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Roadmap to Deploying Technologies for Sustainable Development

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Contents

Abstract

The study found that a radical transition to energy systems based on renewable and fuel cells is plausible if one takes a long time span (over 100 years). The resulting global energy system would contribute to achieving sustainable development. The potential of advanced technologies for CO_2 emission mitigation and energy conservation is enormous in all end-use sectors. In particular, contribution of advanced transportation technologies is significant and reliance on oil in that sector reduces from current level of 97% to 8%.

The study suggests that, if successful, technology policies could lead to a path towards sustainable development that does not deteriorate life style and, generally, is consistent with ever-increasing economic prosperity, i.e., allows more cars, permits the world population to travel more and more, lets everyone enjoy high-quality energy service. We illustrate that such a future is possible and achievable, provided an appropriate targeted policy effort is made.

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Leo Schrattenholzer has been affiliated with IIASA since 1973, after graduating from the Technical University of Vienna in mathematics. He received his Ph.D. in energy economics in 1979, also from the Technical University of Vienna. His Ph.D. thesis was on modeling long-term energy supply strategies for Austria. Presently he is Leader of IIASA's ECS Program. The focus of his present work is the application of large-scale energy-economy-environment models for the formulation of long-term global scenarios. Since 1981 Dr. Schrattenholzer has served as one of two co-directors of an international network of energy analysts, the International Energy Workshop (IEW), a joint venture between IIASA and Stanford University, USA. He was also Lead Author of IPCC's Second Assessment Report.

Roadmap to deploying technologies for sustainable development

1 Introduction

The objective of this study was to analyze the potential of technologies using renewable sources to contribute to achieving sustainable development (SD) of the global energy system. We did the analysis on the basis of a global long-term Energy-Economy-Environment (3E) scenario that was developed at IIASA.

In the past reports to the Collaboration project, we illustrated that the choice of technologies can be the key to achieving a gradual transformation to an environmentally sustainable world. An energy system based on renewable energy sources is regarded as an advantageous option for delivering high-quality energy services while minimizing environmental impact, both in terms of consumption of natural resources and of pollutant emissions – including greenhouse gases (GHGs) as well as other hazardous particles. Renewable primary energy sources such as wind and solar power have already found wide acceptance as a means to achieve CO_2 emission reductions as well as to increase energy security by reducing the reliance on the fossil fuels.

The advantage of using renewable energy sources is enhanced by the deployment of hydrogen-fueled energy technologies. Hydrogen can be produced from a variety of fossil and non-fossil primary energy carriers. This flexibility on the primary-energy side can lead to a faster penetration of hydrogen can than what would be possible if hydrogen production would have to rely on renewable energy alone. Over time, the share of renewables in hydrogen production can then be increased further and further, thus facilitating the transition to a sustainable energy system based on renewable resources. This is so because hydrogen can be used in a variety of applications in an efficient and clean manner. It can provide an ideal complement to electricity, with the advantage of its storability (Barreto *et al.*, 2003).

Renewable resources combined with hydrogen technology have a strategic importance in the pursuit of a low-emission, environmentally benign, and sustainable energy system. In the more distant future, renewable resources and hydrogen could become important energy commodities at the global level. Achieving this goal, however, will require significant cost and performance improvements of the according technologies. Only a successful combination of research, development, and demonstration (RD&D) efforts, as well as commercial deployment would lead to the necessary technology improvements and cost reductions. Intensive R&D efforts are still required in a number of areas and policy support for the deployment of the renewable energy sources is essential (Barreto, *et al.*, 2003).

The transformation of the global energy system from its current structure to one that is compatible with the strategic goal of sustainable development and that includes a maximum use of renewable energy is a long-term process involving gradual change of energy supply infrastructure. One concrete path of such a transformation is illustrated with a long-term (until 2100) E3 (energy-economy-environment) scenario formulated with an engineering ("bottom-up") model called MESSAGE, developed by IIASA-ECS (Messner and Strubegger, 1995). MESSAGE has been used to formulate possible technological choices for a global energy system under different assumptions on possible geopolitical, economic, and technologic developments. The scenario that is analyzed in depth and extensively interpreted in this report is the SRES-A1T scenario developed at IIASA, one of the 40 “background” scenarios of overall demographic, economic technological development drawing on the Special Report on Emissions Scenarios (SRES, Nakićenović *et al.*, 2000) by the Intergovernmental Panel on Climate Change (IPCC), which assessed the uncertainties on future GHG emissions in absence of climate policies.

The SRES-A1T scenario describes the development of the global energy system in a world with high income growth, significant income disparity reduction, and with a maximum deployment of renewable energy sources. The A1T scenario belongs to the so-called A1 family, in which all family members are characterized by vigorous economic growth and economic convergence among world regions, global population peaking in the middle of the 21st century and declining thereafter, and by the rapid introduction of new and more efficient energy conversion technologies. The A1 scenario family includes three – somewhat extreme – alternative directions of technological change in the energy system and a fourth, balanced, scenario. The three “technological” scenarios are an oil and gas-intensive (A1G), a clean-coal technology (A1C), and a renewables scenario (A1T). The balanced scenario is dubbed A1B (Riahi *et al.*, 2000).

In the past reports contributed to this Collaboration Project, we demonstrated the usefulness of analyzing such scenarios by describing two contrasting scenarios, A1T and A1G. The comparison was particularly instructive because these two scenarios illustrate that different technological developments lead one scenario (A1T) to sustainable development and the other (A1G) to non-sustainable development.

As we presented in our previous reports, we have used four criteria to distinguish sustainable-development and non-sustainable-development scenarios (Box 1). According to these criteria, the A1T scenario can be classified as a sustainable-development scenario, whereas the A1G scenario cannot. In this report, we continue describing the A1T scenario in more detail and interpreting its results further so as to demonstrate the technical potential of renewable-based technologies to achieve sustainable development. To better reflect this spirit, we call the A1T scenario as a Post Fossil (PF) scenario throughout the report.

It is important to note that the scenarios formulated by the MESSAGE model are characterized by a number of specific methodological features, described in the sequel, which need to be borne in mind when interpreting the study results.

The most important methodological feature is that MESSAGE is an optimization model, which minimizes total energy-related system cost while satisfying the given energy demand. Thus MESSAGE addresses a hypothetical global social planner, which makes our scenarios present normative views of the choice among energy technologies. In this sense, the energy system as illustrated by MESSAGE is interpreted as the result of a sequence of technological choices or strategies, not as the projection of the future technological development. It does not necessarily represent the decision-making mechanism regarding choice of technologies.

The model selects technologies from a given menu, which is an input to the model, to describe an energy system that has minimum system cost while maintaining an engineering consistency. In MESSAGE, technical, economic, and environmental parameters for over 400 technologies are specified explicitly. Engineering consistency of the global energy system is assured in terms of the reference energy systems, which describes possible combinations of

Box 1: The IIASA-ECS definition of sustainable development scenarios

Sustainable development (SD) is a widely accepted principle in the design of long-term energy-economy-environment (E3) strategies. Despite a broad consensus on the general idea of sustainability, varying degrees of agreement exist on specifics, in particular on trade-offs between incommensurable objectives.

In an effort to perhaps contribute one step to a possible future consensus building in the field of sustainable development, IIASA-ECS has proposed a working definition of sustainable-development E3 scenarios. This working definition consists of quantitative criteria, which can be used to classify existing long-term E3 scenarios, such as those calculated by IIASA-ECS's principal model, MESSAGE (Messner and Strubegger, 1995). The criteria cover economic and environmental sustainability as well as inter-general and intra-generational equity (Klaassen *et al.*, 2002). They do not cover some areas, such as biodiversity, desertification, ozone layer depletion, and others. The significance of the fact that our criteria have been designed to analyze existing scenarios is that doing so not only limits the scope of their applicability, but also means that they were not used as a basis for deriving SD scenarios in a deductive way.

