia Institute of Technology, Atlanta, USA, and calculates national shares of global greenhouse gas obligations based on a combination of responsibility (contribution to climate change) and capacity (ability to pay). Crucially, GDRs take inequality within countries into account and calculate national obligations on the basis of the estimated capacity and responsibility of individuals. Individuals with incomes below a "development threshold"—specified in the default case as $7,500 per capita annual income, PPP adjusted—are exempted from climate-related obligations. Individuals with incomes above that level are expected to contribute to the costs of global climate policy in proportion to their capacity (amount of income over the threshold) and responsibility (cumulative CO2 emissions since 1990, excluding emissions corresponding to consumption below the threshold).

Appendix

Table 9 Global final energy demand in PJ/a

PJ/a	2007	2015	2020	2030	2040	2050
Total (including non-energy use)	337,329	364,357	374,301	381,812	377,670	368,650
Total energy use	305,093	329,380	338,056	343,263	337,271	326,476
Transport	82,068	87,277	88,691	86,355	78,012	69,467
Oil products	76,535	78,901	76,682	62,767	41,671	18,448
Natural gas	3,131	3,327	3,253	2,878	2,130	1,424
Biofuels	1,429	3,258	4,832	8,062	9,000	9,723
Electricity	973	1,772	3,574	11,888	23,420	36,354
RES electricity	171	401	1,321	7,692	19,531	34,613
Hydrogen	0	18	349	760	1,791	3,517
RES share Transport	1,9%	4,2%	7,3%	19,1%	38,9%	68,9%
Industry	99,249	112,145	115,603	118,509	118,870	115,865
Electricity	24,995	31,759	33,787	36,531	38,720	39,770
RES electricity	4,627	7,622	12,038	20,944	30,606	37,202
District heat	9,424	10,605	12,347	15,249	19,596	23,718
RES district heat	560	2,213	4,542	8,800	15,123	21,468
Coal	19,546	21,902	20,114	16,417	6,334	515
Oil products	13,517	12,407	9,889	6,084	2,802	815
Gas	23,872	25,277	25,926	24,663	18,398	6,025
Solar	5	741	2,182	5,518	12,048	17,457
Biomass and waste	7,878	8,991	10,042	11,197	12,252	12,564
Geothermal	12	462	1,315	2,850	7,743	11,330
- Hydrogen	0	0	0	0	976	3,670
RES share Industry	13,2%	17,9%	26,1%	41,6%	65,4%	86,3%
Other Sectors	123,776	129,959	133,763	138,399	140,389	141,145
Electricity	33,253	37,880	39,973	44,424	48,406	52,551
RES electricity	5,842	9,618	16,114	27,991	39,913	50,000
District heat	6,546	7,968	9,770	12,740	16,136	18,145
RES district heat	439	1,701	3,610	7,160	12,504	16,629
Coal	4,535	4,007	3,146	2,658	978	23
Oil products	19,059	17,886	15,015	8,687	4,329	1,090
Gas	25,970	24,768	24,429	19,529	11,441	2,865
Solar	378	1,380	3,834	11,373	18,762	26,992
Biomass and waste	33,884	35,345	36,084	35,758	33,587	28,815
Geothermal	152	725	1,513	3,230	6,750	10,665
RES share other Sectors	32,9%	37,5%	45,7%	61,8%	79,4%	94,3%
Total RES	55,376	72,462	97,605	151,116	220,158	284,295
RES share	18,2%	22,0%	28,9%	44,0%	65,3%	87,1%
Non-energy use	32,236	34,977	36,245	38,549	40,398	42,174
Oil	24,832	26,267	27,026	28,444	29,627	30,761
Gas	6,084	6,901	7,289	7,951	8,400	8,817
Coal	1,320	1,808	1,930	2,154	2,371	2,595

Table 10 Primary energy demand under the advanced energy revolution per region

PJ/a	Primary energy					
	2007	2015	2020	2030	2040	2050
OECD	230,864	216,760	202,070	180,841	157,571	138,280
North America	115,751	108,607	101,969	90,853	81,332	70,227
Europe	77,525	72,095	66,504	59,077	50,784	46,754
Pacific	37,588	36,059	33,596	30,911	25,455	21,299
Non-OECD	259,335	302,512	314,672	319,802	321,902	327,715
World	490,199	519,272	516,742	500,642	479,473	465,995

