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# Energy [R]evolution 2008 – a sustainable world energy perspective

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## Abstract

The Energy [R]evolution 2008 scenario is an update of the Energy [R]evolution scenario published in 2007. It takes up recent trends in global socio-economic developments, and analyses to which extent they affect chances for achieving global climate protection targets. The main target is to reduce global $CO_2$ emissions to 10 Gt per year in 2050, thus limiting global average temperature increase to 2°C and preventing dangerous anthropogenic interference with the climate system. 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 energy 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 half of the world's energy needs by 2050. Developing countries can virtually stabilise their $CO_2$ emissions, whilst at the same time increasing energy consumption through economic growth. OECD countries will be able to reduce their emissions by up to 80%.

**Key-words:** Global energy scenario; $CO_2$ reduction; renewable energies; energy efficiency

## 1. The need for change

Nearly two years after publishing the first Energy [R]evolution scenario in 2007 (Greenpeace/EREC, 2007; Krewitt et al. 2007), the new Energy [R]evolution 2008 scenario picks up recent trends in global socio-economic developments, and analyses to which extent they affect chances for achieving the still valid overall target: transforming our unsustainable global energy supply system into a system which complies with climate protection targets, and at the same time offers perspectives for a fair and secure access to affordable energy services in all world regions. The Energy [R]evolution scenario aims at demonstrating the feasibility of reducing global $CO_2$ emissions to 10 Gt per year in 2050 (with a peak of global $CO_2$ emissions before 2020), which according to IPCC recommendations (IPCC 2007) is a prerequisite to limit global average temperature increase to 2°C (compared to pre-industrial level) and thus preventing dangerous anthropogenic interference with the climate system. While the IPCC's 4$^{th}$ Assessment Report (IPCC 2007), the G8 Summit in Heiligendamm, Germany, and preparations for the upcoming post-Kyoto negotiations at the COP15 conference in Copenhagen created positive momentum and support towards climate protection policy on a global level, once again the pace of energy consumption and increasing $CO_2$ emissions accelerated. Although struggling with high energy prices and security of supply, the industrialised countries still perceive restructuring of the energy system as a burden rather than a chance, and for countries like China and India there seem to be few incentives to exploit opportunities for leap-frogging energy consumption patterns of the Western world. At the same time there is increasing new scientific evidence which indicates that long-term feedback loops within the climate system might have been underestimated (Hansen et al., 2008), thus emphasising the need for even more drastic reduction of global $CO_2$ emissions.

The Wold Energy Outlook 2008 of the International Energy Agency (IEA, 2008) in very clear words also emphasises the need for changing global energy demand and supply patterns, as 'the consequences for the global climate of policy inaction are shocking' (IEA, 2008). It is a paradigm shift that the IEA for the first time in its World Energy Outlook (WEO) presents target oriented scenarios which aim at the stabilisation of atmospheric $CO_2$ concentration at 550 ppm and 450 ppm, respectively. While the 450 ppm stabilisation is a fundamental prerequisite for achieving the 2°C target, the IEA expresses strong scepticism towards the feasibility of their own 450 ppm scenario: 'Even leaving aside any debate about the political feasibility of the 450 Policy Scenario, it is uncertain whether the scale of the transformation envisaged is even technically achievable, as the scenario assumes broad deployment of technologies that have not yet been proven' (IEA, 2008). Although the WEO 2008 points out that renewable energies will become the second largest source of electricity (behind coal) soon after 2010, it states that achieving the ambitious climate protection target is not possible without a massive expansion of nuclear and carbon capture and sequestration (CCS) power plants.

The Energy [R]evolution scenario is much more optimistic: it shows that even without relying on nuclear and CCS there is no principal technical obstacle in curbing $CO_2$ emissions at the pace required to achieve the 2° target, and that a strategy which is based on energy efficiency and renewable energies also offers economic benefits and new options for economic development. What is required is the political will for change. Appropriate policy measures are needed that provide incentives to overcome the inertia inherent in our current energy supply system.

## 2. Approach

The Energy [R]evolution scenario is a target oriented scenario which has been developed in a back-casting process. The main target is to reduce global $CO_2$ emissions to 10 Gt per year in 2050, which is a prerequisite to limit global average temperature increase to 2°C and preventing catastrophic anthropogenic interference with the climate system. As we do not consider nuclear energy as an option that supports the transition towards a sustainable energy supply system, a second constraint in addition to $CO_2$ reduction is the phasing out of nuclear power plants until 2050.

A 10-region global energy system model implemented in the MESAP-PlaNet environment (MESAP, 2008) is used for simulating global energy supply strategies. MESAP-PlaNet is a so-called accounting model. Energy and material flows are calculated over different conversion stages form primary energy sources (like coal mines) to the driving forces of demand (population, GDP). MESAP-PlaNet is a static model: Each model year is calculated independently from the previous or following model period. If necessary, storage commodities can transfer material or energy flows between model periods. The model offers different rules for the balancing of production or consumption of commodities. Typically the production of a commodity is assigned to different processes by user-defined market shares. The cost calculation uses a macro-economic approach. The annual capital costs are calculated with the annuity method.

The ten world regions correspond to the regions as specified by the IEA's World Energy Outlook 2007 (Africa, China, India, Latin America, Middle East, OECD Europe, OECD North America, OECD Pacific, Other Developing Asia, Transition Economies) (IEA, 2007a). Model calibration for the base year 2005 is based on IEA energy statistics (IEA, 2007b, c). Population development projections are taken from the United Nations' World Population Prospects (UNDP, 2007), which are similar to the IEA population projections. Projection of gross domestic product (GDP) is taken from the IEA WEO 2007, and extrapolated to 2050. For illustrative purposes, we adopt the WEO 2007 Reference scenario as the business-as-usual projection, also extrapolated to 2050 based on own assumptions.

Similar to the Energy [R]evolution 2007 edition, demand and supply scenarios were developed in an iterative process in close cooperation with regional counterparts, representing research organisations and NGOs from the respective world regions (see Greenpeace/EREC 2008), and the renewable energy industry represented by the European Renewable Energy Council (EREC). The regional counterparts provided input on renewable energy potentials, and reviewed scenario assumptions, taking into account the energy policy context in the respective world regions.

The following sections summarise key assumptions and the main results of the scenario development. More details in particular on region specific data are available from Greenpeace/EREC (2008). All costs and prices given in the paper are in $\$_{2005}$.

## 3. Key system drivers

*Population development projection.* 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. Population growth affects the size and composition of energy demand. Following the 'medium fertility' projection of the United Nations' World Population Prospects (UNDP, 2007), world population will grow from today 6.7 billion people to 9.2 billion in 2050. Population growth will slow over the projection period, from 1.2% per year during 2005-2010 to 0.4% per year during 2040-2050. However, compared to the Energy [R]evolution 2007, world population in 2050 now is almost 300 million higher, which further increases the demand for energy. 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 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 86% in 2050. China's contribution to world population will drop from 20% today to 15% in 2050. Africa will remain the region with the highest growth rate, leading to a share of 21% of world population in 2050.

*Economic growth.* Economic growth is the second key driver for energy demand. Regional growth rates of gross domestic product (GDP) are taken from the IEA WEO 2007 (IEA, 2007 a) for the period 2005-2030, and extrapolated to 2050 based on own assumptions. Based on material published before the appearance of the world financial crisis, prospects for GDP growth have increased considerably compared to the Energy [R]evolution 2007, resulting in an average world GDP growth rate of 3.3% per year over the period 2005-2050, which is 0.5%-points higher than in the Energy [R]evolution 2007. It is difficult to foresee to which extent the financial crisis started in 2008 will affect long-term economic growth, but recent projections are likely to tend towards a more pessimistic appraisal of future economic development. Against this background, the Energy [R]evolution 2008 might be considered as a high economic growth scenario for which compliance with ambitious $CO_2$ reduction targets is even more challenging.

As summarised in Table 1, China and India are expected to grow faster than other regions, followed by the other Developing Asian countries, Africa and the Transition Economies. The Chinese economy will slow as it becomes more mature, but will nonetheless become the largest in the world in purchase power parity adjusted terms early in the 2020s. GDP in OECD Europe and OECD Pacific is assumed to grow by less than 2% per year over the projection period, while economic growth in OECD North America is expected to be slightly higher. The OECD share of global purchase power parity adjusted GDP will decrease from 55% in 2005 to 29% in 2050.

