This document is one of four non-technical summaries prepared in the context of an analysis of the multiples benefits of measures to improve energy efficiency. The document has been written by Cecilie Larsen, on the basis of a technical report entitled "Impact of Energy Efficiency Measures on Greenhouse Gas Emission Reduction", prepared by ECN, a research institution. All reports are available for download from http://www.unepdtu.org/

Impacts of Energy Efficiency Measures on Greenhouse Gas Emission Reduction

Introduction

Mitigating climate change requires a shift from traditional carbon-intensive energy transformation towards a lower-carbon energy system. One option to reduce greenhouse gas emissions is to provide energy services at reduced fossil fuel intensity by using technology with improved energy conversion efficiency and by implementing energy saving measures. Limited knowledge exists about the role that energy efficiency improvements can play in a future carbon-constrained world. There is growing demand among interest groups for quantitative assessment of the scope for, and impacts associated with, energy efficiency gains. This study aims to address that need with a dedicated analysis of climate policy induced greenhouse gas (GHG) emission reductions resulting from energy efficiency improvements. This is done on a global level and for G20 member countries in particular.

For this analysis a model-based approach has been chosen by using three global energy models, namely TIAM-ECN (run by the Energy research Centre of the Netherlands, ECN), POLES (run by ENERDATA) and the energy-econometric model E3ME (run by Cambridge Econometric). In this report the TIAM-ECN model has been used for a multiple scenario analysis in which three carbon tax scenarios are assessed against a business as usual scenario.

The TIAM-ECN model

For the purpose of this project we apply TIAM-ECN which is the TIMES Integrated Assessment Model of the Energy research Centre of the Netherlands, used for long-term energy systems and climate policy analysis. TIAM-ECN has a global scope with a world energy system disaggregated in 20 distinct regions with 10 of the G20 members being represented as separate regions in the model.

TIAM-ECN is a linear economic optimisation model, based on energy system cost minimisation with perfect foresight until 2100. It simulates the development of the global energy economy over time, from resource extraction to consumption of final energy, to satisfy demand for useful energy. As any energy systems model, TIAM-ECN can analyse greenhouse gas reduction pathways over the entire energy supply chain, up to end-use energy demand. In this way, horizontal and vertical interdependencies and substitution effects of the energy supply can be incorporated in the analysis. Besides this integrated approach, TIAM-ECN features peculiarities of energy extraction, conversion and demand, like available fossil and renewable resources, potentials of storage of CO_2 and region specific demand developments.

TIAM-ECN is operated with a comprehensive technology database that includes many possible fuel transformation and energy supply pathways, and encompasses technologies based on fossil, nuclear and renewable energy resources. Both currently applied technologies and future advanced technologies are available in the model’s technology portfolio. With regard to climate change mitigation measures, the model covers reduction options for the three main greenhouse gases, namely carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), for both energy and non-energy related emission sources. TIAM-ECN also covers emissions from land use, land-use change and forestry.

Methodology

Energy efficiency measures in the TIAM-ECN model

The model structure of TIAM-ECN includes several measures and technologies that effectively represent reductions in the energy intensity of fuel transformation (including both the supply and demand sides). These include more efficient technologies for transport, for energy conversion (in the residential and commercial sectors), for industrial applications and for power plants. The model also takes into account energy savings in the demand sectors.

Due to the bottom-up model approach, energy efficiency measures are represented as separate processes in the model, with different fuel conversion efficiencies and corresponding costs.

Energy efficiency measures for *road transport* are divided into technologies for private motor vehicles and for diesel trucks. Specifically, the model contains five steps for energy efficiency improvements for gasoline cars and diesel trucks and six steps for diesel cars.

For the *residential and commercial sector* TIAM-ECN distinguishes among different types of end-use energy – in other words, to satisfy end-use demand the model can choose between different technologies, including different levels of energy intensity and different fuels. Also considered in the model is a reduction in end-use demand.

In TIAM-ECN, the *industry sector* consists of seven sub-sectors, namely iron and steel, chemicals, non-metallic minerals, non-ferrous metals, pulp and paper, other industries, and energy consumption for non-energy use (mainly feedstock for chemical industry). The model’s technology database contains both standard technologies to cover the industrial demand but also advanced technologies with higher fuel conversion efficiencies (and also including carbon dioxide capture and storage, CCS).

For electricity generation, TIAM-ECN’s technology repository contains several power plant technologies for renewable, fossil and nuclear energy conversion. For instance, with regards to coal-based power production, the model distinguishes among technologies with atmospheric circulating fluidised-bed combustion (standard and advanced technology), pressurised fluidised-bed combustion, oxygen-blown combustion and integrated gasification combined cycle. These technologies are characterised by different power plant parameters, including different net efficiencies. Also for natural gas, fuel oil, waste and biomass, technologies with different energy conversion efficiencies are implemented in the model. In addition to pure electricity generation technology, the model contains the option of cogeneration of electricity and heat for public and industrial purposes. Co-generation units typically operate at higher net efficiencies compared to the separated production of heat and electricity and, hence, represent an energy efficiency improvement option for public utilities and industry.