Table 11 GDP development in all three scenarios

	2007–2015	2015–2030	2030–2040	2040–2050	2007–2050
World	3.30%	3.00%	2.70%	2.44%	.2.86%
OECD Europe	1.00%	1.80%	1.30%	1.10%	1.37%
OECD North America	1.80%	2.27%	1.55%	1.45%	1.77%
OECD Pacific	1.10%	1.23%	1.33%	1.40%	1.27%
Transition economies	4.60%	3.77%	2.60%	2.54%	3.38%
India	7.00%	5.90%	3.20%	2.50%	4.65%
China	8.80%	4.40%	3.20%	2.55%	4.74%
Other developing Asia	7.20%	4.60%	2.50%	2.20%	4.13%
Latin America	3.10%	2.50%	2.60%	2.40%	2.65%
Africa	4.70%	3.10%	3.40%	3.40%	3.65%
Middle East	4.50%	4.00%	2.30%	2.00%	3.20%

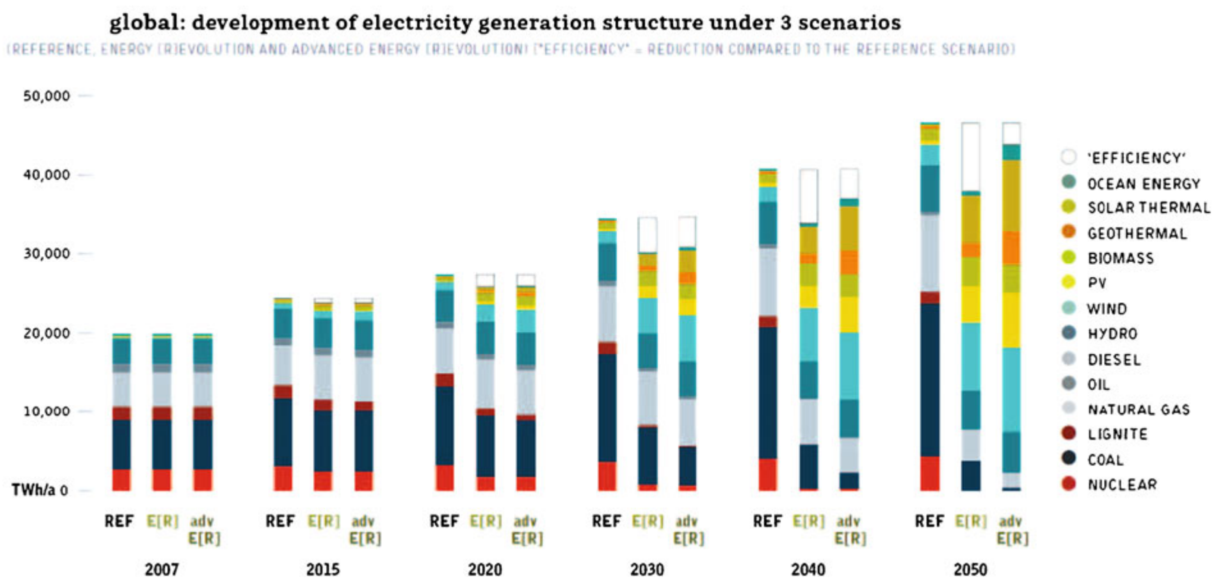

Fig. 4 Global: development of electricity generation structure under three scenarios (Reference, Energy [R]evolution and advanced Energy [R]evolution) ["Efficiency" reduction compared to the reference scenario]

Table 12 Global: projection of renewable electricity generation capacity under both Energy [r]evolution scenarios