*Future energy price projections.* In the context of the global economic crisis we are currently experiencing an unprecedented volatility of oil and gas prices, which makes any short-term projection of energy prices extremely difficult. As a result of an in depth assessment of global oil and natural gas markets the IEA WEO 2008 (IEA, 2008) now suggests much higher oil and gas prices than in previous WEOs. Under the reference scenario IEA expects the oil price to reach \$110 per barrel in 2030 ($\$_{2007}$122/barrel). With \$90/barrel ($\$_{2007}$100/barrel) in 2030 the oil price remains slightly lower in the IEA WEO 450 ppm climate protection scenario because of the lower demand. Our assumptions on future oil and gas price development (Table 2) are in relatively good agreement with the IEA price projections. We expect oil prices to reach \$120/barrel in 2030, and a continuous increase up to \$140/barrel in 2050. In contrast to IEA, we assume that coal prices continue to rise, reaching \$250/t in 2030 and \$360/t in 2050. This assumption is based on the assessment of global coal reserves provided by Zittel and Schindler (2007). Biomass prices vary from no or low costs for biomass residues or traditional biomass resources to comparatively high costs for energy crops. As our energy system model does not support the detailed differentiation by biomass fraction, we use an aggregated price for biomass in the OECD regions and in the other regions. The increase in biomass prices reflects the growing competition between energy crops and food crops. Biomass prices in Europe are significantly higher than in other world regions because of the large amount of traditional biomass use in developing countries and the high potential of yet unused residues in North America and the Transition Economies.

*$CO_2$ emission costs*. In the absence of a global market for $CO_2$ allowances any estimate of future $CO_2$ emission costs is subject to large uncertainty. Marginal abatement costs for achieving a given $CO_2$ reduction are often taken as an estimate of future $CO_2$ prices. The IEA WEO 2008 suggests that compliance with the 2°C target in the 450 ppm scenario leads to $CO_2$ costs of up to \$160/$t_{CO2}$ (\$$_{2007}$180/$t_{CO2}$). $CO_2$ abatement costs, however, depend on the abatement technologies applied, and because of the incomplete exploitation of cost-effective renewable energy potentials in the WEO scenario from our point of view $CO_2$ reduction can be achieved at much lower costs. Like in the Energy [R]evolution 2007 we assume that $CO_2$ emission costs rise linearly from \$10/$t_{CO2}$ in 2010 to \$50/$t_{CO2}$ in 2050. $CO_2$ emission costs are accounted for in Non-Annex B countries only after 2020.

*Power plant investment costs.* While fossil fuel based energy technologies are at an advanced phase of market development, we assume a further potential for cost reduction, which however is limited due to high level of technical maturity (Table 3). Although carbon capture and storage (CCS) technologies might have a potential for mitigating the effect of fossil fuel consumption on climate change, we do not consider CCS technologies in our scenarios (see also discussion in Krewitt et al., 2007). The future economic performance of CCS technologies is uncertain, and there are major uncertainties on long-term $CO_2$ storage with regard to environmental impacts, social acceptance and legal implications. In the IEA WEO 2008 CCS technologies play a major role in the climate protection scenarios, although it is assumed that CCS does not become economically competitive even until 2030, thus boosting $CO_2$ abatement costs.

The renewable energy technologies considered in the Energy [R]evolution scenario all have a record of commercial operation, but they significantly differ in terms of their technical maturity, costs, and development potentials. While some of them are not yet fully competitive, we expect a large potential for cost reductions due to further technical learning (see e.g. Neij 2008). Table 3 exemplarily shows the expected development of specific investment costs for key electricity generation technologies. Note that the capacity factors might differ significantly between the respective renewable energy technologies, but also between world regions. Investment costs for concentrating solar thermal power plants include thermal storage systems which facilitate high capacity factors.

## 4. Exploitation of efficiency potentials curbs global energy demand

A growing population and an increase in economic activity do 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 [R]evolution low energy demand scenario has been developed in a three-step process (for more details see Graus and Blomen, 2008):

- development of a business-as-usual Reference scenario,
- assessment of technical potentials for energy efficiency measures by demand sector and world region,
- development of a low energy demand scenario, taking into account implementation constraints in terms of costs and other barriers.

The Reference energy demand projection is based on the IEA WEO 2007 Reference scenario, extrapolated to 2050 based on the assumptions on population and GDP development discussed above, and on assumed autonomous decrease of energy intensity. If we continue with business-as-usual, final energy demand (excluding non-energy use) will nearly double until 2050, from 299 EJ in 2005 to 570 EJ in 2050. In the light of increasing fossil fuel prices, depleting resources and climate change, business-as-usual is simply not an option.

The assessment of potentials for improving energy efficiency is based on the analysis of individual energy efficiency measures in the transport sector, industry sector and in the ‘other’ sectors (residential, trade and commerce, agriculture). The energy saving potential of each efficiency measure is estimated in comparison to the Reference scenario, so that the savings are additional to efficiency improvements already occurring in the Reference Scenario. It is assumed that equipment is replaced only at the end of its economic lifetime.

*Transport sector*. Changes in patterns of passenger travel are partly a consequence of growing wealth. As GDP per capita increases, people tend to migrate towards faster, more flexible and more expensive travel modes. With faster modes, people also tend to travel further. There is also a strong correlation between GDP growth and increase in freight transport. More economic activity will mean more transport of raw materials, intermediary products and final consumer goods. We analysed three options for reducing energy demand in the transport sector, namely the reduction of transport demand, modal shift from high energy intensive to low energy intensive transport modes, and energy efficiency improvements.

We assume that due to appropriate policy measures (price incentives, promoting tele-working, etc.) transport demand in OECD countries and in the Transition Economies can be reduced by 5% in 2050 compared to the Reference scenario. For non-OECD countries we assume no reduction in per capita transport demand, because the current per capita transport demand in these countries is quite low compared to OECD countries. Reduction in transport energy demand is also achieved through modal shift. For passenger transport, we take Japan as a best practice country, which due to its well-established urban and regional rail system has a share of passenger-km by rail of nearly 30%. Comparing other world regions with the example of Japan, we assume that compared to the Reference scenario 2.5% of passenger transport shifts from air (short distance) to rail, 2.5% from car to rail, and 2.5% from car to bus. For freight transport we assume that 5% of the transport volume shifts from medium trucks to rail, and 2.5% from heavy trucks to rail (compared to Reference scenario). More details on region specific data are given in Greenpeace/EREC (2008).

The energy intensities of light duty vehicles are currently highest in OECD North America (11.5 l/100 km) and Africa (13.5 l/100 km), and lowest in Europe (8 l/100 km). A substantial reduction of vehicle fuel consumption can be achieved due to power train improvements, weight reduction and friction and drag reduction. Although we expect further improvements in fuel efficiency of conventional gasoline and diesel vehicles, the shift towards hybrid power trains offers a more substantial potential for reducing fuel demand. Advantages of hybrid-electric drive trains arise from avoiding inefficient working regimes of the internal combustion engine (ICE), recuperation of breaking energy, and engine displacement downsizing. Fuel consumption of a small size hybrid vehicle is expected to be at 1.6 litre gasoline-equivalents ($l_{ge}$) per 100 km in 2050 (new European drive cycle – NEDC), 2.5 $l_{ge}$/100 $km_{NEDC}$ for medium size cars and 3.5 $l_{ge}$/100 $km_{NEDC}$ for large-size vehicles. Battery electric vehicles are even more efficient, we assume a fuel consumption of 0.7 $l_{ge}$/100 $km_{NEDC}$ for small-size cars in 2050, and 1.4 $l_{ge}$/100 $km_{NEDC}$ for medium-size cars. We do not consider battery vehicles for the large vehicle segment. Test cycle values are adjusted to real-world driving by applying a factor of 1.2 for fossil fuel and 1.7 for battery electric driven vehicles (Fulton 2004).

Plug-in hybrids are a combination of conventional hybrids and battery electric vehicles. Fuel consumption depends on the system layout and control strategy. We expect that 80% of vehicle kilometres will be driven in electric mode. It is assumed that by 2050 plug-in hybrids due to their higher weight will use 10% more energy in electric mode compared to battery electric vehicles, and that fuel consumption is 10% higher compared to a conventional hybrid vehicle when operated in the ICE/generator mode. In the Energy [R]evolution scenario the market introduction of plug-in hybrid electric vehicles starts in 2015. In the OECD regions, by 2050 sale shares for hybrid power trains reach 65%, and 50% in all other regions, except for Africa, where market share will be 20%. As a consequence, in the Energy [R]evolution scenario the world average vehicle stock fuel consumption drops from 10 $l_{ge}$/100 km today to 4 $l_{ge}$/100 km in 2050.