Scenario definitions and related assumptions

In this project four scenarios have been analysed: a business as usual (BAU) scenario and three carbon tax scenarios (40, 70 and 100 US$/t$CO_2$e in 2030). For 2020 the carbon tax is assumed to be one third of the tax in 2030 and for the periods past 2030 the tax is assumed to remain at the level of 2030. The carbon tax is applied to all GHG emissions, independent of their origin (combustion, land-use, industrial processes). Apart from the carbon tax no further climate change mitigation policies or support schemes for low-carbon technologies are assumed for the future, unless they were in place before 2010.

Key parameters, such as global GDP development, population, power plant parameters and assumptions of biomass availability, have been harmonised with the other energy systems model used in this study (POLES). Regional and sector-specific data on fuel consumption, GHG emissions, investments and prices of major fuels and emission certificates has been harmonised with the third model used in this study (E3ME).

With regards to storage capacity of CO_2, the TIAM-ECN model assumes a limit at 1660 $GtCO_2$. Approximately half of the storage potential is available in the Middle East and in the transition economies in Eastern Europe and the former Soviet Union, which results from their large hydrocarbon fields. Europe is expected to provide the largest biomass potentials with about 20 % of the global potential, followed by Africa with 17 % and China with around 13 %. (The reader is referred to Appendix 1 for more information on model input data.)

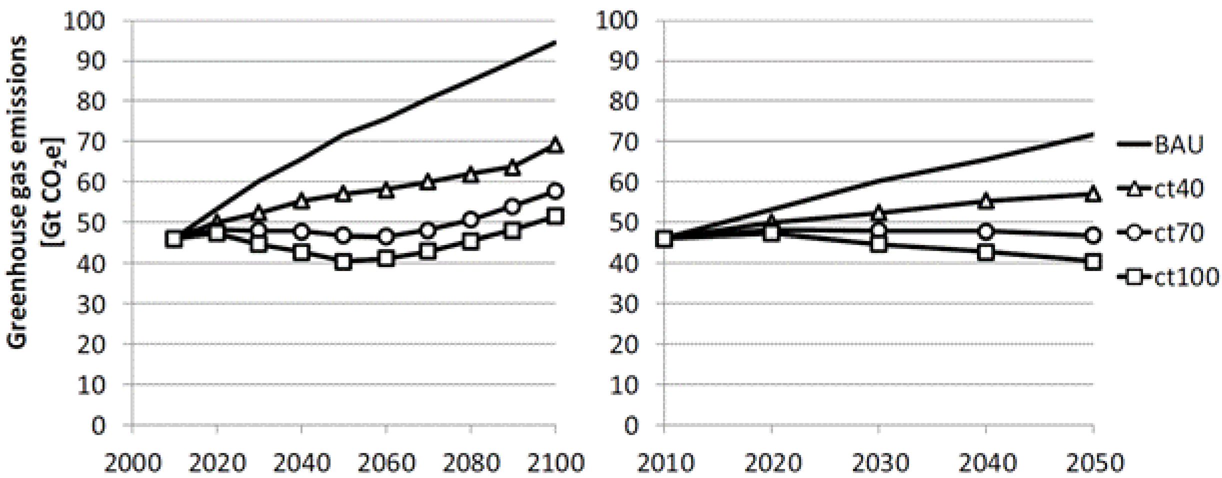
Results of the model-based analysis

In this analysis we use TIAM-ECN to project GHG emission reductions for each of the scenarios above, with the objective of understanding the potential impact of energy efficiency measures. Finally, we present a regional perspective of GHG emission reductions resulting from energy efficiency improvements.

Global GHG emissions by scenario

In the BAU scenario global GHG emissions increase to 60 $GtCO_2e$ in 2030, and further to 72 $GtCO_2e$ and 94 $GtCO_2e$ in 2050 and 2100, respectively (Figure 1). These trends are driven by assumed growth in population, steady economic activity, and dominance of hydrocarbons in the fuel mix. A tax on GHG emissions reduces cumulative GHG emissions through the century by 20 % in the 40 $ carbon tax scenario, by 30 % in the 70 $ tax scenario and by 36 % in the 100 $ carbon tax scenario (Figure 1).

Figure 1: Global GHG emissions in the BAU scenario and in the three carbon tax scenarios (2010-2100 and 2010-2050 projections)