More specifically, we define SD scenarios as those that meet the following four criteria.

(1) Economic growth (GDP/capita) is sustained throughout the time horizon of the scenario.

(2) Socioeconomic inequity among world regions, expressed as the world-regional differences of GDP (gross domestic product) per capita, is reduced significantly over the 21st century, in the sense that by 2100, the per-capita income ratios between all world regions are reduced to ratios close to those prevailing between OECD countries today.

(3) Long-term environmental stress is mitigated significantly. In particular, carbon emissions at the end of the century are approximately at or below today's emissions. Other GHG emissions may increase, but total radiative forcing, which determines global warming, is on a path to long-term stabilization. Other long-term environmental stress to be mitigated includes impacts on land use, e.g., desertification. Short- to medium-term environmental stress (e.g., acidification) may not exceed critical loads that threaten long-term habitat well being.

(4) The reserves-to-production (R/P) ratios of exhaustible primary energy carriers do not decrease substantially from today's levels.

technologies (so-called energy chains) from resource extraction, energy conversion, energy distribution, to the end use. Feasible energy chains are defined by constraints on resource endowments and energy supply infrastructures among others. In contrast, GDP, population growth, and energy demand are a-priori assumptions to the model, not its outcome. Uncertainties regarding the values of such assumptions are reflected by formulating different scenarios.

In connection to MESSAGE's "social planner" view, we should underline that a technological strategy such as the one illustrated with the PF scenario is not the *only* technological strategy suited to achieve sustainable development, although A1T is the only sustainable-development scenario out of four A1 scenarios formulated with MESSAGE. We can only say that with the very rapid economic growth assumed for the A1 scenario family, strategies aiming at fostering renewable technologies (described by A1T scenario) are consistent with sustainable development whereas neither clean-coal technologies nor oil and gas-intensive technologies (scenarios A1C and A1G) are consistent with it. As reported in the first working report to the first phase of the Collaboration Project (Riahi *et al.,* 2000), IIASA-ECS has produced also other sustainable-development scenarios relying on other technological options such as nuclear and/or natural gas[1].

This point is particularly important given that we address only one scenario at a time, thus compressing the uncertainty in a possibly unrealistic way. Without this caveat, our readers might be misled by the impression that we could regard the issue of uncertainty as not important. This is definitely not true. To substantiate this assertion, we refer to the IIASA-ECS contribution to the first phase of the Collaboration project. In the first working report (Riahi *et al., op. cit.*) we analyzed a larger set of scenarios and their uncertainty range. As to the robustness of the findings regarding the technological strategies presented in this report, we refer to the second working paper of the first Collaboration project (Roehrl *et al.,* 2000), which addresses this issue using the technology cluster approach. In this report, we briefly touch upon this issue in Section 2.

To emphasize the policy relevance of our study, we present the technological options illustrated by our PF scenario as a "technological road map to sustainable development", focusing on aggregate fuels on the supply side and specific technologies in the power generation sector. More precisely speaking, the research question IIASA-ECS addressed in the Collaboration project was: "Which energy technologies are most characteristic of Sustainable Development (SD) scenarios and should therefore be the target of increased R&D support?" This final report concludes our investigation into this research question by looking into each aggregated end-use sector (transportation, residential and commercial, and industry sector) separately.

Given this overall plan, the remainder of the report is organized as follows. After this introductory Section 1, assumptions that characterize the PF scenario are described in Section 2, together with the environmental implications of the PF scenario. Section 3 presents the technological strategies in the area of transportation technologies based on the PF scenario. It also provides detailed view on the future passenger automobile technologies. Section 4 and 5 present the technological strategies in the area of technologies for residential and commercial as well as for industry use. Section 6 addresses supply-side issues related to production of hydrogen, methanol, and ethanol. Section 7 concludes, highlighting policy implications of this study.

2 The Post-Fossil (PF) scenario and sustainable development

The Post-Fossil (PF) scenario describes a possible future world energy system where technological progress is concentrated on energy technologies converting renewable energy and producing synthetic fuels including hydrogen as well as on efficiency improvements of end-use technologies. The PF scenario illustrates the potential contribution of renewable energy sources to the global energy mixes in the 21st century if favorable conditions for its penetration were in place.

The PF scenario distinguishes 11 world regions each of which is characterized by different assumptions on economic growth, population growth and speed of its technological development. Table 1 presents the 11 world regions giving their short names and geographical definition. In addition to these 11 world regions, we use four "aggregated world regions" to show more aggregated view at some places in this report.

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[1] One example would be the IIASA-WEC-A3 scenario relying on natural gas and nuclear energy.

Table 1: The 11 regions defined in the MESSAGE model.

Regions		Main countries
OECD90 (OECD in 1990 regions)		
NAM	North America	Canada, USA
PAO	Pacific OECD	Australia, New Zealand, Japan
WEU	Western Europe	European Community (as in 2003) plus Norway, Switzerland, and Turkey
REF (Reforming regions)		
FSU	Former Soviet Union	Russia, Ukraine
EEU	Eastern Europe	Bulgaria, Hungary, Czech and Slovak Republics, Former Yugoslavia, Poland, Romania
ASIA (the developing Asia regions)		
CPA	Centrally Planned Asia	China, Mongolia, Vietnam
SAS	South Asia	Bangladesh, India, Pakistan
PAS	Other Pacific Asia	Indonesia, Malaysia, Philippines, Singapore, South Korea, Taiwan, Thailand
ALM (The rest of the world)		
LAM	Latin America	Argentina, Brazil, Chile, Mexico, Venezuela
MEA	Middle East & North Africa	Algeria, Gulf States, Egypt, Iran, Saudi Arabia
AFR	Sub-Saharan Africa	Kenya, Nigeria, South Africa, Zimbabwe

GDP is assumed to grow vigorously, an assumption that in our opinion is consistent with that of fast technological improvements (a world with high economic growth are likely to generates fast turn over of capital stock and massive R&D investments on advanced technologies are possible). For population growth, we used the assumptions given in IIASA population projections, Low Growth case (Lutz *et al*., 1996, 1997). We selected a low-growth case because also historically, higher economic growth was associated with lower population growth.

Numerical assumptions for GDP growth and population growth in the PF scenario are given below. Figure 1 shows the development of GDP for the 11 world regions of our study.

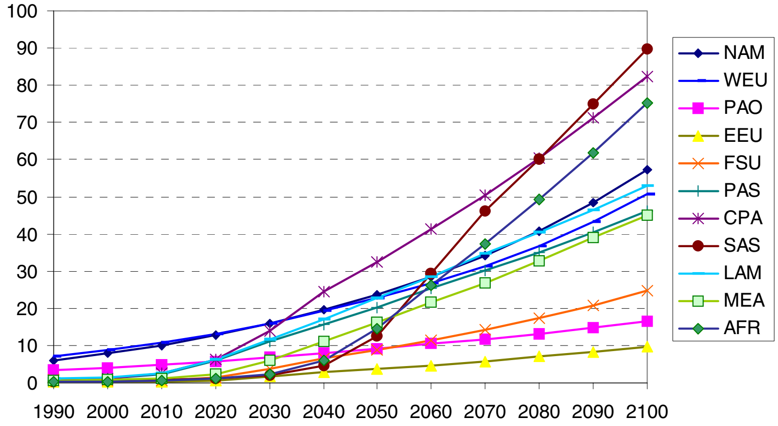

Figure 1: GDP assumptions used in the PF scenario, in trillion US1990 dollars.