Based on data from Akerman (2005) we assume that in the Energy [R]evolution scenario energy intensity of world average air passenger transport declines from 2.6 MJ/person-km today to 1.2 MJ/person-km in 2050. Average energy intensity for rail transport is reduced by 1% per year (Fulton and Eads, 2004), from 0.3 MJ/person-km today to 0.2 MJ/person-km in 2050 for passenger transport, and from 0.24 MJ/tonne-km today to 0.1 MJ/tonne-km in 2050 for freight transport.

*Industry sector.* The worldwide average share of industry in total final energy demand today is 30%, with the highest share of 47% in China, and the lowest share of 19% in Africa. The industry sectors with the highest energy demand are the chemical and petrochemical industry, the iron and steel industry, and the processing of non-metallic minerals. These three industry sectors contribute to nearly 60% of worldwide industrial final energy consumption. To estimate long-term energy efficiency potentials, we analysed a set of individual measures in these industry sectors. The energy efficiency potential of the remaining industry is assessed based on an estimate of the decrease in energy intensity. The resulting average worldwide total energy efficiency improvement in the period 2010 to 2050 in the key industry sectors is summarised in Table 4. More sector and region specific details are available in Graus and Blomen (2008).

*Other sectors.* Energy consumption in the 'other' sectors (residential, commercial and public services, agriculture) represents about 40% of global final energy consumption. In all world regions, the share of agriculture in final energy demand is much smaller than the share of the residential sector, and the share of residential energy demand is larger than the share of the commercial and public service sector (except in OECD Pacific). Since households account for the largest share of energy demand in the residential sector, we analysed in detail saving potentials in households by world regions. Because of a lack of data for all world regions, for the commercial and public service sector we assume the same percental saving potential as for the residential sector. The key energy saving measures analysed in detail include reduced demand for heating and cooling due to improved insulation and building design, and the use of efficient electric appliances, lighting and air conditioning. The average potential for energy efficiency improvement for different types of energy use in the residential sector is summarised in Table 5. Percentage savings given in Table 5 are total efficiency improvements per year, including 1% autonomous energy improvement. Again, more sector and region specific details are given in Graus and Blomen (2008).

The exploitation of the energy efficiency potentials result in an only moderate growth of global energy demand from 2005 to 2050. In the Energy [R]evolution scenario, growth in worldwide final energy demand is limited to 350 EJ in 2050 (Table 6), a reduction of 40% compared to the Reference scenario. In spite of increasing transport volume, the more efficient use of energy in the transport sector allows to reduce transport energy demand even slightly below the current level. The highest increase is expected in the 'other sector', in which energy demand until 2050 grows by 26% compared to 2005.

Figure 1 shows how energy efficiency measures in the different demand sectors affect the development of energy demand in the world regions in the Energy [R]evolution scenario. Figure 1 shows that in spite of the energy savings due to energy efficiency improvement, the energy demand will still grow considerably in developing regions, while we expect a reduction of energy consumption in the OECD regionas and in the Transition Economies. In particular in OECD North America efficiency measures in the transport sector contribute to the reduced energy demand. In spite of the significant energy savings compared to the Reference scenario, India shows the highest relative increase in energy demand (270% compared to 2005).

The implementation of energy efficiency measures leads to a convergence of energy intensities (final energy use per unit of gross domestic product), which today show huge differences between world regions, but they still differ by more than a factor of two in 2050 (Figure 2). In the Energy [R]evolution scenario average worldwide energy intensity decreases by an average of 3% per year from 4.7 MJ/$ in 2005 to 1.3 MJ/$ in 2050. Figure 3 shows that in spite of considerable reduction of energy demand in the industrialised world there remains a large imbalance in per capita energy consumption across the world regions. In the Energy [R]evolution scenario, OECD North America shows the largest decrease in per capita energy consumption, but together with the other OECD regions, the Middle East and the Transition Economies remain well above the 2050 world average. China is the only country that today is below world average per capita energy consumption, and will be above world average in 2050. Even when taking into account differences in climatic conditions and cultural background, a factor of five difference between the regions with the lowest and the highest per capita energy demand seems to be high. On the long-term, a further convergence of per capita energy demand is required to ensure a fair and peaceful access to the world's energy resources for the world population.

## 5. Shifting towards renewables – a sustainable global energy supply perspective

Worldwide renewable energy resources exceed current energy demand several times, but the availability of renewable energy sources differs considerably between world regions. We use information on renewable energy potentials by world region and technology from (REN21 2008; Hoogwijk and Graus, 2008) as a basis for developing a renewable energy oriented supply scenario. 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 potential for energy crops strongly depends on food supply patterns and assumptions on agricultural production. Results for global biomass potentials from energy crops in 2050 range from 97 EJ in a business-as-usual scenario to only 6 EJ in a scenario which assumes no forest clearing, reduced use of fallow areas for agriculture, and expanded ecological protection areas. The global potential for biomass residues is estimated to be 88 EJ in 2050. With a total biomass consumption of 94.7 EJ in 2050 the Energy [R]evolution scenario complies with the most stringent requirements towards sustainable biomass use.

*Electricity generation.* The development of the electricity sector in the Energy [R]evolution scenario is characterised by a dynamically growing renewable energy market and an increasing share of renewable electricity (Figure 4). The phasing out of nuclear energy and rising electricity demand is met by bringing into operation new highly efficient fossil power plants, together with an increasing capacity of wind turbines, biomass, concentrating solar power plants and photovoltaics. Fossil electricity generation are expected to peak around 2020, followed by a continuous decline of fossil power plant capacity, with a shift from coal to gas fired power plants. The electricity generation from renewable energies in the Energy [R]evolution scenario reaches 28,599 TWh/a in 2050, which is 77% of the electricity produced worldwide. In the long-term, solar energy can be the main source of electricity generation, both from PV cells and from concentrating solar thermal power plants.

Concentrating solar thermal power plants equipped with heat storage systems will provide dispatchable bulk power from solar energy. In the Energy [R]evolution scenario the installed capacity of renewable energy technologies grows from the current 1,000 GW to 9,100 GW in 2050. Growing electricity generation in combined heat and power (CHP) applications (2005: 1915 TWh; 2050: 6400 TWh) improves the overall efficiency of the energy supply system, with biomass being the main fuel for CHP applications in 2050. In spite of energy efficiency measures, after 2030 there is a rapidly growing electricity demand which is induced by the market introduction of electric vehicles (see below). This additional electricity demand from the transport sector can largely be covered by renewable energy sources.

The structure of the electricity generation varies significantly by region (Table 7). Because of the vast solar resources the Middle East until 2050 can satisfy growing electricity demand nearly completely from renewable energy sources. 900 TWh solar electricity from concentrating solar power plants in Africa and the Middle East are exported to Europe in 2050. In Latin America and OECD North America more than 90% of renewable electricity generation is feasible because of favourable wind, hydro and solar conditions. In the regions with rapidly growing electricity demand (Africa, China, India, Other Developing Asia) the contribution of renewables in 2050 is expected to be lower (between 60 and 75%). Nevertheless, in 2050 China will be the largest market for renewable energy technologies.

Due to growing demand we face a significant increase in society's expenditures on electricity supply. In the Reference scenario, the growth in demand, the increase in fossil fuel prices and the costs of $CO_2$ emissions result in total global electricity supply costs rising from today's $1,740 billion per year to around $8,400 billion in 2050. Figure 5 shows that the Energy [R]evolution scenario not only complies with global $CO_2$ reduction targets but also helps to stabilise energy costs and relieve the economic pressure on society. Increasing energy efficiency and shifting energy supply to renewables lead to long-term costs of electricity supply that are more than one third lower than in the Reference scenario.

The overall global level of investment required in new power plant capacity up to the year 2030 will be between $11 and 15 trillion. The investment value required to realise the Energy [R]evolution scenario is $14.7 trillion, about 30% more than in the Reference scenario, which will require $11.3 trillion (Table 8). While in the Reference scenario investment in renewable energy is slightly lower than for fossil power plants, in the Energy [R]evolution scenario most of the investment is shifted towards renewable energy technologies. The cumulated fuel cost savings in the Energy [R]evolution scenario in the period 2005 to 2030 reach $18.7 trillion compared to the Reference scenario. Fuel cost savings thus do several times outweigh the additional investment requirements of the Energy [R]evolution scenario.