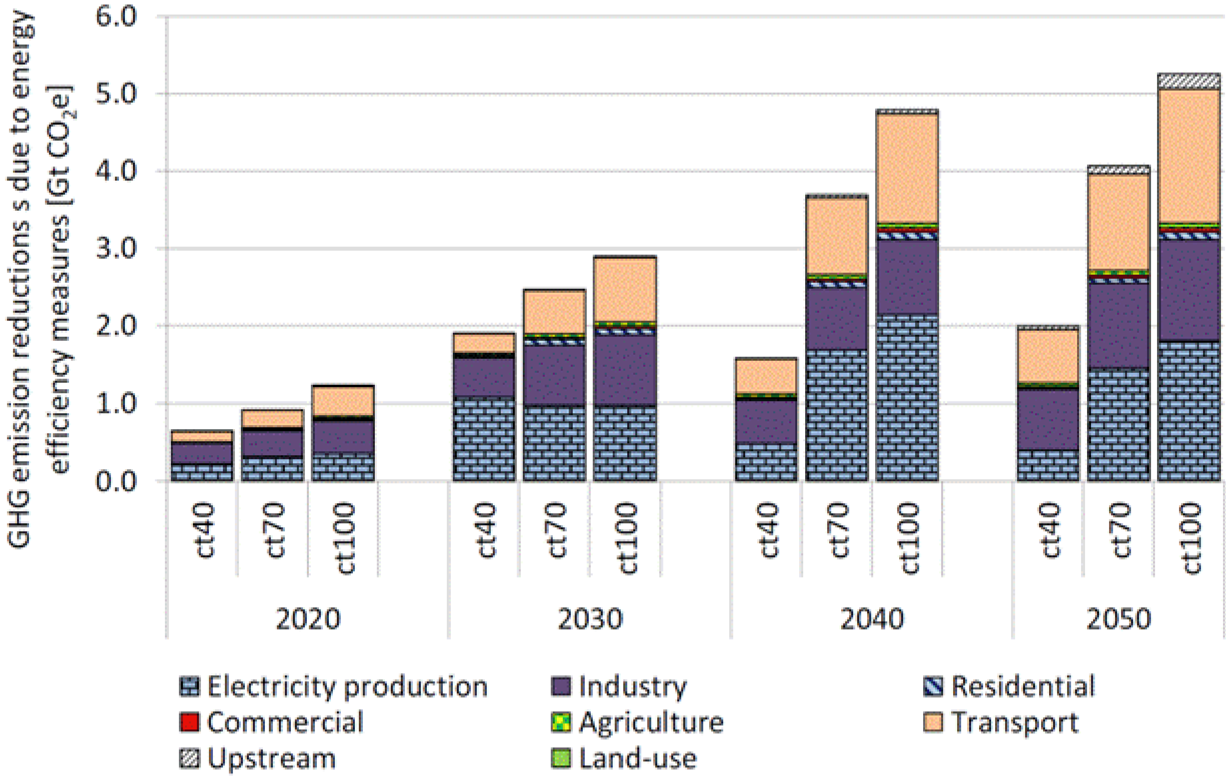


Compared to the cumulative reductions until 2100, carbon taxes are less effective in the short to medium-term (2020-2030) than in the longer term (2050), with worldwide relative reductions towards the BAU scenario between 13 % (in the 40 US$/t$CO_2$e scenario) and 26 % (in the 100 US$/t$CO_2$e scenario) in 2030. This corresponds to absolute GHG emission reductions from the BAU scenario between 8 and 16 GtCO_2e in 2030 and 15 and 31 GtCO_2 in 2050, with the electricity sector being responsible for about 60 % of the emission reductions. Besides the electricity sector, industry and upstream fuel supply contribute between 2030 and 2050 with 10 to 20 % each to the total GHG emission reduction when carbon taxes are introduced. The transport sector makes up for about 5-10 % of the total emission reductions in the period to 2050. Compared to emission reductions from energy supply and in the industry and transport sectors, contributions from the residential and commercial sector appear very limited.

Sector specific impacts from energy efficiency measures

Energy efficiency measures are responsible for 15-25 % of the total global GHG emission reductions until 2050, with a tendency to have a higher contribution in the near- and mid-terms (2020-2030) than in the long-run (2050). In the 40 $ carbon tax scenario 22 % of the total GHG emission reductions in 2030 are realised via energy efficiency measures. With increasing tax levels this share declines to about 20 % under the 70 $ and 100 $ carbon tax levels. By 2030, and compared to the BAU scenario, improvements in energy efficiency could offset about 2 GtCO_2e for a price of carbon of 40 $ per ton of CO_2 and up to 3 GtCO_2e under a 100 $ carbon tax scheme. By 2030 emission reductions attributable to energy efficiency resulting from a 40 $ carbon tax are limited until 2050, whereas under a 100 $ carbon tax regime emission reductions due to energy efficiency increase from 2030 by 80 %, to reach more than 5 GtCO_2e in 2050 (Figure 2). Most of the GHG emission reduction potential attributable to energy efficiency occurs in the electricity, industry and transport sectors.

Figure 2: Global GHG emission reductions in the carbon tax scenarios (ct40, ct70, ct100) compared to the BAU scenario due to energy efficiency measures



Until 2030 the electricity sector has the largest potential, with about 8-9 $GtCO_2e$ in all carbon tax scenarios, which corresponds to roughly 1 $GtCO_2e$ avoided worldwide in 2030.