Total global GDP was 21 trillion (10^{12}) US dollars in 1990, and the world-regional projections add up to a global total of 55 trillion in 2020, 190 trillion in 2050 and 550 trillion in 2100.

Figure 2 shows the development of population in the 11 world regions. These world-regional population numbers add up to a global total of 5.3 billion in 1990, 7.6 billion in 2020, a peak in 2050 at 8.7 billion and 7 billion by 2100.

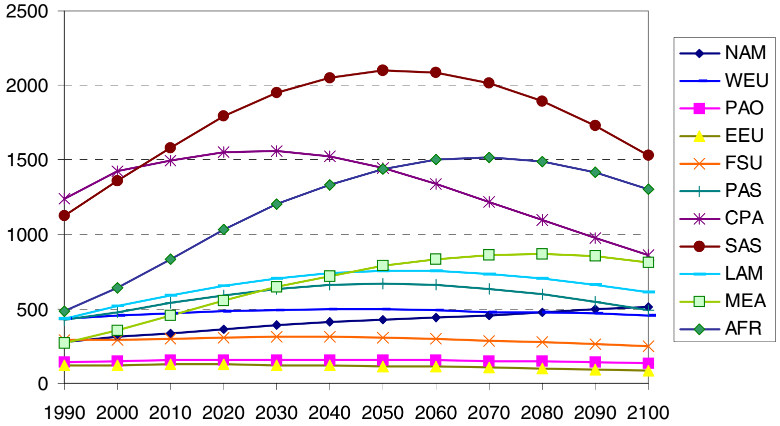

Figure 2: Population assumptions used in the PF scenario, in million people.

MESSAGE's main input assumptions are final-energy demands for the 11 world regions of the scenario. Total final-energy demand is divided into three end-use sectors. With the given final-energy demand, MESSAGE calculates the energy supply mix of the global as well as world-regional energy systems that achieves the minimum energy system cost for each world region. Figure 3 shows the total final-energy demand assumptions given to MESSAGE for the 11 world regions.

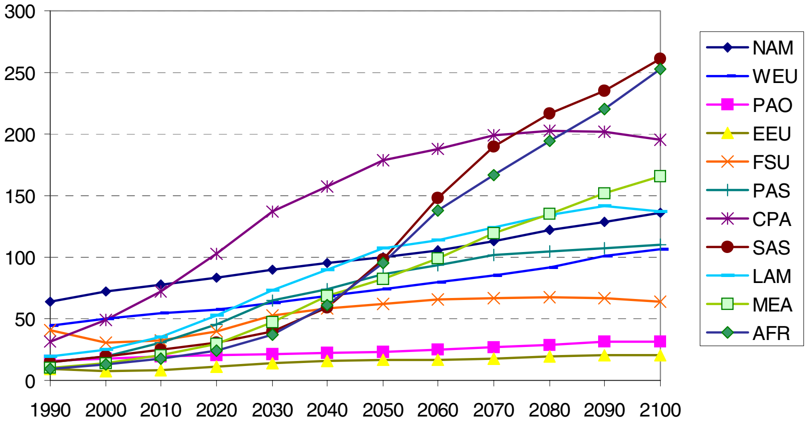

Figure 3: Final-energy demand assumptions used in the PF scenario, in EJ.

With these basic assumptions, plus more detailed assumptions on the speed of technological development of specific technologies, MESSAGE calculates the cost minimum choice of the energy systems that are consistent with various physical constraints related to energy systems, such as regional resource endowments, inflexibility of energy-related infrastructures, physical limits of the available renewable energy supplies, and others. The energy systems described under the PF scenario are consistent with all of the criteria for the sustainable development scenario (Box 1). The PF scenario fulfills Criterion 1 on the sustained economic growth as well as Criterion 2 on decreasing income disparity by definition (or by assumption). Criterion 4 on the non-decreasing reserves-to-production ratio is also fulfilled by definition (or by assumption). To judge whether the PF scenario fulfills Criterion 3 on the GHG emission stabilization and on the non-critical short-term environmental load, we need to analyze the implication of the technological choice to the GHG emissions. As presented in our previous reports, such analysis shows that the PF scenario fulfills Criterion 3 as well.

Figure 4 illustrates the global energy-related and industrial CO_2 emissions in the PF scenario, in comparison with the range of all the 500 emission scenarios from the SRES scenario database. The CO_2 emissions path for the PF scenario is much lower than the median case, suggesting the drastic change in the energy related technologies. The CO_2 emissions in 2100 is 4 GtC and it is below the level in 1990 (7.5 GtC).

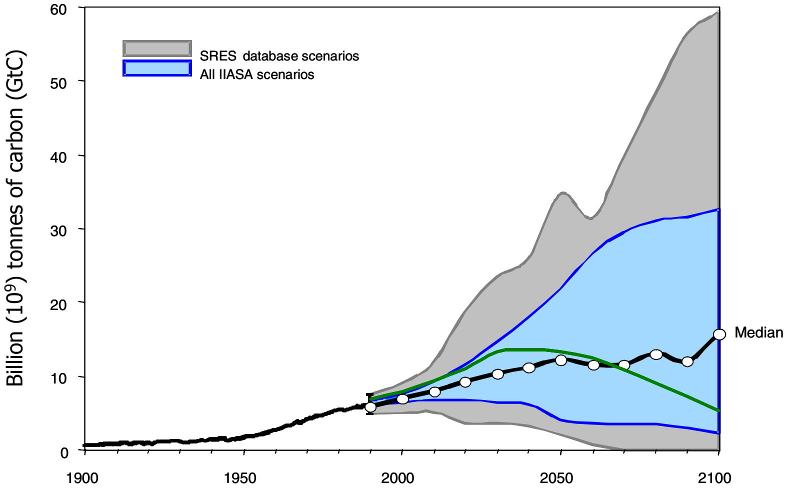

Figure 4: Global carbon dioxide emissions, actual development from 1900 to 1990 and PF scenario projections (green line) in comparison to other scenarios (140 of which from the SRES database) from 1990 to 2100. Historical data: Marland, 1994; Database: Morita and Lee, 1998.

3 The transportation sector and the global automobile market

In 1990, the transportation sector accounted for approximately 25% of the global final-energy use. 96% of the fuels used in the transportation sector are comprised of oil products, such as motor gasoline, diesel oil, kerosene type jet fuel and so on. In the OECD region, the transportation sector accounts for 60% of the total oil consumption by the end-use sectors, and road vehicles are the major consumers (more than 90%). In this section we discuss the whole transportation sector, but pay special attention to passenger road vehicle transportation, which accounts for a large share of road transport energy use.

Figure 5 shows final-energy use for the transportation sector and its share in the total final energy use for the 11 world regions of our study in 1990. Shares of the transportation sector differ considerably across regions, perhaps reflecting regional geographical characteristics and transportation infrastructures, rather than the state of economic development. In absolute terms, NAM and WEU have comparatively high transportation energy demands.