*Heat supply.* Today, 24% of global heat demand is covered by renewable energies, the main contribution coming from the traditional use of biomass. In the Energy [R]evolution scenario solar collectors, modern biomass and geothermal energy are increasingly substituting fossil fuel-fired systems, reaching 114,540 PJ/a in 2050, which is 71% of the total heat demand. Heat supply from CHP to an overall shrinking heat market grows from 10,140 PJ/a in 2005 to 26,070 PJ/a in 2050, thus increasing its share to 16%.

*Transport.* Due to the fast growing demand for transport services, in the Energy [R]evolution scenario energy demand will further increase up to the year 2015. After 2015 demand will decrease, falling slightly below its current level (Table 6). On the global level, the share of biofuels of total transport energy demand will reach 5% in 2020, and 15% in 2050. Because of the massive market introduction of electric vehicles (both battery vehicles and electric hybrid vehicles) after 2020 electricity will provide 24% of the transport sector's total energy demand in 2050. Taking into account the renewable shares in electricity generation, in the Energy [R]evolution scenario by 2050 36% of transport energy will come from renewable sources. In spite of the fast market uptake of new propulsion technologies, fossil fuels are still the dominant energy source in 2050, covering 61% of total transport energy demand. Figure 6 shows that due to the availability of biomass resources Latin America and OECD North America will have the highest biofuel shares. It is expected that electric vehicles will gain the largest market shares in the OECD regions and in Latin America. Because of the anticipated successful market breakthrough of electric vehicles we assume that hydrogen as a transport fuel will only play a role in niche applications.

*Primary energy supply.* The resulting primary energy supply in the Energy [R]evolution scenario is summarised in Figure 7. Compared to the Reference scenario, the overall primary energy demand is reduced by 45% in 2050. We see a continuous decline in oil and coal consumption after the year 2010. The consumption of natural gas will peak around 2020, but than also declines to well below current consumption levels. In 2050, 56% of the remaining primary energy demand is covered by renewable energy sources, with biomass being the main source of renewable energies, followed by solar, geothermal, wind and hydro.

Note that because of the ‘efficiency method’ used for the calculation of primary energy consumption, which postulates that the amount of electricity generation from hydro, wind, solar and geothermal energy equals the primary energy consumption, the share of renewables appear to be smaller than their actual importance as energy suppliers. Also the decrease in total primary energy consumption partly is a statistical effect resulting from the shift from fossil to renewable fuels and the application of the ‘efficiency method’ for the calculation of primary energy demand.

## 6. Development of $CO_2$ emissions

In the Energy [R]evolution scenario, global $CO_2$ emissions are expected to peak around 2015, and then go down to 10.6 Gt in 2050, which is less than half of global $CO_2$ emissions in 1990 (Table 9). Reducing $CO_2$ emissions to 10 Gt in 2050 is a prerequisite for limiting global average temperature rise to 2°C. In spite of phasing out nuclear energy and increasing electricity demand, $CO_2$ emissions in the power sector peak around 2010, and until 2050 can be reduced to about one third of today’s emissions.

The development of $CO_2$ emissions differs between world regions. It is expected that OECD regions can continuously reduce $CO_2$ emissions after 2010. In contrast, $CO_2$ emissions in the emerging market regions like China, India and Other Developing Asia will peak only between 2020 and 2030. Due to the fast economic growth, $CO_2$ emissions in China are expected to increase by 65% until 2020 (compared to 2005), but until 2050 can be reduced to below the current emission level. In India and Africa $CO_2$ emissions in 2050 will be higher than today, but in both regions the per capita emissions in 2050 are below world average (Figure 8).

In the Energy [R]evolution scenario, global average per capita $CO_2$ emissions in 2050 are 1.15 t/capita. In spite of continuous convergence of economic performance, lifestyle and energy intensity between world regions, significant differences between regional per capita emissions remain, partly due to the regional availability of renewable energy sources. While OECD North America, which today has the highest per capita $CO_2$ emissions (2005: 14.7 t/capita), will manage to bring emissions down to below 2 t/capita, in 2050 China will be the region with the highest per capita $CO_2$ emissions (Figure 8). Taking 2050 global average per capita emissions of 1.15 t/capita as an indicator of equal global emission rights, we see that China, the OECD regions and the Transition Economies exceed their emission allowances, while in particular Africa, but also India, Latin America and Other Developing Asia do not fully utilise their $CO_2$ emission budget. Assuming a global $CO_2$ market with a $CO_2$ price of $50/t, this would correspond to a net financial flow between world regions of $130 billion per year in 2050. Africa would be the main beneficiary, receiving $70 billion per year, while China would have to pay around $80 billion per year to compensate for excess $CO_2$ emissions. Using the money from $CO_2$ emission trading for building up a fund that is used to finance renewable energy projects e.g. through paying guaranteed feed-in tariffs for renewable electricity can help to stimulate early market introduction of renewable energy technologies in particular in developing regions.

## 7. Conclusions

Business-as-usual is clearly not an option for future generations, as this would have dramatic consequences for the environment, the economy and human society. The Energy [R]evolution scenario shows that options for change are at hand. Energy efficiency measures and renewable energies can play a leading role in the world's energy future. Towards the mid of the century, renewable energy can provide more than half of the world's energy needs, at the same time ensuring the continuous improvement of global living conditions, in particular in developing regions. In the days of a global financial and economic crisis, scenario results offer a positive message: investment in innovative energy efficiency and renewable energy technologies contributes to economic growth, to the creation of jobs, and in the medium- to long-term helps to reduce the costs of global energy supply. By moving towards renewable energies, forward-thinking governments can act now to increase employment and investment opportunities.

There is no doubt that a global $CO_2$ emission trading system will be a key element in the portfolio of policy measures that is required to ensure compliance with climate protection targets. However, while it will take time until a difficult international negotiation process will finally succeed in establishing a global $CO_2$ trading system, we know from the IPCC 4$^{th}$ Assessment Report that we need urgent action now to curb $CO_2$ emissions. Complementary policy measures like feed-in tariffs for renewable energies have proved to be cost-effective in many countries, and are easy to implement on a national level. Facing the challenge ahead, there is no time to loose.

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Table 1: GDP development projections (average annual growth rates, purchase power parity adjusted)

| | 2005-2010 | 2010-2020 | 2020-2030 | 2030-2040 | 2040-2050 | 2005-2030 | 2005-2050 |
|---|---|---|---|---|---|---|---|
| World | 4,6% | 3,6% | 3,2% | 3,0% | 2,9% | 3,6% | 3,3% |
| Africa | 5,0% | 3,9% | 3,5% | 3,2% | 3,0% | 3,9% | 3,6% |
| China | 9,2% | 5,7% | 4,7% | 4,2% | 3,6% | 6,0% | 5,0% |
| India | 8,0% | 6,2% | 5,7% | 5,4% | 5,0% | 6,3% | 5,8% |
| Latin America | 4,3% | 3,2% | 2,8% | 2,6% | 2,4% | 3,2% | 2,9% |
| Middle East | 5,1% | 4,2% | 3,2% | 2,9% | 2,6% | 4,0% | 3,4% |
| OECD Europe | 2,6% | 2,1% | 1,7% | 1,3% | 1,1% | 2,0% | 1,7% |
| OECD North America | 2,7% | 2,4% | 2,2% | 2,0% | 1,8% | 2,4% | 2,2% |
| OECD Pacific | 2,5% | 1,8% | 1,5% | 1,3% | 1,2% | 1,8% | 1,6% |
| Other Developing Asia | 5,1% | 3,8% | 3,1% | 2,7% | 2,4% | 3,8% | 3,2% |
| Transition Economies | 5,6% | 3,6% | 2,7% | 2,5% | 2,4% | 3,6% | 3,1% |

Table 2: Assumptions on fuel price development

| | 2005 | 2010 | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|---|
| Crude oil in $/bbl | 52.5 | 100 | 110 | 120 | 130 | 140 |
| Natural gas in $/GJ | | | | | | |
| - America | 5.7 | 11.5 | 14.7 | 18.4 | 21.9 | 24.6 |
| - Europe | 5.8 | 10.0 | 13.3 | 17.2 | 20.6 | 23.0 |
| - Asia | 5.6 | 11.5 | 14.7 | 18.3 | 21.9 | 24.6 |
| Hard coal $/t | 76.8 | 142.7 | 194.4 | 251.4 | 311.2 | 359.1 |
| Biomass in $/GJ | | | | | | |
| - Europe | 7.5 | 7.9 | 9.4 | 10.3 | 10.6 | 10.8 |
| - OECD Pacific, North America | 3 | 3.3 | 3.8 | 4.3 | 4.7 | 5.2 |
| - other regions | 2.5 | 2.8 | 3.5 | 4.0 | 4.6 | 4.9 |