In GW		2007	2020	2030	2040	2050
Hydro	E[R] Advanced E[R]	922	1,206	1,307	1,387	1,438
		922	1,212	1,316	1,406	1,451
Biomass	E[R] Advanced E[R]	46	212	336	500	625
		46	214	343	501	621
Wind	E[R] Advanced E[R]	95	878	1,733	2,409	2,943
		95	1,140	2,241	3,054	3,754
Geothermal	E[R] Advanced E[R]	11	49	108	196	279
		11	69	238	469	693
PV	E[R] Advanced E[R]	6	335	1.036	1,915	2,968
		6	439	1.330	2,959	4,318
CSP	E[R] Advanced E[R]	0	105	324	647	1,002
		0	225	605	1,173	1,643
Ocean energy	E[R] Advanced E[R]	0	29	73	168	303
		0	58	180	425	748
Total	E[R] Advanced E[R]	1,080	2,813	4,917	7,224	9,585
		1,080	3,359	6,252	9,987	13,229

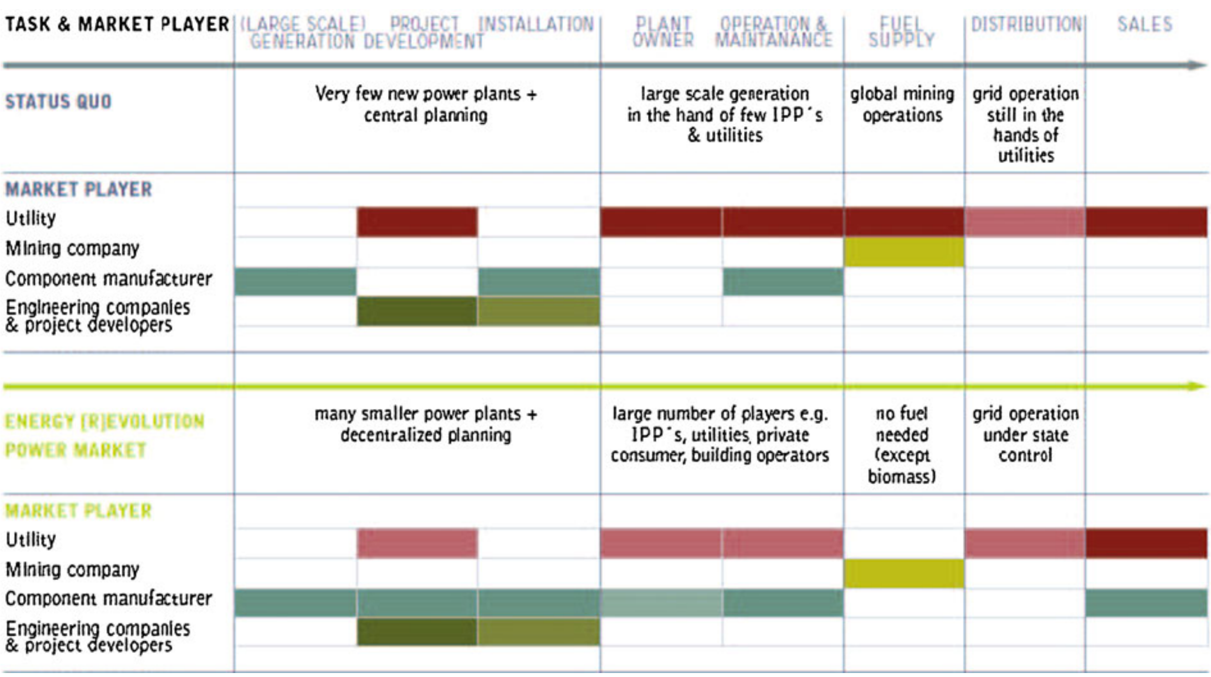

Fig. 5 Value chain in the power market today and under the Energy [r]evolution model (*red* utilities, *light green* mining companies, *blue* renewable industry, *dark green* project developer)

References

Dessus, B., Devin, B., Pharabod, F. (1993). World potential of renewable energies. World Solar Summit, Paris. Retrieved May 10, 2008 from http:/unesdoc.unesco.org/

EEA. (2010). European environment agency, EN17 Total Energy Intensity, July 2010

EC (European Commission). (2005). A vision for photovoltaic technology, report by the photovoltaic technology research advisory council (PV-TRAC), European Commission, 2005

GHF. (2009). Human impact report: climate change—the anatomy of a silent crisis, published by the global humanitarian forum—Geneva 2009, Global Humanitarian Forum, Villa Rigot, Avenue de la Paix 9, 1202 Geneva, Switzerland