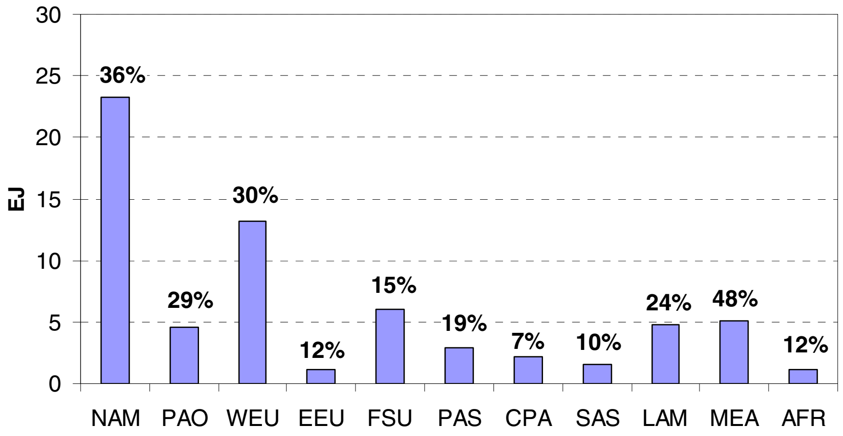

Figure 5: Global final-energy use in the transportation sector in 1990 in EJ. Percentages refer to the shares in total final energy consumed by the transportation sector.

Transportation services are broadly categorized into freight transportation and passenger travel. These services are provided by different transportation modes such as automobiles, trucks, buses, trains, ships, airplanes and others. In this section, we focus on generic technologies, that is, technologies that are common to many of these transportation modes, rather than on the modes themselves.

In Section 3.1, we describe the characteristics of fuels used in the transportation sector, illustrating which transportation mode the fuels are used for. In Section 3.2, we focus on characteristics of technologies that are analyzed under the PF scenario. Section 3.3 describes technological development for the transportation sector in the PF scenario. In Section 3.4, we present fuel efficiency targets for future automobiles that are consistent with sustainable development. In Section 3.5, we present the development of the global automobile market that is consistent with the PF sustainable development scenario. Section 3.6 quantifies the contribution of the technologies to energy demand saving, as well as the effects of CO_2 mitigation. Section 3.7 gives targets timing of the introduction of fuel-cell based passenger automobile.

3.1 Fuels used in the transportation sector in 1990

The global total of final-energy use in the transportation sector in 1990 was about 60 petajoules (PJ, 10^{15} joules). 96% of the fuels used were oil products, and the rest were coal, gas and electricity. Figure 6 summarizes global fuel consumption and use in the transportation sector in 1990 (IEA 2002a, IEA 2002b)[2]. “Other” in the figure corresponds to the IEA statistics’ unspecified transportation use. Oil products were mainly used for road transport (freight and passenger transport). 70% of the oil products used for road transport was gasoline and 30% was diesel oil. Synthetic liquid fuels on biomass basis (mainly ethanol) were also used, but their share in the road transportation was less than 1%. Ethanol is usually often blended – at various percentages – with gasoline to increase octane rating and improves the emission quality of gasoline.

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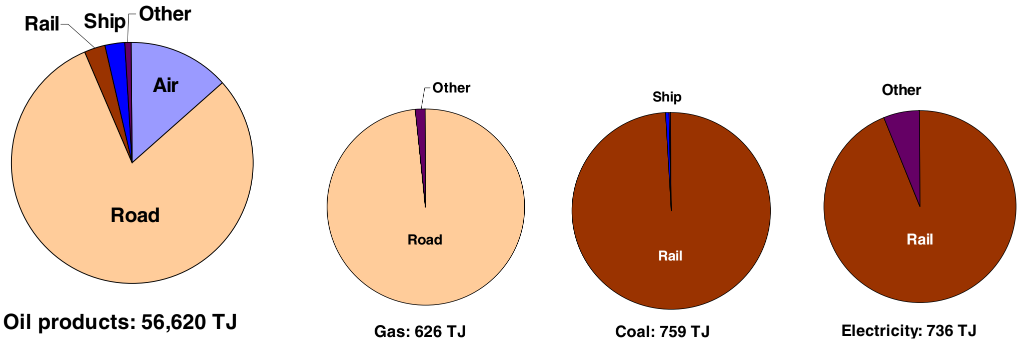
[2] In this figure, liquefied petroleum gas (LPG) is included under gas and not under oil products, although IEA’s statistics classify LPG as an oil product to make it consistent with the MESSAGE’s definition of gas.



Oil products: 56,620 TJ

Gas: 626 TJ

Coal: 759 TJ

Electricity: 736 TJ

Figure 6: Global fuel consumption and use in the transportation sector, in 1990 in terajoule (TJ, 1012 joules). "Other" corresponds to the unspecified transportation use. Source: IEA (2002a, 2002b).

In 1990, 14% of the oil products were consumed by air transport. The main airplane fuel used is a kerosene type of jet fuel. For domestic air transport, also a gasoline type of jet fuel is used. For ship and rail transport, diesel oil is the major fuel used.

Gases, mainly natural gas and liquefied petroleum gas (LPG) for road transport, supplied approximately 1% of road transport demands in 1990. LPG, usually propane, is a by-product of refining. Natural gas can be used as a motor fuel either compressed in cylinders as compressed natural gas (CNG) or as liquefied natural gas (LNG). In practice, LNG is rarely considered, since it is more expensive and more difficult to handle than CNG (IEA, 1997a).

The remaining transportation sector demand was met by coal and electricity. Both are mainly used for rail transport. Coal and electricity use account for nearly half of the total fuel consumed by rail transport (the remainder comes from oil products).

3.2 Description of the key transportation technologies

In the MESSAGE model, transportation technologies are specified in a generic manner. The model distinguishes eleven kinds of technologies supplying transportation demand:

- coal technologies (mainly locomotive trains with steam engines),
- fuel oil technologies (mainly – 70% in 1990 – ships and long-distance locomotive trains with diesel engines),
- light-oil technologies (mainly – 80% in 1990 – cars and trucks with diesel or gasoline engines; most other applications – 15% in 1990 – are airplanes with jet engines),
- gas technologies (mainly cars and trucks with internal combustion engines),
- electric engines (mainly trains using electric motors),
- internal combustion engines using methanol (mainly cars and trucks),
- internal combustion engines using ethanol (mainly cars and trucks),
- fuel-cells using methanol (all kinds of transportation technologies),
- fuel-cells using ethanol (all kinds of transportation technologies), and
- fuel-cells using hydrogen (all kinds of transportation technologies).

In the following subsections, we briefly discuss the characteristics of some of the technologies. First, we summarize the main technology characteristics (efficiency and CO_2 coefficient) assumed in the PF scenario in Table 2.

Table 2: Technology characteristics assumed in the MESSAGE model for the PF Scenario in the base year (1990). Fuel efficiencies are expressed relative to fuel oil (=100), and CO_2 efficiency in ton C/TJ.

	Abbreviation	Efficiency	CO_2 coefficient
Coal	Coal	30	25.8
Fuel oil	F Oil	100	21.1
Light oil	L Oil	100	20.0
Gas	Gas	100	15.3
Electricity	Elec	300	17.4
Methanol Internal Combustion Engine (ICE)	Meth IC	100	17.4
Ethanol ICE	Eth IC	100	17.4
Methanol fuel cell	Meth FC	150	Zero emission (0.0)
Ethanol fuel cell	Eth FC	150	Zero emission (0.0)
Hydrogen fuel cell	LH2 FC	180	Zero emission (0.0)

Note that efficiencies here are given relative to the efficiency of the light-oil technologies because a technology in MESSAGE is defined by its fuel usage, and no further distinction is made with respect to different transportation modes. For example, an oil technology in MESSAGE includes technologies for bus, car, truck, airplanes, ships, trains, etc., and in the real world their end-use efficiencies vary. We calculated absolute end-use efficiencies of different transportation technologies using a study by Nakićenović *et al.* (1996). Table 3 summarizes the results (world-regional results are given in Appendix 8.1). The table shows that end-use efficiencies vary across different applications even for one and the same fuel. In contrast, efficiencies of fuels within the same application (or mode), are found more similar to each other, even for different fuels. MESSAGE's assumptions shown in Table 2 represent such relative relationships.