Table 3: Assumptions on specific investment cost development (in $/kW) for selected power plant technologies

| | 2010 | 2030 | 2050 |
|---|---|---|---|
| Coal condensing power plant | 1230 | 1160 | 1100 |
| Natural gas combined cycle | 690 | 610 | 550 |
| Wind onshore | 1370 | 1110 | 1090 |
| Wind offshore | 3480 | 2200 | 1890 |
| Photovoltaic | 3760 | 1280 | 1080 |
| Biomass CHP | 4970 | 3380 | 2950 |
| Geothermal CHP | 13050 | 7950 | 6310 |
| Concentrating solar power plant | 6340 | 4430 | 4320 |
| Ocean energy | 5170 | 2240 | 1670 |

Table 4: Average worldwide energy efficiency improvement in % per year in the Energy [R]evolution scenario in the period 2010 to 2050 in the industry sector

| | Autonomous energy efficiency improvement in Reference scenario | Energy efficiency improvement in addition to reference scenario | Total energy efficiency improvement |
|---|---|---|---|
| Iron and steel | 1.0 | 1.4 | 2.4 |
| Aluminium production | 1.0 | 0.9 | 1.9 |
| Chemical industry | 1.0 | 0.8 | 1.8 |
| Non-metallic minerals | 1.0 | 0.4 | 1.4 |
| Other industries | 1.0 | 1.2 | 2.2 |
| Average industry | 1.0 | 1.2 | 2.2 |

Table 5: Average energy efficiency improvement in % per year in the Energy [R]evolution scenario in the period 2010 to 2050 in the residential sector

| | Heating, new | Heating, retrofit | Standby | Lighting | Appliances | Cold appliances | Air conditioning | Computer | Other |
|---|---|---|---|---|---|---|---|---|---|
| Africa | 1.2 | 1.2 | 3.1 | 2.7 | 1.7 | 2.5 | 2.0 | 2.0 | 2.2 |
| China | 1.2 | 1.2 | 3.1 | 1.1 | 1.7 | 2.5 | 2.0 | 2.0 | 1.9 |
| India | 1.2 | 1.2 | 3.1 | 2.7 | 1.7 | 2.5 | 2.0 | 2.0 | 2.2 |
| Latin America | 1.2 | 1.2 | 3.1 | 2.7 | 1.7 | 2.5 | 2.0 | 2.0 | 2.2 |
| Middle East | 1.2 | 1.2 | 3.1 | 2.7 | 1.7 | 2.5 | 2.0 | 2.0 | 2.2 |
| OECD Europe | 2.1 | 1.3 | 3.1 | 2.3 | 1.7 | 2.5 | 2.0 | 2.0 | 2.1 |
| OECD N. America | 1.2 | 1.1 | 3.1 | 1.7 | 1.7 | 2.5 | 2.0 | 2.0 | 2.0 |
| OECD Pacific | 1.1 | 1.1 | 3.1 | 1.4 | 1.7 | 2.5 | 2.0 | 2.0 | 1.9 |
| Other Develop. Asia | 1.2 | 1.2 | 3.1 | 2.7 | 1.7 | 2.5 | 2.0 | 2.0 | 2.2 |
| Transition Economies | 1.4 | 1.1 | 3.1 | 2.7 | 1.7 | 2.5 | 2.0 | 2.0 | 2.2 |

Table 6: Development of final energy demand in PJ/a under the Energy [R]evolution scenario by region (excluding non-energy use)

| | 2005 | 2010 | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|---|
| **World** | **299,300** | **327,393** | **347,127** | **354,335** | **353,803** | **349,845** |
| Transport | 83,936 | 92,889 | 92,233 | 89,980 | 85,796 | 83,306 |
| Industry | 91,759 | 102,321 | 112,295 | 114,021 | 113,583 | 110,787 |
| Other | 123,665 | 132,183 | 142,598 | 150,334 | 154,423 | 155,752 |
| **Africa** | **18,073** | **20,003** | **22,174** | **24,412** | **26,409** | **28,286** |
| Transport | 2,812 | 3,254 | 3,759 | 4,265 | 4,770 | 5,276 |
| Industry | 3,345 | 3,720 | 3,933 | 4,016 | 4,111 | 4,071 |
| Other | 11,916 | 13,029 | 14,482 | 16,132 | 17,527 | 18,939 |
| **China** | **43,677** | **55,359** | **67,869** | **71,370** | **72,412** | **73,120** |
| Transport | 5,062 | 7,557 | 9,992 | 12,054 | 13,970 | 17,296 |
| Industry | 20,405 | 27,453 | 34,646 | 35,245 | 34,024 | 31,365 |
| Other | 18,210 | 20,349 | 23,231 | 24,071 | 24,419 | 24,458 |
| **India** | **13,569** | **16,009** | **21,188** | **26,174** | **31,247** | **36,263** |
| Transport | 1,549 | 2,156 | 3,786 | 5,417 | 7,047 | 8,677 |
| Industry | 4,145 | 5,431 | 7,582 | 9,531 | 11,525 | 13,421 |
| Other | 7,875 | 8,422 | 9,819 | 11,227 | 12,676 | 14,165 |
| **Latin America** | **15,484** | **17,288** | **18,894** | **20,242** | **21,637** | **23,229** |
| Transport | 5,131 | 5,595 | 5,718 | 5,842 | 5,965 | 6,089 |
| Industry | 5,683 | 6,547 | 7,288 | 7,722 | 7,978 | 8,136 |
| Other | 4,670 | 5,146 | 5,888 | 6,679 | 7,694 | 9,005 |
| **Middle East** | **12,011** | **14,266** | **16,437** | **17,575** | **18,648** | **19,564** |
| Transport | 4,460 | 5,226 | 5,004 | 4,686 | 4,332 | 3,990 |
| Industry | 3,324 | 4,266 | 5,604 | 6,198 | 6,637 | 6,751 |
| Other | 4,226 | 4,774 | 5,829 | 6,690 | 7,680 | 8,823 |
| **OECD Europe** | **53,833** | **54,781** | **48,833** | **43,902** | **40,751** | **39,231** |
| Transport | 16,080 | 16,860 | 14,377 | 11,770 | 9,779 | 8,693 |
| Industry | 15,380 | 15,374 | 13,636 | 12,430 | 12,038 | 11,908 |
| Other | 22,374 | 22,547 | 20,821 | 19,702 | 18,934 | 18,630 |
| **OECD North America** | **72,218** | **74,483** | **74,003** | **72,152** | **65,727** | **55,459** |
| Transport | 31,310 | 32,466 | 30,419 | 27,520 | 22,297 | 16,721 |
| Industry | 16,067 | 15,337 | 14,332 | 13,719 | 13,106 | 12,356 |
| Other | 24,840 | 26,680 | 29,252 | 30,913 | 30,324 | 26,383 |
| **OECD Pacific** | **21,322** | **22,243** | **21,678** | **20,397** | **18,513** | **16,669** |
| Transport | 6,716 | 7,256 | 6,515 | 5,774 | 5,033 | 4,035 |
| Industry | 6,847 | 7,159 | 7,251 | 6,913 | 6,284 | 5,723 |
| Other | 7,760 | 7,828 | 7,912 | 7,710 | 7,196 | 6,911 |
| **Other Developing Asia** | **20,553** | **23,448** | **26,357** | **28,651** | **30,330** | **31,625** |
| Transport | 4,964 | 5,988 | 6,637 | 7,189 | 7,740 | 8,292 |
| Industry | 6,285 | 7,334 | 8,292 | 8,898 | 9,203 | 9,300 |
| Other | 9,305 | 10,126 | 11,428 | 12,565 | 13,387 | 14,033 |
| **Transition Economies** | **28,620** | **29,511** | **29,693** | **29,460** | **28,128** | **26,399** |
| Transport | 5,853 | 6,531 | 6,025 | 5,464 | 4,863 | 4,237 |
| Industry | 10,277 | 9,700 | 9,732 | 9,350 | 8,678 | 7,756 |
| Other | 12,491 | 13,280 | 13,936 | 14,645 | 14,587 | 14,405 |