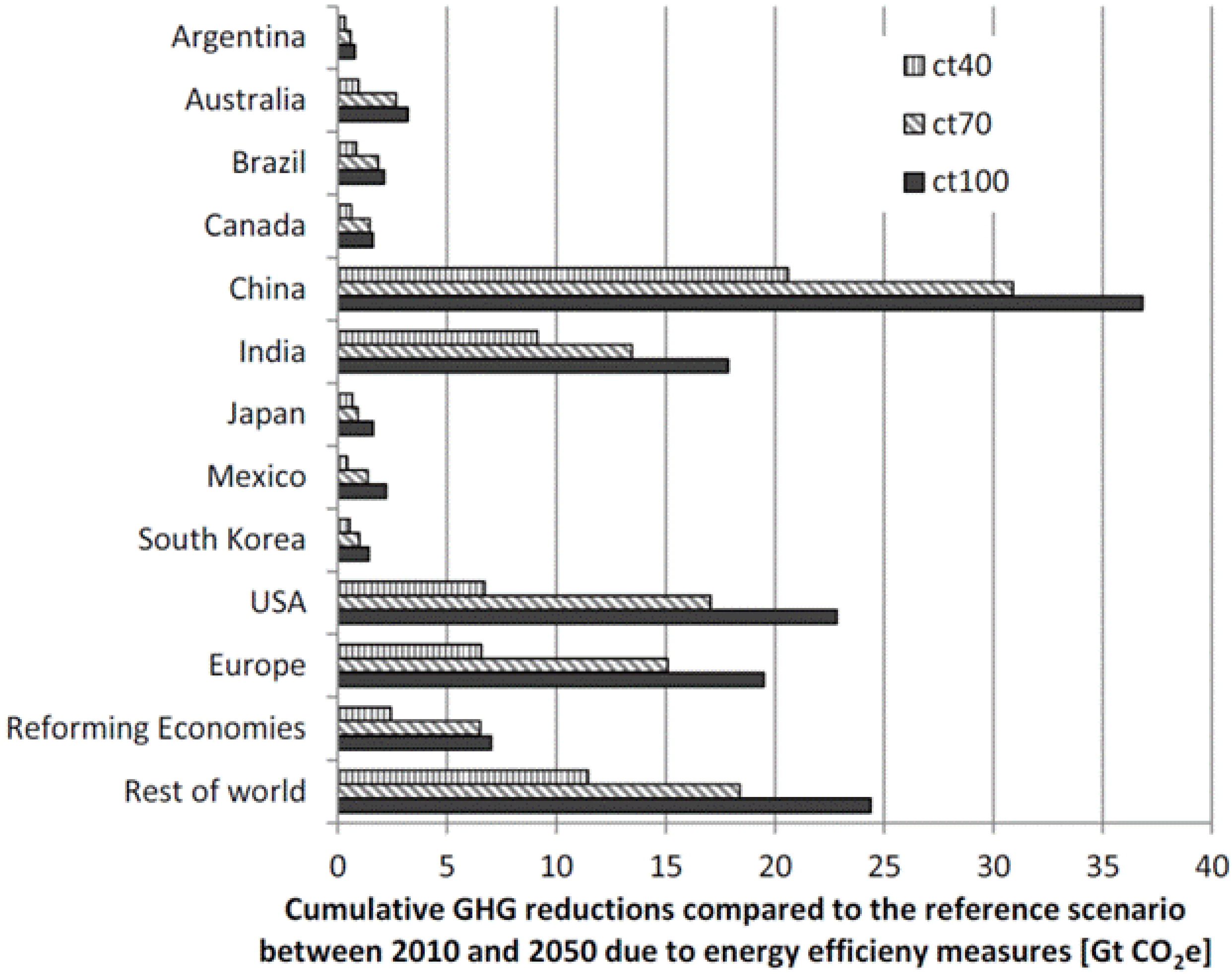
In the period from 2015 to 2030, and compared to a baseline, cumulative GHG emission reductions in the industry sector attributable to energy efficiency measures amount to about 5 $GtCO_2e$ in the 40 $ carbon tax scenario and almost 9 $GtCO_2e$ in the 100 $ carbon tax scenario. Iron and steel and non-metallic minerals (mainly, cement production) account for the bulk of these reductions.

In the period from 2015 to 2030, and compared to the BAU scenario, cumulative GHG emission reductions in the transport sector attributable to energy efficiency measures amount to about 3 $GtCO_2e$ under a 40 $ carbon tax scenario and up to 8 $GtCO_2e$ under a 100 $ carbon tax. Improvements of the energy efficiency of road transport technology (mainly, buses and trucks) show the highest sensitivity to carbon taxes.

Regional impacts of measures to improve energy efficiency

China, India and the USA offer prime opportunities for GHG emission reductions resulting from improvements in energy efficiency. The potential is largest in China, with around 25-35 % of the cumulative global reduction potential until 2050, followed by India, the USA and Europe, with 10-16 % each. A comparison of a measure of the potential by region across the three carbon tax scenarios reveals that emerging economies, such as China and India, offer a highest energy efficiency-based mitigation potential under low carbon price policy (Figure 3). A key reason for this are the good opportunities in emerging countries to replace energy intensive fossil-fuel-based technologies with advanced technologies, in particular in the electricity and industry sectors.

Figure 3: Cumulative regional GHG emission reductions in the carbon tax scenarios (ct40, ct70, ct100) compared to the BAU scenario between 2010 and 2050 due to energy efficiency measures



The regional share of global emissions reductions (compared to a baseline) attributable to energy efficiency improvements changes across carbon tax scenarios (Table 1). In most regions this share is in the range of between 10 and 20 %, and none of the regions displayed in the table exceed 30 %. The shares of China and India are highest under a 40 $ carbon tax scheme and decrease with the increasing carbon tax (as a result of accelerating deployment of other GHG abatement options, such as renewable energy and CCS). For Europe and the USA the opposite trend can be observed, because in these regions renewable energy technologies are already competitive at lower carbon taxes (due to a higher electricity price level in these countries, compared to China and India). Because of this, and compared to renewable energy, energy efficiency improvements gain importance in European and the USA under increasing carbon taxes.