Table 3: Global average of end-use efficiencies in 1990, in % (calculated based on Nakićenović *et al.*, 1996).

	Coal	**Oil**	**Gas**	**Electricity**
Transportation sector total	**6.3**	**15.1**	**12.2**	**76.8**
Bus and Truck	---	13.8	13.5	---
Car and Truck	---	11.0	10.4	---
Airplanes	---	26.3	---	---
Ships	---	31.0	31.8	---
Rail	6.0	25.0	---	75.8
Other	45.8	55.8	48.2	88.8

As far as the efficiencies of fuel cell technologies are concerned, our assumption is consistent with the fuel economy estimation of the Fuel Cell Vehicles (FCV) done by the California Fuel Cell Partnership (CaFCP) who has published a FCV commercialization scenario for the state of California. They estimate that an ethanol-based FCV with an on-board reformer, achieves a relative fuel economy (expressed as miles per gallon, for instance) of 1.39-1.54 compared to 1.0 for a gasoline car. For an ethanol-based car, they estimated the upper value of 1.4, while their fuel economy estimation for the hydrogen FCV achieved 1.50-1.74, in comparison to 1.0 for a gasoline car (Bevilacqua Knight, Inc., 2001).

Gasoline and diesel cars with internal combustion engines (ICE)

Essentially all road vehicles are powered by internal combustion engines (ICEs), in which combustion is induced by a spark (gasoline-fuelled) or by compression (diesel-fuelled). At present, the spark ignition engine is cheaper and offers good performance but at the expense of poor fuel efficiency. Compression ignition engines offer better fuel consumption, particularly at part load, but at a higher capital cost and with more noise, vibration, bulk and weight. As there are a lot of capital and technology investments made for the ICE, it is likely that it will remain the basic technology for automobiles and trucks for the foreseeable future. As far as ICE's technical potential is concerned, the International Energy Agency (IEA) reports that the ICE could improve its fuel efficiency by improvements to the exhaust treatment, combustion, and faster warm-up. These improvements are estimated to have efficiency potentials of 5%, 10%, and 5% respectively at maximum (IEA, 1997a). The issue of efficiency improvement potentials of gasoline and diesel vehicles is discussed in more detail in Section 3.4.

Natural-gas cars with ICEs

Natural gas is mainly used for cars and trucks and stored on board of a vehicle as compressed natural gas (CNG) or as liquefied natural gas (LNG). In practice, LNG vehicles are much less used, both for economic as well as for technical reasons[3]. The interest in natural gas as an alternative fuel is mainly due to its clean burning, the size of the domestic resource base in some regions, and its commercial availability to end-users. Natural gas produces significantly fewer harmful emissions than reformulated gasoline and diesel. In addition, commercially available medium and heavy-duty natural-gas engines have achieved over 90% reduction of CO and particulate matter and over 50% reduction in NO_X, both relative to commercial diesel engines (AFDC, 2003).

Natural gas is a relatively well-tested alternative fuel; around a half million vehicles currently use CNG in IEA countries. In addition to emitting much less carbon monoxide than gasoline or methanol vehicles, CNG mixes better with air than liquid fuels do. A CNG-fueled engine therefore requires less enrichment for engine start-up, but the extent of the reduction in pollutant will depend upon the emission control system. Natural gas vehicles (NGVs) will emit similar or possibly higher levels of nitrogen oxide than gasoline or methanol vehicles, but will emit essentially no unregulated pollutants (e.g., benzene), smoke, or sulfur oxides, and slightly less formaldehyde than gasoline vehicles. The use of NGVs can therefore be expected to lower ozone levels in comparison with the use of gasoline vehicles (IEA, 1997a).

Liquefied petroleum gas (LPG) is a by-product of crude-oil refining, and consists mainly of butane and propane. This fuel currently represents only a small proportion, but it is considered to offer, in the longer term, some advantages over natural gas (such as higher energy density and easier transportation) (IEA, 1997a)

Flexible-fuel cars with ICEs

Alcohol fuels, typically methanol and ethanol, are proven alternatives to gasoline and diesel.

Ethanol – sometimes also called ethyl alcohol and grain alcohol – is similar to methanol, but is less toxic and less corrosive. It is a clear, colorless liquid with a characteristic, agreeable odor. Ethanol is usually produced by fermenting and distilling starch crops that have been

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[3] In the United States, the total number of CNC vehicles (light-duty, medium-duty plus heavy-duty) on the road was 11,000 in 2001. In comparison, the number of LNG vehicles was 400, all for heavy duty and number of LPG car is 3,200 (EIA, 2003d).

converted into simple sugars. Viable feedstocks for this fuel include corn, barely, and wheat. Ethanol can also be produced from "cellulose biomass" such as trees and grasses. Produced in this way it is also called bioethanol. The combustion of ethanol produces very low levels of articulate emissions. Adding ethanol to gasoline also increases the octane rating and improves the emissions quality, thus reducing air pollution. Ethanol is low in reactivity and high in oxygen content, making it an effective tool in reducing ozone pollution (AFDC, 2003). One area of possible concern with both ethanol and methanol vehicles could be the emission of formaldehyde, the first oxidation product of alcohol fuels. Very high emissions of formaldehyde could result in harmful local health effects (IEA, 1997a).

In some areas of the United States, ethanol is added to gasoline to make a 10% mixture (E10), but it can also be used in higher concentrations such as 85% (E85) or in its pure form. Today's commercially available vehicles that can use up to 85% ethanol and the rest gasoline are called flexible fuel vehicles or FFVs (AFDC, 2003). Brazil, Sweden, and Canada are also among the countries that have commercially introduced ethanol in blends with gasoline (such as gasohol) on a large scale, using existing retail systems and with minor vehicle modifications (IEA, 1997a).

The EU is planning to introduce ethanol fuel up to 2% by 2005 and to 5.75% by 2010. The IEA also suggests introducing ethanol fuel up to 8% by 2020. China and India are also moving to introduce it (Ministry of Environment, 2003).

However, ethanol is still expensive to produce and requires large harvests of appropriate crops and large amounts of energy for its production, which leads to other environmental problems, in particular soil degradation (IEA, 1997a).

Methanol – sometimes also called wood alcohol – is mainly produced from natural gas, but can also be produced also from coal, crude oil, biomass, or organic waste. A significant decrease in greenhouse gas emissions would occur with a straight substitution of methanol for gasoline in a standard car, even with natural gas as the feedstock. It has been used as an alternative fuel in flexible-fuel vehicles that run on M85 (a blend of 85% methanol and 15% gasoline). However, in the United States it is not commonly used as such because automakers are no longer supplying methanol-powered vehicles and there are no fueling stations available to the public. Another disadvantage of combustion engines fueled by methanol is that they emit large amounts of formaldehyde. Still, in the long run, methanol has the potential of bridging the path to a hydrogen future because it can be used to produce hydrogen and the methanol industry is working on technologies that would allow methanol to be used as a source of hydrogen for fuel cell vehicle applications (AFDC, 2003).