Table 7: Electricity generation in 2050 by region in the Energy [R]evolution scenario in TWh

| | Africa | China | India | Latin Amer. | Middle East | OECD Europe | OECD N. A. | OECD Pacific | Other Devel. Asia | Trans. Econom ies | World |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Total generation | 2076 | 9261 | 4435 | 2615 | 2171 | 3252 | 6756 | 2111 | 2356 | 2083 | 37116 |
| - Fossil | 553 | 3401 | 1791 | 140 | 95 | 463 | 442 | 459 | 769 | 404 | 8517 |
| - Coal | 253 | 2581 | 1131 | 1 | 0 | 10 | 19 | 118 | 174 | 4 | 4291 |
| - Natural gas | 292 | 820 | 660 | 137 | 92 | 453 | 422 | 339 | 585 | 400 | 4202 |
| - Oil | 8 | 0 | 0 | 2 | 3 | 0 | 0 | 2 | 10 | 0 | 24 |
| - Nuclear | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| - Renewables | 1523 | 5860 | 2644 | 2475 | 2076 | 2789 | 6315 | 1652 | 1587 | 1679 | 28599 |
| - Hydro | 195 | 1530 | 474 | 822 | 50 | 520 | 902 | 194 | 286 | 375 | 5348 |
| - Wind | 133 | 1510 | 520 | 720 | 230 | 1040 | 1534 | 811 | 530 | 710 | 7738 |
| - PV | 350 | 810 | 480 | 160 | 420 | 410 | 1018 | 281 | 325 | 95 | 4349 |
| - Biomass | 48 | 630 | 365 | 462 | 39 | 487 | 818 | 198 | 110 | 370 | 3527 |
| - Geothermal | 32 | 130 | 150 | 86 | 72 | 152 | 789 | 49 | 160 | 85 | 1705 |
| - Concentr. Solar power | 750 | 990 | 630 | 200 | 1260 | 125 | 1078 | 47 | 160 | 15 | 5255 |
| - Ocean energy | 15 | 260 | 25 | 25 | 5 | 54 | 175 | 72 | 16 | 30 | 677 |
| Share renewable electricity | 73% | 63% | 60% | 95% | 96% | 86% | 94% | 78% | 67% | 81% | 77% |

Table 8: Fuel and investment costs in trillion $, cumulated over the period 2005 to 2030

| | Reference | Energy [R]evolution | Difference |
|---|---|---|---|
| **Power plant investment** | | | |
| Fossil and nuclear power plants | 5.4 | 2.8 | -2.6 |
| Renewables | 4.7 | 9.0 | 4.3 |
| Cogeneration | 1.2 | 2.9 | 1.7 |
| Total | 11.3 | 14.7 | 3.4 |
| **Fuel costs** | | | |
| Fuel oil | 4.6 | 3.2 | -1.4 |
| Natural gas | 17.8 | 16.7 | -1.1 |
| Coal and lignite | 58.2 | 42.0 | -16.2 |
| Total | 80.6 | 61.9 | -18.7 |

Table 9: Development of $CO_2$ emissions in the Energy [R]evolution scenario (in Mill. t per year)

| | 2005 | 2010 | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|---|
| Africa | 780 | 890 | 977 | 991 | 980 | 895 |
| China | 4,429 | 6,210 | 7,287 | 6,249 | 4,779 | 3,209 |
| India | 1,074 | 1,400 | 1,706 | 1,824 | 1,816 | 1,661 |
| Latin America | 827 | 894 | 749 | 655 | 513 | 369 |
| Middle East | 1,173 | 1,358 | 1,352 | 1,148 | 781 | 393 |
| OECD Europe | 4,062 | 3,837 | 2,895 | 1,991 | 1,290 | 884 |
| OECD North America | 6,433 | 6,452 | 5,131 | 3,808 | 2,272 | 1,058 |
| OECD Pacific | 1,895 | 2,016 | 1,858 | 1,499 | 970 | 433 |
| Other Dev. Asia | 1,303 | 1,576 | 1,596 | 1,482 | 1,330 | 1,148 |
| Transition Economies | 2,375 | 2,321 | 1,830 | 1,334 | 850 | 539 |
| World | 24,351 | 26,954 | 25,381 | 20,981 | 15,581 | 10,589 |
| - industry | 4,292 | 4,553 | 4,463 | 3,875 | 2,993 | 2,067 |
| - other sectors | 3,405 | 3,526 | 3,213 | 2,651 | 2,004 | 1,333 |
| - transport | 5,800 | 6,332 | 5,891 | 5,272 | 4,378 | 3,493 |
| - electricity & steam | 10,854 | 12,543 | 11,814 | 9,183 | 6,206 | 3,696 |

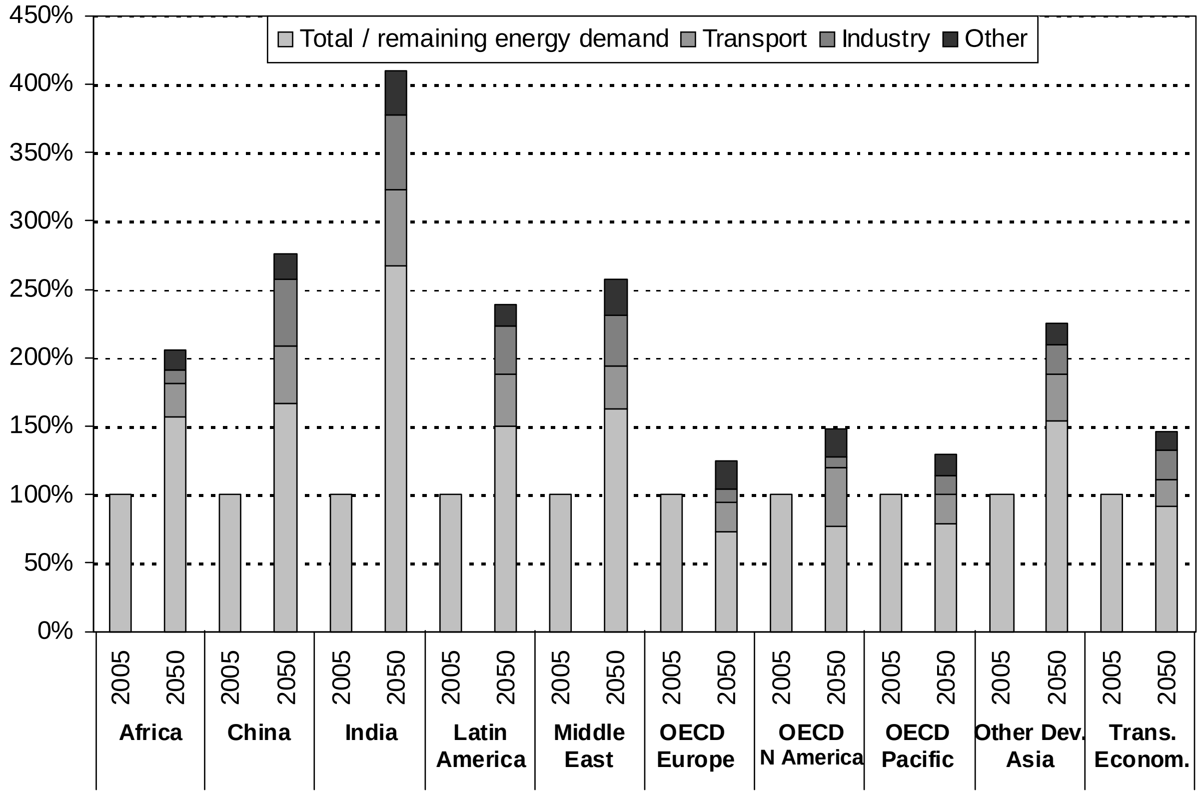


Figure 1: Potentials for energy efficiency improvement per region in the Energy [R]evolution scenario (normalised to the 2005 final energy demand per region)

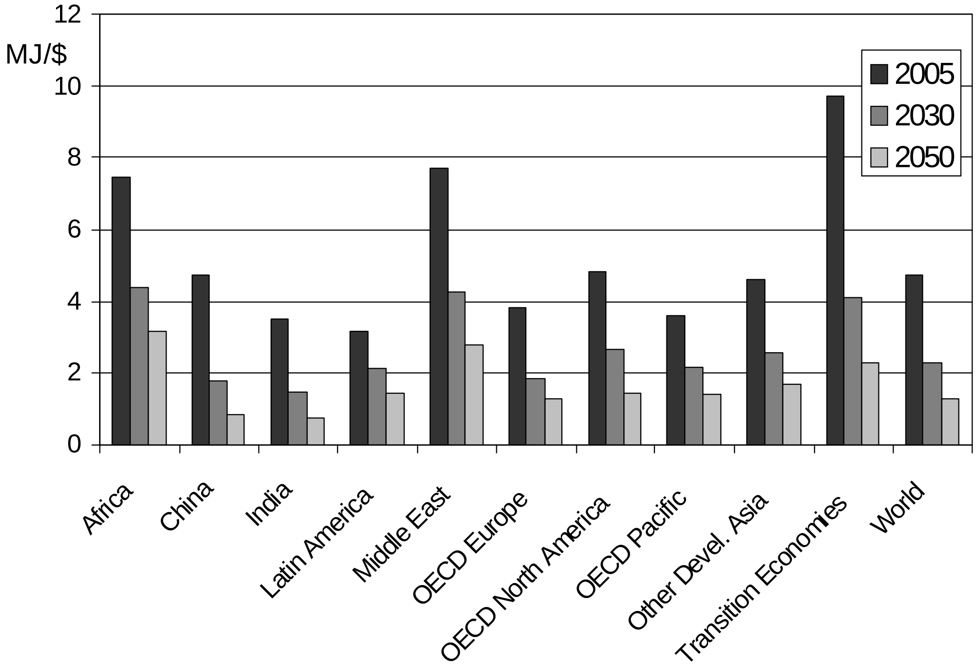


Figure 2: Development of energy intensities by region in the Energy [R]evolution scenario