Graus, W., Blomen, E. (2008). Global low energy demand scenarios—[R]evolution 2008. Report prepared for Greenpeace International and EREC, PECSNL 073841, Ecofys Netherlands bv, Utrecht

Greenpeace/EREC. (2007). Energy [R]evolution—a sustainable world energy outlook. GPI REF JN 035. Published by Greenpeace International and the European Renewable Energy Council (EREC), www.energyblueprint.info

Hansen, J., Sato, M., Kharecha, P., Beerling, D., Masson-Delmotte, V., Pagani, M., Raymo, M., Royer, D., Zachos, J. (2008). Target Atmospheric CO_2: where should humanity aim? NASA Goddard Institute for Space Studies. http://www.columbia.edu/~jeh1/2008/TargetCO2_20080407.pdf

Hoogwijk, M., Graus, W. (2008). Global potential of renewable energy sources: a literature assessment. Background report prepared for REN21. Ecofys NL PECSNL072975, Utrecht. http://www.ren21.net/pdf/REN21_RE_Potentials_and_Cost_Background%20document.pdf

IEA. (2007). *World energy outlook 2007*. Paris: OECD/IEA.

IEA. (2009a). *World energy outlook 2009*. Paris: OECD/IEA.

IEA. (2009b). *Energy balances of OECD countries* (2009th ed.). Paris: OECD/IEA.

IEA. (2009c). *Energy balances of non-OECD countries* (2009th ed.). Paris: OECD/IEA.

IPCC. (2007). Summary for policymakers. In B. Metz, O. R. Davidson, P. R. Bosch, R. Dave, & L. A. Meyer (Eds.), *Climate change 2007: Mitigation. Contribution of working group III to the fourth assessment report of the intergovernmental panel on climate change*. United Kingdom and New York: Cambridge University Press.

Krewitt, W., Simon, S., Graus, W., Teske, S., Zervos, A., & Schäfer, O. (2007). The 2°C scenario—a sustainable world energy perspective. *Energy Policy, 35*(2007), 4969–4980.

MESAP. (2008). http://www.seven2one.de/mesap.php

Neij, L. (2008). Cost development of future technologies for power generation—a study based on experience curves and complementary bottom-up assessments. *Energy Policy, 36*(2008), 2200–2211.

Nielson, P., Lemming J. K., Morthorst P. E., Lawetz H., James-Smith, Clausen N. E., Strøm S.18, Larsen J., Bang N., & Lindboe H. (2010). The economics of wind turbines. EMD 19 International, Aalborg, Denmark, 86 pp

Nordhaus, W. (2005) Alternative measures of output in global economicenvironmental models: purchasing power parity or market exchange rates? Report prepared for IPCC Expert Meeting on Emission Scenarios, USEPA, Washington DC, January 12–14, 2005

REN21. (2008). Renewable energy potentials—summary report. REN21 Secretariat, Paris. http://www.ren21.net/pdf/REN21_Potentials_Report.pdf

Schmid, S. (2008). *Light duty vehicle global scenario to 2050—contributing part to the global energy [r]evolution scenario. DLR—German Aerospace Center*. Stuttgart: Institute of Vehicle Concepts.

Seidenberger, T., Thrän, D., Offermann, R., Seyfert, U., Buchhorn, M., Zeddies, J. (2008). Global biomass potentials. Report prepared for Greenpeace International, German Biomass Research Center, Leipzig

Smeets, E., Faaij, A., Lewandowski, I., & Turkenburg, W. (2007). A bottom-up assessment and review of global bioenergy potentials to 2050. *Progress in Energy and Combustion Science, 33*, 56–106.

UBA. (2009). Role and potential of renewable energy and energy efficiency for global energy supply. DLR, Wuppertal Institute, ECOFYS, commissioned by the German Federal Environment Agency, March 2009

UNFCCC. (1992). United Nations Framework Convention on Climate Change, New York, May 1992, full text available from http://unfccc.int/resource/docs/convkp/conveng.pdf

UNPD. (2009). World population prospects: the 2008 revision, United Nations, Department of Economic and Social Affairs, Population Division. http://esa.un.org/unpp/ (1.2.2008)s