Today most of the world's methanol is produced by steam-reforming of natural gas to create synthesis gas (a combination of carbon monoxide and hydrogen), which is then fed into a reactor vessel in the presence of a catalyst to produce methanol and water vapor. While a large amount of synthesis gas is used to produce methanol, most synthesis gas is used in ammonia production. As a result, most methanol plants are adjacent to or are part of ammonia plants. The synthesis gas is fed into another reactor vessel under high temperatures and pressures and CO and hydrogen are combined in the presence of a catalyst to produce methanol. Finally, the reactor product is distilled to purify and separate the methanol from the reactor effluent (AFDC, 2003). For the future, the possibility to produce methanol from non-petroleum feedstocks such as coal or biomass (e.g., wood) is of also interest for reducing petroleum imports, but under the current prices, the use of natural gas is more competitive.

Electric vehicles

The main attractiveness of electric vehicles is the absence of emissions, and consequently the promise of improved urban air quality. Using electricity to power vehicles allows greater flexibility of the source of primary-energy supply. If renewable sources like solar, wind or hydroelectric power are used to generate the electricity, EVs will essentially be non-polluting (IEA, 1997a).

Electricity is unique among the alternative energy carriers in that it can be converted to mechanical power directly. Whilst other fuels release stored chemical energy through combustion to provide mechanical power, motive power is produced directly from electricity by an electric motor. Electricity used to power vehicles is commonly stored by batteries that are part of the electric cars (AFDC, 2003).

Emissions that must be attributed to EVs would be the emissions that are generated in the electricity production process at the power plant. The economies of using EVs – once the initial capital cost is made – incur lower fuel and maintenance costs because they have fewer moving parts to service and replace, although the batteries must be replaced every three to six years (AFDC, 2003). The cost of an equivalent amount of fuel for an EV is less than current end-use prices of gasoline.


Ford: Think: http://www.elfeinberg.com/Ford%20Think%202.pdf

Ultimately, the cost and performance of batteries will determine the cost and performance of EVs. Currently, several types of automotive batteries are available and/or under development. However, even the best of these can store only a few percent of the energy of a liter of gasoline in the same volume. The greater efficiency of electric motors (75% in comparison to approximately 20% for the gasoline cars) helps, but the range of EVs is still limited (USDOE and USEPA, 2003a).

Since 2000, five main models of cars have been introduced to US market, and their fuel consumptions range between 1.9 to 4.3 liters of gasoline equivalent per 100 kilometers, and their driving ranges lay between 68 km to 219 km (USDOE and USEPA, 2003a)[4].

Hydrogen Fuel cell cars

Fuel cell vehicles (FCVs) represent a radical departure from vehicles with conventional internal combustion engines. Like electric vehicles with batteries, FCVs are propelled by electric motors. But while battery electric vehicles use electricity from an external source (and store it in a battery), FCVs generate their own electric power on board through an electrochemical process using hydrogen fuel (pure hydrogen or hydrogen-rich fuel such as methanol, natural gas, or even gasoline) and oxygen from the air. The possibility of producing hydrogen from a variety of primary-energy sources and its clean-burning properties make it an extremely attractive alternative fuel. FCVs fueled with pure hydrogen emit no pollutants – only water and heat – while those using hydrogen-rich fuels and a reformer produce only small amounts of air pollutants. In addition, the system efficiency of FCVs could exceed 60% (IEA, 1997a) – compared with 20% for gasoline-based internal

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[4] For comparison, the EV version of the RAV4 from Toyota has fuel consumption of 2.1 liter per 100 kilometers whereas gasoline version of the RAV4 2WD has 8.7 liter per 100 kilometers.

combustion engines and may also incorporate other advanced technologies to increase efficiency.

(Honda FCX: http://www.fueleconomy.gov/feg/fcv_whatsnew.shtml)

Pure hydrogen can be stored onboard in high-pressure tanks. When fueled with hydrogen-rich fuels, these fuels must first be converted into hydrogen gas by an onboard device called a "reformer" (see the next section, "fuel cell car with on-board reformer").

The hydrogen-fueled Honda FCX is the first fuel cell vehicle that was certified by U.S. EPA and the California Air Resources Board (CARB). The FCX has been certified as a Zero Emission Vehicle by CARB and has been given the lowest (best) national emission rating by EPA (US DOE and US EPA, 2003). Demonstration fuel cell vehicles by other manufacturers are also available.

The California Fuel Cell Partnership (CaFCP) estimated the fuel economy of FCVs based on comparisons of existing vehicles and model estimates. Their comparisons were made for vehicles that are close to identical except for the fuel. Energy economy ratios (EERs) were calculated relative to a single baseline gasoline fuel economy. Based on the prototype hydrogen fuel cell vehicles built by Ford and Daimler-Chrysler, EERs of 1.50-1.74 were calculated for hydrogen fuel cell vehicles (Bevilacqua Knight, Inc., 2001). The combined fuel efficiency for city and highway driving cycles was 67.1 miles per gallon (mpg) (3.5 liter per 100 kilometers) in comparison with comparable gasoline vehicle of 44.2 mpg (5.3 liter per 100 kilometers) for Ford, and in the case of Daimler Chrysler it was 53.5 mpg (4.4 liter per 100 kilometers) in comparison to 33.1 mpg (7.1 liter per 100 kilometers).

(Toyota FCHV: Author's photo)

From a technical perspective, the most obvious way of fuelling fuel cell vehicles is by using pure hydrogen gas, stored onboard as a compressed gas. Since hydrogen gas has a low energy density, it is difficult to store enough hydrogen to generate the same amount of energy as with conventional fuels such as gasoline. This is a significant problem for fuel cell vehicles, which should have a driving range of 300-400 miles (480-640 kilometers) between refueling in order to be competitive with gasoline vehicles. High-pressure storage tanks are currently being developed to allow larger amounts of hydrogen to be stored in tanks small enough for passenger cars and trucks. Research is also being conducted into the use of other storage technologies such as metal hydrides, carbon nanostructures (materials that can absorb and retain high concentrations of hydrogen) (EERE, 2003) and liquid hydrogen (Doyle, 1998).

Besides these technical difficulties of storing hydrogen on board of a vehicle, the distribution of hydrogen may be the other major barrier to its widespread use. The cost of its cryogenic transport to retail fuelling stations, as well as of storage (infrastructure, refrigeration costs), could be relatively high (IEA, 1997a). For these difficulties, alternatives, such as using a hydrogen carrier that is a more conveniently handled (methane or ammonia) and that could be separated from gaseous hydrogen on board the vehicle, have been tested and show technical potential (see the next section, "fuel cell car with on-board reformer").

Another technical challenge facing fuel cells is the need to increase their durability and dependability. PEM fuel cells must have effective water management systems to operate dependably and efficiently. Also, all fuel cells are prone, in varying degrees, to "catalyst poisoning", which decreases fuel cell performance and longevity. Research into these areas is ongoing, and DOE is sponsoring and participating in demonstration programs to test the durability of new components and designs (EERE, 2003).

Hydrogen can be obtained from a variety of primary-energy sources, including fossil fuels, renewable sources, and nuclear energy. Since the fuel can thus be produced from domestically available resources, fuel cells have the potential to improve security of the energy supply by reducing dependence on imported oil. Today the two most common methods used to produce hydrogen are steam reforming of natural gas and electrolysis of water. Currently steam methane (major component of natural gas) reforming accounts for 95% of the hydrogen produced in the US (EERE, 2003). Biomass and coal can also be gasified and used in a steam reforming process. Electrolysis uses electrical energy to split water into hydrogen and oxygen. The electrical energy can come from any electricity production sources including renewable fuels (ADEC, 2003).