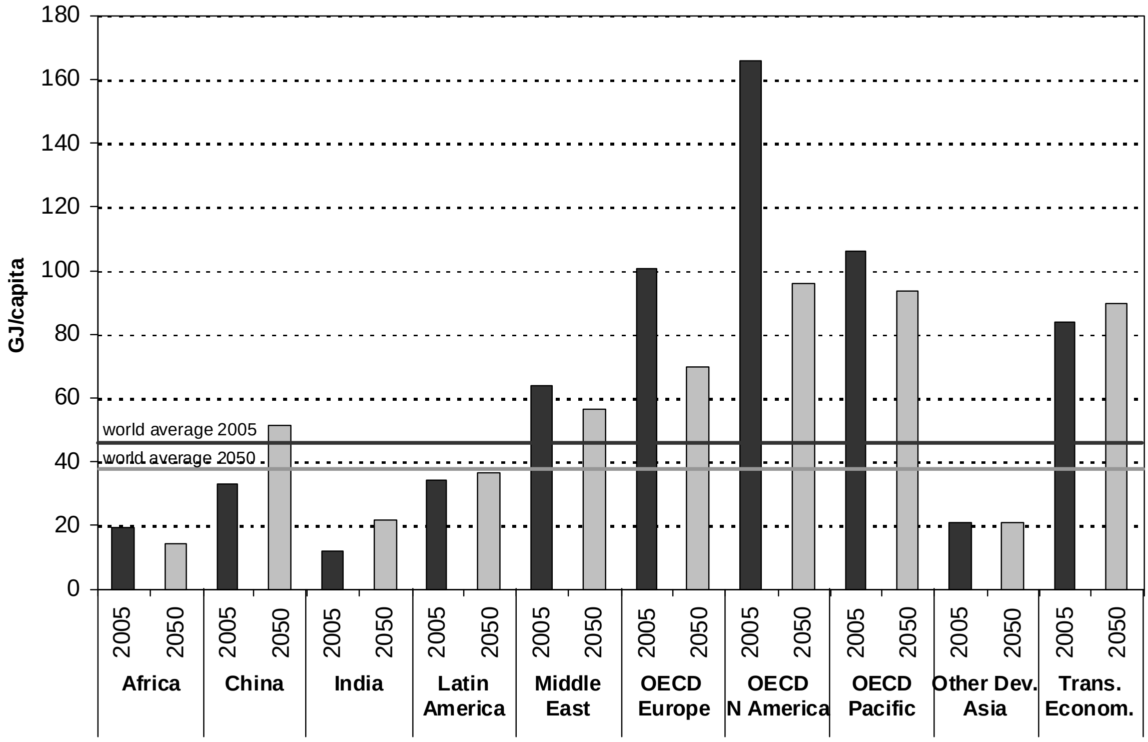


Figure 3: Development of per capita energy demand in the Energy [R]evolution scenario

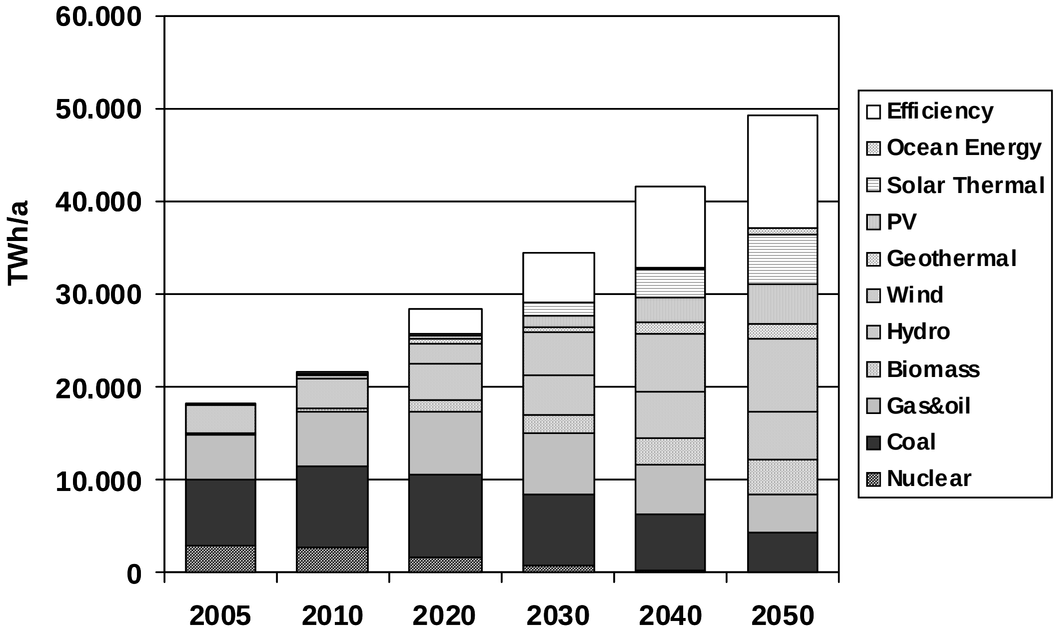


Figure 4: Development of global electricity generation in the Energy [R]evolution scenario ('efficiency': savings compared to Reference scenario)