Table 1: Breakdown of regions according to the contribution of energy efficiency measures to total cumulative GHG emission reductions, by carbon tax scenario

	Share of emission reductions due to energy efficiency measures of total cumulative GHG emission reductions between 2010 and 2050				
Scenario	0 - 9 %	10 - 14 %	15 - 19 %	20 - 24 %	25 - 29 %
ct40	Ref. Econ.	Argentina Australia Brazil Canada Mexico South Korea USA	Japan Europe Rest of world		China India
ct70		Japan South Korea	Argentina Brazil Canada China Mexico USA Ref. Econ. Rest of world	Australia India	Europe
ct100		Brazil Canada South Korea Ref. Econ.	Argentina Japan Mexico Rest of world	Australia China India USA	Europe

N. B.: Ref. Econ. refers to Reforming Economies

Core findings

A general finding from the TIAM-ECN model, which is also supported by POLES, is that some energy efficiency measures, in particular in the energy demand sectors, result in net cost savings even in the absence of a carbon tax policy (because of the resulting fuel savings). Indeed, model results suggest that, even in the absence of a carbon tax, the overall energy intensity decreases significantly over time. This is because certain new (more efficient) technologies can be price competitive. Consequently, for these technologies, carbon taxes are a comparably weak driver for the realisation of energy efficiency measures.

In addition, the results from the TIAM-ECN model conclude that energy efficiency improvements in the energy supply sector contribute significantly to GHG emission reductions, specifically with regards to electricity and heat production. The industry sector offers additional substantial emission reduction opportunities through energy efficiency, notably in the cement sector.

Limitations of the analysis

TIAM-ECN might underestimate possible future GHG emission reductions associated with improvements in energy efficiency. This is partly due to the difficulty of separating the contribution of energy efficiency to emission reductions, compared to changes in the fuel mix or CCS. Increased technology detail in the model would reduce this shortcoming.

As a result, TIAM-ECN estimates of emission reduction potentials are lower than other estimates in the scientific literature. The difference is also due to TIAM-ECN projecting about 3 $GtCO_2$ of emission reductions to be economical without increased carbon prices (that is, these emission reductions are part of the baselines scenario in TIAM-ECN).

In TIAM-ECN the industry sector is broken down in seven sub-sectors, containing different technology and fuel groups. While this allows for a reasonably detailed analysis of energy efficiency impacts, industry branches are often so heterogeneous that a finer breakdown would provide a more accurate description of the impact of energy efficiency measures in the industrial sector. Similarly, additional detail on the building sector would provide more accurate descriptions for the commercial and residential sectors.

Appendix 1: Input data for the TIAM-ECN model

Socio-economic development

On a global level a quadrupling of gross domestic product (GDP) from 67 tln US$ in 2010 to 295 tln US$ in 2050 and a further increase to 853 tln US$ in 2100 is assumed (Table 2).

World population is expected to grow rapidly in the first half of the century, to reach 9 bln persons in 2050, and to remain at this level until the end of the century (table 4). This population development mimics the medium fertility projections of the United Nations (UN-DESA 2013), and is characterised by the strong population growth in three of the main economies, namely Africa to 2.1 bln persons in 2050, India to 1.7 bln persons in 2050 and Other Asia to 1.4 bln persons in 2050. China's population is supposed to peak around 2025 with 1.4 bln persons and to decline afterwards down to 0.9 bln persons in 2100. The underlying population development of most of the countries of the Organisation for Economic Cooperation and Development (OECD) is rather stable with a total average increase of 0.1%/yr. for the period 2010 to 2100.

In comparison to population growth, the increase of the number of households is more pronounced, as a result of changing living patterns towards smaller household sizes. The total number of households amounts to almost 4 bln in 2050 and 4.4 bln in 2100 (table 6).

Table 2: Assumptions on the development of the GDP

billion $US\$_{2005}$	2010	2020	2030	2040	2050
Africa	2759	4988	7454	10515	14832
Argentina	580	819	1155	1522	2006
Australia	888	1125	1372	1639	1960
Brazil	1970	2501	3622	5486	8310
Canada	1202	1554	1932	2378	2927
Chile	248	378	523	703	944
China	9417	21058	41851	68041	96910
Colombia	393	599	828	1113	1496
Eastern Europe	1791	2519	3336	4143	5145
India	3763	7901	14016	22400	35798
Japan	3897	4750	5678	6720	7954
Mexico	1411	2029	2754	3630	4784
Middle East	3382	6114	9137	12889	18181
Other Developing Asia	3706	6211	8762	12722	18473
Other Latin America	938	1429	1978	2658	3572
Reforming Economies	2952	4412	6105	7739	9810
South Korea	1321	1674	2041	2440	2916
USA	13085	16913	21025	25882	31861
Venezuela	316	481	666	895	1203
Western Europe	12736	15526	18558	21965	25998
World	66755	102981	152792	215480	295082