Fuel cell car with on board transformer car using menthol or ethanol

Fuel cell vehicles can be fueled with hydrogen-rich fuels, such as methanol, ethanol, natural gas, or petroleum distillates, including gasoline. These fuels must be passed through onboard "reformers" that extract pure hydrogen from the fuel for use in the fuel cell. Reforming does emit some CO_2, but much less than a gasoline engine would (US DOE and US EPA, 2003). In MESSAGE, only alcohol-based fuels (ethanol and methanol), which we consider to have significantly higher technical feasibility than other options, are considered as options for fuel cell vehicles with reformers. In particular, some researchers argue that the onboard reformer using gasoline-based fuel faces a difficult task of removing SO_X (Bevilacqua Knight, Inc., 2001). Lovins and Williams (1999) also note that fuel-cell systems based on onboard gasoline reformers offer little or no advantage over advanced gasoline-fuelled internal-combustion-engine propulsion.

For the purposes of modeling, it is reasonable to assume that methanol is manufactured from natural gas or coal, whereas ethanol is produced by processing agricultural crops such as sugar cane or corn, and this is what is therefore included in MESSAGE. Both alcohols can easily be used to produce hydrogen, but more attention is being given to methanol as much of the demonstration projects by car manufacturers such as Daimler, Toyota, and General Motors are focused on vehicle utilizing methanol, rather than ethanol reformers. Doyle (1998) pointed out that in general, on-board reforming of methanol holds little promise to mitigate global warming, unless the methanol is derived from biomass instead of fossil fuels.

The main advantages of fuel cell vehicles with an onboard reformer over fuel cells using pure hydrogen are twofold. First reformers allow the use of fuels with higher energy density than that of pure hydrogen gas. Second, and more importantly, it allows the use of conventional fuels delivered using the existing infrastructure. Although the fuel economy of a fuel cell vehicle with hydrogen produced from an on-board reformer is less than a fuel cell vehicle using hydrogen as stored fuel, it still could achieve high fuel economies in the 60-80 mpg (2.9-3.9 liters per 100 kilometer) range (while hydrogen pure vehicles could achieve 70-85 mpg: 2.8-3.4 liters per 100 kilometer) (Marx, 2000).

However, there are disadvantages as well. The main disadvantage is that onboard reformers add to the complexity, cost, and maintenance demands of fuel cell systems (EERE, 2003). Another disadvantage is that the reforming process emits CO_2, although less than conventional ICE-based vehicles. For these reasons, fuel cell vehicles with hydrogen-rich alcohol fuels can be considered as a transition technology to fuel cell vehicles using pure hydrogen as input until the technological barriers related to hydrogen storage and hydrogen distribution are overcome.

High-temperature fuel cell systems can reform fuels within the fuel cell itself—a process called internal reforming—removing the need for onboard reformers and their associated costs. Internal reforming, however, does emit carbon dioxide, just like onboard reforming. In addition, impurities in the gaseous fuel can reduce cell efficiency.

3.3 Technology development in the transportation sector in the PF scenario

The PF scenario describes a transition from the dominance of conventional oil-based technologies to fuel cell technologies for the global transportation sector. The potential contributions of the key technologies discussed in Section 3.2 to the global technology mix in the transportation sector are shown in Figure 7.

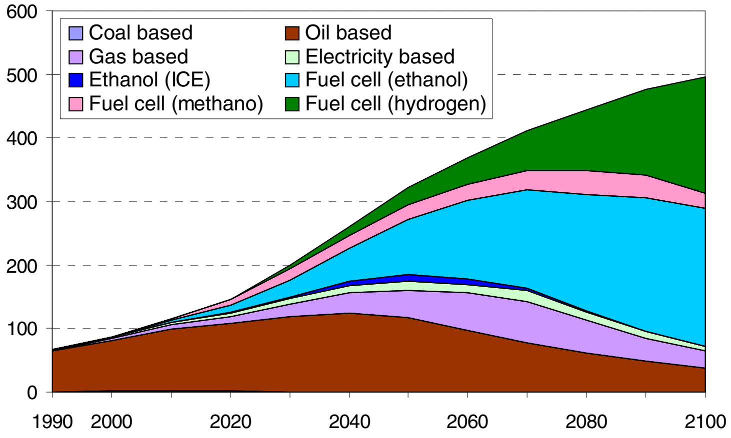

Figure 7: The development of technology mix in the transportation sector of the PF scenario, in EJ.

The PF scenario illustrates a situation in which fuel cell technologies have become the preferred transportation technologies over the currently dominating ICE technologies. The introduction of the fuel cell technologies begins around 2010, and their share gradually increases to become dominant by the end of the 21st century. As to energy carriers, ethanol will play a particularly important role in the fuel cell applications. Towards the end of the century, a substantial share of the fuel cell applications uses hydrogen as a fuel, but still to a lesser extent than ethanol. Methanol-fuelled fuel cells coexist with ethanol and hydrogen-fueled fuel cells, reflecting preferences for the methanol reflecting the different resource endowments in different world regions (see Figure 19).

To look at the same results in a different way, Figure 8 shows the same mix of transportation technologies in the PF scenario in 1990, 2050 and 2100, but this time in the form of a pie chart, which illustrates the extent of the structural change that the transportation sector undergoes in the PF scenario. In 1990, oil-based technologies dominate, satisfying 97% of the total transportation demand. This dominance of conventional oil-based technologies begins to decrease around 2020, and the share of alternative technologies (non-oil-based technologies) expands rapidly from that year onwards. The share of the oil-based technologies then keeps decreasing over the century, but the technologies will not be phased out completely. By 2040, the share of alternative technologies will have overtaken that of conventional oil-based technologies. The share of oil-based technologies will be reduced to 36% by 2050, and by 2100 the share will be only 8%.

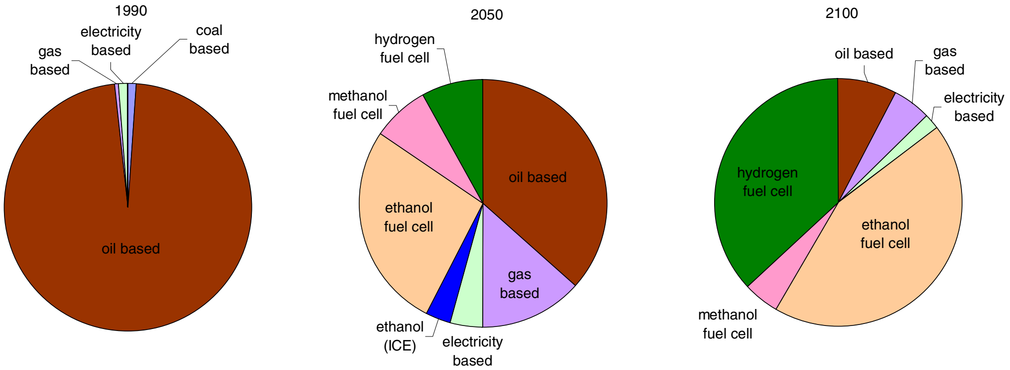

Figure 8: Shares of transportation technologies in the PF scenario in 1990, 2050, and 2100, in EJ.

Natural gas-fueled ICE technologies become the first alternative technologies to have significant shares in the oil-dominated transportation technologies. As early as 2010, gas-fueled ICEs are introduced to supply 6% of the global transportation energy use. This share increases further, but the role of gas-based technology is limited to that of a transition technology, i.e., it has an important, but limited role during the transition from an oil-based transportation system to a transportation system based on fuel cell technologies. By 2060, the gas-fueled ICE supplies 16% of the global transportation energy but this role is subsequently taken over by hydrogen-based fuel cell technologies, which are introduced massively after 2060.