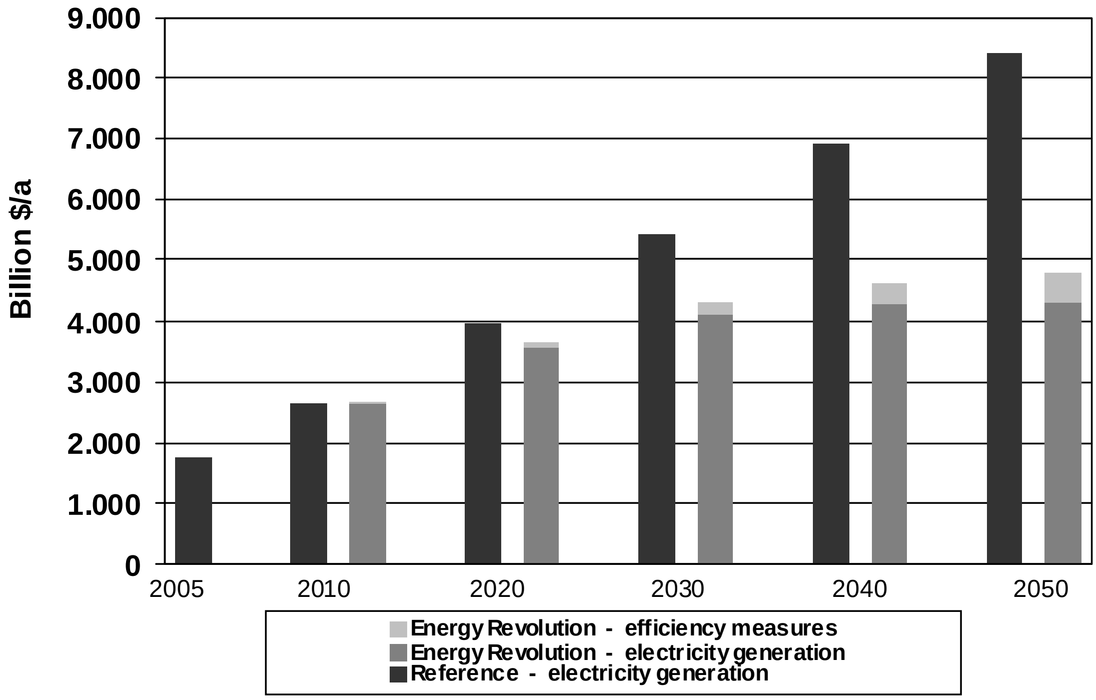


Figure 5: Projection of global electricity supply costs

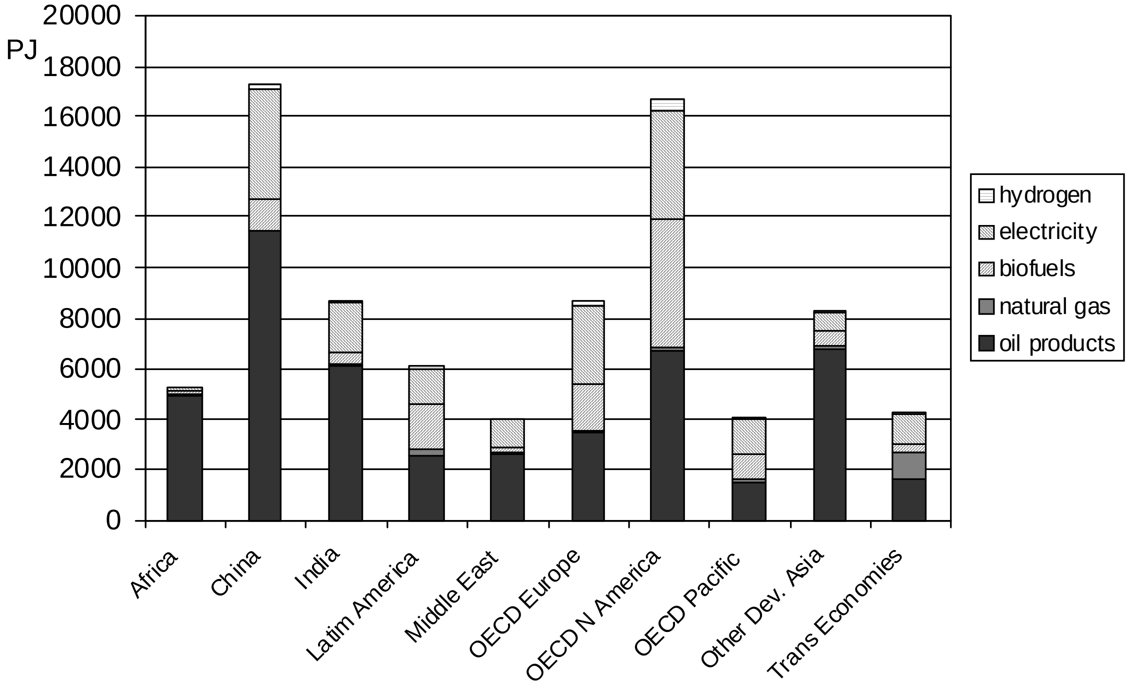


Figure 6: Transport energy demand by fuel and region in 2050 in the Energy [R]evolution Scenario

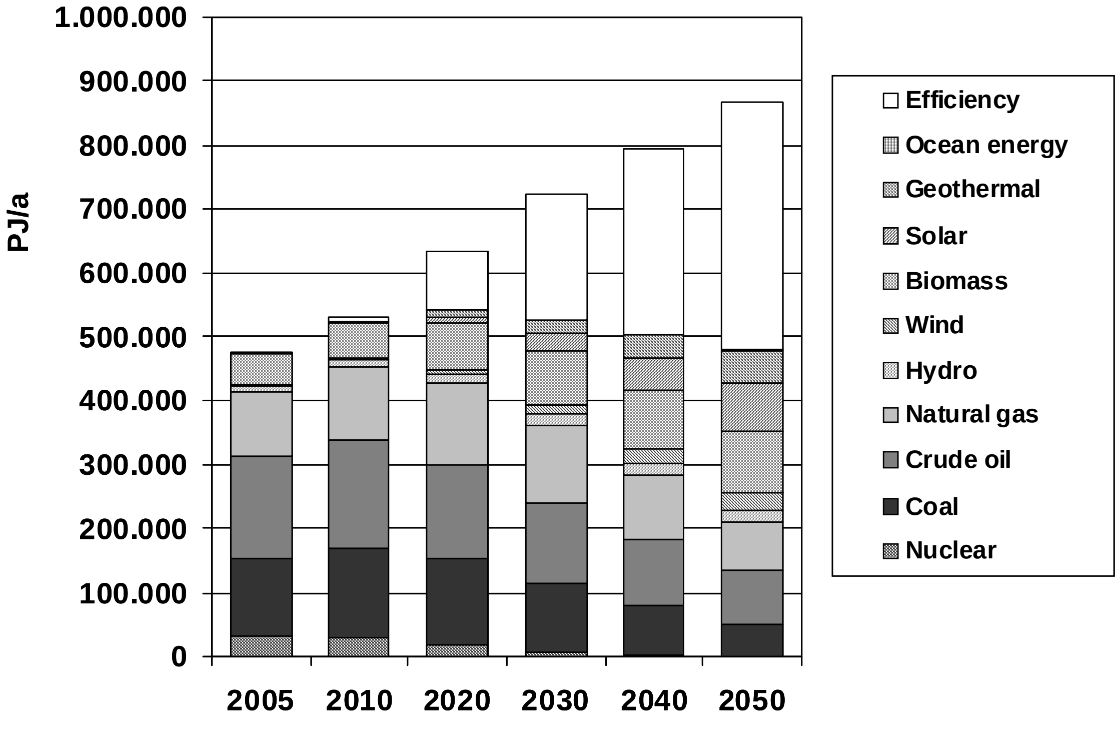


Figure 7: Development of global primary energy supply in the Energy [R]evolution scenario ('efficiency': savings compared to Reference scenario)

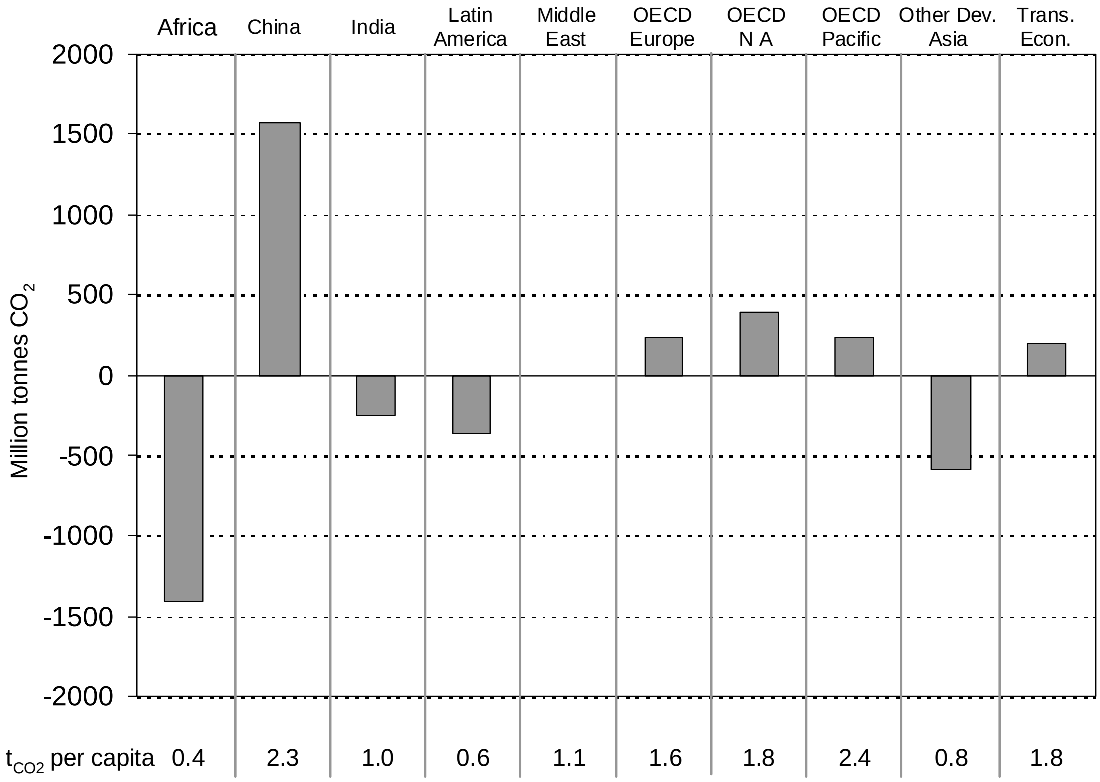


Figure 8: '$CO_2$ balance' between world regions in 2050 in the Energy Revolution scenario (based on average per capita emission rights of 1.15 $t_{CO2}$ per capita per year)

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