Based on IEA (2012), World Bank (2013) and Kejun (2014)

Table 3: Average annual GDP growth

%/yr	2005 –2010	2010 –2020	2020 –2030	2030 –2040	2040 –2050
Africa	5.2	6.1	4.1	3.5	3.5
Argentina	6.8	3.5	3.5	2.8	2.8
Australia	2.8	2.4	2.0	1.8	1.8
Brazil	4.6	2.4	3.8	4.2	4.2
Canada	1.2	2.6	2.2	2.1	2.1
Chile	3.5	4.3	3.3	3.0	3.0
China	10.9	8.4	7.1	5.0	3.6
Colombia	4.6	4.3	3.3	3.0	3.0
Eastern Europe	3.2	3.5	2.9	2.2	2.2
India	8.3	7.7	5.9	4.8	4.8
Japan	0.2	2.0	1.8	1.7	1.7
Mexico	1.7	3.7	3.1	2.8	2.8
Middle East	3.4	6.1	4.1	3.5	3.5
Other Developing Asia	5.4	5.3	3.5	3.8	3.8
Other Latin America	4.2	4.3	3.3	3.0	3.0
Reforming Economies	3.9	4.1	3.3	2.4	2.4
South Korea	3.7	2.4	2.0	1.8	1.8
USA	0.8	2.6	2.2	2.1	2.1
Venezuela	3.7	4.3	3.3	3.0	3.0
Western Europe	0.8	2.0	1.8	1.7	1.7
World	3.4	4.4	4.0	3.5	3.2

Table 4: Assumptions on the development of the population

million inhabitants	2010	2020	2030	2040	2050
Africa	1031	1312	1634	1999	2393
Argentina	40	44	47	49	51
Australia	27	30	34	37	40
Brazil	195	211	223	229	231
Canada	34	38	41	43	45
Chile	17	19	20	21	21
China	1367	1440	1461	1444	1393
Colombia	46	52	57	61	63
Eastern Europe	120	119	116	110	105
India	1206	1353	1476	1566	1620
Japan	127	125	121	115	108
Mexico	118	132	144	152	156
Middle East	289	341	386	424	455
Other Developing Asia	1059	1193	1309	1395	1449
Other Latin America	150	170	189	205	217
Reforming Economies	287	289	285	279	273
South Korea	48	51	52	52	51
USA	312	338	363	383	401
Venezuela	29	33	37	40	42
Western Europe	412	424	431	435	436
World	6916	7717	8425	9039	9551

Based on UNPD (2013)

Table 5: Average annual population growth

%/yr	2005 –2010	2010 –2020	2020 –2030	2030 –2040	2040 –2050
Africa	2.5	2.4	2.2	2.0	1.8
Argentina	0.8	0.8	0.7	0.5	0.3
Australia	1.7	1.2	1.0	0.9	0.8
Brazil	1.0	0.8	0.5	0.3	0.1
Canada	1.2	1.0	0.8	0.6	0.5
Chile	1.0	0.8	0.6	0.4	0.1
China	0.6	0.5	0.1	-0.1	-0.4
Colombia	1.6	1.2	0.9	0.6	0.4
Eastern Europe	0.0	-0.1	-0.3	-0.4	-0.5
India	1.4	1.2	0.9	0.6	0.3
Japan	0.0	-0.2	-0.4	-0.5	-0.6
Mexico	1.2	1.1	0.9	0.6	0.3
Middle East	2.3	1.7	1.2	1.0	0.7
Other Developing Asia	1.4	1.2	0.9	0.6	0.4
Other Latin America	1.4	1.3	1.1	0.8	0.6
Reforming Economies	0.2	0.1	-0.1	-0.2	-0.2
South Korea	0.6	0.5	0.3	0.0	-0.2
USA	1.0	0.8	0.7	0.6	0.5
Venezuela	1.7	1.4	1.1	0.8	0.5
Western Europe	0.6	0.3	0.2	0.1	0.0
World	1.2	1.1	0.9	0.7	0.6

Table 6: Assumptions on the development of the number of households

million households	2010	2020	2030	2040	2050
Africa	233	344	511	698	945
Argentina	12	15	19	23	28
Australia	10	13	16	17	19
Brazil	57	65	68	74	73
Canada	14	17	20	22	23
Chile	5	6	8	10	12
China	386	472	571	628	683
Colombia	12	15	18	21	21
Eastern Europe	42	45	49	51	54
India	272	355	462	547	640
Japan	67	70	71	70	68
Mexico	29	38	48	57	67
Middle East	59	80	106	131	160
Other Developing Asia	217	284	372	443	520
Other Latin America	46	60	77	91	105
Reforming Economies	82	91	99	106	115
South Korea	11	14	17	19	21
USA	119	141	167	181	194
Venezuela	8	10	12	14	14
Western Europe	189	214	241	247	252
World	1871	2347	2952	3448	4015

Table 7: Average annual growth of the number of households

%/yr	2005 –2010	2010 –2020	2020 –2030	2030 –2040	2040 –2050
Africa	5.2	4.0	4.0	3.2	3.1
Argentina	6.8	2.1	2.1	2.1	2.1
Australia	2.8	2.1	2.0	1.1	1.0
Brazil	4.6	1.2	0.5	0.8	-0.1
Canada	1.2	1.8	1.7	0.7	0.6
Chile	3.5	2.1	2.1	2.0	1.9
China	10.9	2.0	1.9	0.9	0.8
Colombia	4.6	2.1	1.8	1.4	0.3
Eastern Europe	3.2	0.8	0.8	0.5	0.5
India	8.3	2.7	2.7	1.7	1.6
Japan	0.2	0.4	0.2	-0.2	-0.2
Mexico	1.7	2.5	2.4	1.7	1.6
Middle East	3.4	3.1	2.9	2.1	2.0
Other Developing Asia	5.4	2.7	2.7	1.8	1.6
Other Latin America	4.2	2.6	2.6	1.6	1.5
Reforming Economies	3.9	1.0	0.9	0.7	0.8
South Korea	3.7	2.0	2.1	1.1	1.0
USA	0.8	1.7	1.7	0.8	0.7
Venezuela	3.7	2.3	2.0	1.6	0.5
Western Europe	0.8	1.2	1.2	0.3	0.2
World	3.4	2.3	2.3	1.6	1.5

Technology development

Key parameters for selected electricity generation technologies are displayed in table 8 (renewable energy-fuelled generation) and table 9 (fossil- and nuclear energy-fuelled generation). The values used are based on IEA (2014) and ECN's own assessments. The values given in the tables correspond to average European circumstances. The corresponding values for other model regions are not shown.

Table 8: Parameters of selected power plant technologies based on renewable energy

Technology parameter	2010	2020	2030	2050
Hydro power impoundment (medium)				
Invest costs ($US\$_{2005}$/kW)	3500	3410	3330	3150
Fixed O+M costs ($US\$_{2005}$/kW)	35	34	33	32
Variable O+M costs ($US\$_{2005}$/kW)	0.3	0.3	0.3	0.3
Net efficiency (%)	100	100	100	100
Lifetime (years)	80	80	80	80
Average annual availability (hours)	2600	2600	2600	2600
LCOE ($US\$_{2005}$/MWh)	150	146	143	135
Solar photovoltaic				
Invest costs ($US\$_{2005}$/kW)	3180	1960	1610	1260
Fixed O+M costs ($US\$_{2005}$/kW)	10	10	10	10
Variable O+M costs ($US\$_{2005}$/kW)	0.0	0.0	0.0	0.0
Net efficiency (%)	100	100	100	100
Lifetime (years)	20	20	20	20
Average annual availability (hours)	1600	1600	1600	1600
LCOE ($US\$_{2005}$/MWh)	240	150	125	99
Concentrated solar power with storage for base load operation				
Invest costs ($US\$_{2005}$/kW)	10140	6080	4870	4870
Fixed O+M costs ($US\$_{2005}$/kW)	299	179	143	143
Variable O+M costs ($US\$_{2005}$/kW)	0.0	0.0	0.0	0.0
Net efficiency (%)	100	100	100	100
Lifetime (years)	30	30	30	30
Average annual availability (hours)	6100	6100	6100	6100
LCOE ($US\$_{2005}$/MWh)	223	134	107	107
Wind onshore				
Invest costs ($US\$_{2005}$/kW)	1350	1320	1300	1200
Fixed O+M costs ($US\$_{2005}$/kW)	26	24	23	20
Variable O+M costs ($US\$_{2005}$/kW)	0.0	0.0	0.0	0.0
Net efficiency (%)	100	100	100	100
Lifetime (years)	25	25	25	25
Average annual availability (hours)	2200	2200	2200	2200
LCOE ($US\$_{2005}$/MWh)	79	77	75	69
Wind offshore				
Invest costs ($US\$_{2005}$/kW)	3900	2900	2630	2100
Fixed O+M costs ($US\$_{2005}$/kW)	75	69	63	50
Variable O+M costs ($US\$_{2005}$/kW)	0.0	0.0	0.0	0.0
Net efficiency (%)	100	100	100	100
Lifetime (years)	20	20	20	20
Average annual availability (hours)	3800	3800	3800	3800
LCOE ($US\$_{2005}$/MWh)	140	107	97	78

Table 9: Parameter of selected power plant technologies for fossil and nuclear fuels

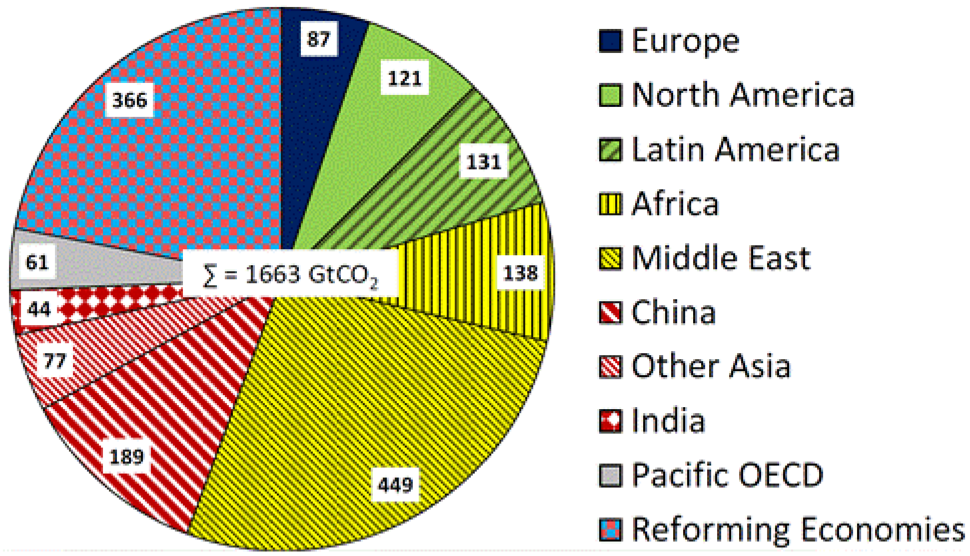
Technology parameter	2010	2020	2030	2050
Hard coal: advanced atmospheric fluidized bed technology				
Invest costs ($US\$_{2005}$/kW)	1750	1750	1750	1750
Fixed O+M costs ($US\$_{2005}$/kW)	53	53	53	53
Variable O+M costs ($US\$_{2005}$/kW)	0.2	0.2	0.2	0.2
Net efficiency (%)	43	43	43	43
CO_2 capture rate (%)	0	0	0	0
Lifetime (years)	40	40	40	40
Average annual availability (hours)	7900	7900	7900	7900
CO_2 emission factor (kg/MWh)	787	787	787	787
LCOE ($US\$_{2005}$/MWh)	64	64	64	64
Hard coal: pulerized coal incl. post combustion CO_2 capture				
Invest costs ($US\$_{2005}$/kW)		3150	2520	2520
Fixed O+M costs ($US\$_{2005}$/kW)		95	77	77
Variable O+M costs ($US\$_{2005}$/kW)		0.2	0.2	0.2
Net efficiency (%)		34	35	35
CO_2 capture rate (%)		85	85	85
Lifetime (years)		30	30	30
Average annual availability (hours)		7900	7900	7900
CO_2 emission factor (kg/MWh)		149	145	145
LCOE ($US\$_{2005}$/MWh)		102	90	90
Natural gas combined cycle				
Invest costs ($US\$_{2005}$/kW)	880	880	880	880
Fixed O+M costs ($US\$_{2005}$/kW)	22	22	22	22
Variable O+M costs ($US\$_{2005}$/kW)	0.1	0.1	0.1	0.1
Net efficiency (%)	60	61	63	63
CO_2 capture rate (%)	0	0	0	0
Lifetime (years)	35	35	35	35
Average annual availability (hours)	7900	7900	7900	7900
CO_2 emission factor (kg/MWh)	456	449	438	438
LCOE ($US\$_{2005}$/MWh)	81	80	78	78
Natural gas combined cycle with fue gas CO_2 capture				
Invest costs ($US\$_{2005}$/kW)		1580	1390	1390
Fixed O+M costs ($US\$_{2005}$/kW)		39	34	34
Variable O+M costs ($US\$_{2005}$/kW)		0.2	0.2	0.2
Net efficiency (%)		53	56	56
CO_2 capture rate (%)		85	85	85
Lifetime (years)		30	30	30
Average annual availability (hours)		7900	7900	7900
CO_2 emission factor (kg/MWh)		57	54	54
LCOE ($US\$_{2005}$/MWh)		84	79	79
Nuclear advanced technology (EPR)				
Invest costs ($US\$_{2005}$/kW)	5780	5430	4380	4380
Fixed O+M costs ($US\$_{2005}$/kW)	173	163	131	131
Variable O+M costs ($US\$_{2005}$/kW)	0.4	0.4	0.4	0.4
Net efficiency (%)	100	100	100	100
Lifetime (years)	60	60	60	60
Average annual availability (hours)	7900	7900	7900	7900
LCOE ($US\$_{2005}$/MWh)	107	101	82	82

Regional input data

TIAM-ECN limits the total storage capacity of captured CO_2 to 1660 $GtCO_2$ (Hendriks *et al.* 2004), with about half of the storage potential coming from the Middle East and in transition economies in Eastern Europe. We assume significant shares of these formations to be available for CO_2 storage in future, either by applying enhanced oil and gas recovery technology or CO_2 storage in depleted oil and gas fields. In the model we also assume an inter-regional transport of liquid CO_2, which means that CO_2 can be stored not only in the region where it is captured, but also in regions where storage potential may be more abundant.

The global potential of various types of biomass amounts to about 110 EJ in 2050 and 150 EJ in 2100, which reflects our judgement that limited biomass may be available when sustainability criteria are accounted for, and food price concerns are taken into account (Hoogwijk *et al.* 2009, IIASA 2012). Eastern and Western Europe is expected to provide the largest biomass potentials, with about 20 % share of the global total, followed by Africa, with 17 %, and China, with around 13 %. The model allows for trade of biomass among regions, which refers to both solid biomass and biofuels.

Figure 4: CO2 storage potential by World regions



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