Technologies based on synthetic fuels (methanol and ethanol) become important substitutes of oil-based technologies. In the second half of the 21st century, the importance of ethanol-based fuel cell technologies increases further, accounting for as much as 44% in 2100. At the same time, similar to the gas-based technologies, the role of methanol-based fuel cells is rather limited in the long run.

In the long run, hydrogen-based fuel cell technologies play a very important role. Hydrogen enters the market around 2040 and expands steadily thereafter. By 2100, its share in the final demand of transportation reaches 37% of the total final energy of the transportation sector. At the same time, ethanol-based fuel cell technology becomes particularly important, accounting for 30% of total transportation demand in 2050 and for 44% in 2100. Such coexistence of fuel cell technologies based on different fuels mainly reflects the preference of a specific feedstock available in that world region. We shall further discuss this issue in Section 3.7 and in Section 6.

3.4 Fuel economy targets

The technological change described by the PF scenario (Section 3.3) results in a major efficiency improvement due to the shift to highly efficient technologies as well as the improvement of conventional technologies. Such technological change does not come automatically, but rather comes as a result of carefully planned investments aimed at specific technologies.

In MESSAGE, the end-use efficiency of the transportation sector is calculated relative to the oil-based technology. The assumption on the amount of the final-energy use in the transportation sector is given in terms of oil equivalent, and the end-use efficiency improvement is assumed to be already included in the given final-energy use, calculated prior to the inclusion in the MESSAGE calculation by the Scenario Generator. Thus, the end-use efficiency calculated by MESSAGE only includes the efficiency improvement due to the substitution of conventional technologies by more advanced alternatives.

In this section, we calculate the end-use efficiency including the efficiency improvement of the conventional technologies, which are not singled out by MESSAGE. We present the result in terms of fuel consumption rates of passenger cars. To do so, we use external assumptions collected from the literature in the field as well as assumptions used in the PF scenario. We combined these assumptions in a way that the resulting end-use efficiency remains consistent with the PF scenario. The fuel consumption rates resulting from this combination of assumptions are interpreted as target values since the PF scenario represents a highly normative world that leads to sustainable development.

Note that in this study, the fuel consumption rate is expressed mainly in terms of (gasoline equivalent) liter per 100 kilometer. Since much of the automobile-related literature is based on American data, we also quote corresponding fuel economy expressed in terms of miles per gallon (mpg), in addition to liter per 100 kilometer.

We calculated the fuel consumption target range for passenger automobiles in the following two steps. The first step was to calculate the fuel economy in the starting year (1990) for the 11 world regions, using the following relationships.

Fuel consumption rate [liter per kilometer for cars in 1990] =
fuel consumption [EJ in 1990] by passenger cars /
vehicle transportation demand [vehicle kilometer in 1990] for passenger cars

We estimated the final-energy consumption by passenger automobiles by disaggregating the IEA data on road transport fuel consumption (IEA 2002a, IEA 2002b), first into passenger and freight transport, and second into bus and automobile fuel consumption. We singled out fuel consumption by the passenger cars in a following manner.

Fuel consumption [EJ in 1990] by cars =
fuel consumption by the road transport [EJ in 1990] ×
share of the passenger transport in fuel consumption [in 1990] ×
share of cars in road transport in fuel consumption [in 1990]

To disaggregate fuel consumption by total road transport into consumption by freight and by passenger transport, we used an econometric relationship that relates GDP and the ratio between passenger and freight transport. This relationship was estimated using parameters derived by Gritsevskii (1996) for 11 world regions. Then we disaggregated fuel consumption for passenger travel on road into passenger vehicle and bus travel. The ratio between the fuel consumed by bus and by passenger vehicles was calculated as follows. We took the passenger travel demand data (in terms of person kilometers) for cars and buses from Schafer

(1995), and using occupancy rates (the number of persons in a vehicle) assumptions[5] for cars and buses for each world region. We then calculated travel demands in terms of vehicle kilometers. Then, we applied the assumption that buses have 80% lower fuel economy compared with cars in developed regions and 75% in developed regions (Schmied, 2003) to get the ratio of fuel consumption for buses and cars (Table 4).

Vehicle transportation demand [vehicle kilometers in 1990] for cars =
passenger transportation demand [passenger kilometer in 1990] for cars /
car occupancy rate [number of passenger per car in 1990]

Share of cars in the road transport demand in 1990 =
vehicle transportation demand [vehicle kilometers in 1990] for cars /
(vehicle transportation demand [vehicle kilometers in 1990] for cars +
vehicle transportation demand [vehicle kilometers in 1990] for buses / 0.8)

The second step was to calculate the fuel consumption rates. To calculate their future development, we first estimated fuel consumption rate improvements of a conventional automobile (gasoline/diesel-based cars with ICE). Then, using the technology mix results from MESSAGE as well as efficiency assumptions of alternative automobiles relative to the conventional automobiles, we calculated overall fuel consumption rate improvement until 2050.

3.4.1 Calculating base year's fuel consumption rates

Table 4 summarizes the occupancy rate assumptions for cars and buses that we used in our calculations. Note that the occupancy rates data, in particular those for less developed regions are quite uncertain, because they are estimated using various methods and different assumptions. Table 4 shows that the occupancy rates for industrial regions tend to be lower than those for developing regions, particularly for buses. In general, the occupancy rates are relatively high in low-income countries, whereas in industrialized countries, they have declined with rising car ownership (Michaelis *et al.* 1996). Data sources and a detailed discussion on the occupancy rate assumptions are given in the appendix (Appendix 8.2).

Table 4: Assumptions on car and bus occupancies (persons) in 1990.

	Car occupancy	Bus occupancy
NAM	1.6	21.0
WEU	1.9	19.3
PAO	1.4	10.2
EEU	2.0	24.5
FSU	2.0	30.0
CPA	2.0	30.0
SAS	2.7	36.0
PAS	2.3	18.3
LAM	2.0	40.0
AFR	2.5	40.0
MEA	2.0	30.0

Table 5 shows the shares of car transport in passenger transport demands, as published by Schafer (1995) and the shares of fuel consumption by cars in the total fuel consumption by passenger vehicles (cars and buses), which we calculated based on the car occupancy rates,

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[5] Data on occupancy rates were collected from the literature (Table 4) as discussed later.

bus occupancy rates and share of cars in passenger transport demand on road as we described earlier. In both cases, the remainder is a corresponding share for the bus transport.

The car shares in road passenger demand (left column) are high in industrialized countries. In contrast, the bus transport appears more important in less developed regions. In Asia, particularly in CPA and SAS, the reliance on bus transportation is significantly high. The share of cars in the road passenger demand naturally corresponds to the share of cars in fuel consumption (right column). Given that the fuel efficiency of a car is higher than that of a bus, the fuel consumption share is higher than the share of the demand for cars.

Vehicle kilometers for the passenger car transport are calculated using the above-mentioned car occupancy rate assumptions and the passenger travel demand (in terms of person kilometers), again as published by Schafer (1995). By dividing fuel consumption by vehicle kilometers, we could obtain average fuel consumption rate for vehicles on the road (Table 6).

Table 5: The shares of car in passenger transport demand by road vehicles and in fuel consumption by passenger vehicles in 1990, own estimates. (The balance is buses.)

	Share of cars in passenger road transport demand	Share of cars in fuel consumption by passenger road transport
NAM	96%	99%
WEU	89%	96%
PAO	83%	93%
EEU	52%	73%
FSU	43%	69%
CPA	3%	10%
SAS	8%	19%
PAS	23%	32%
LAM	56%	84%
AFR	46%	73%
MEA	38%	65%

Table 6: Fuel consumption rate for 11 world regions in 1990 (liter per 100 kilometers), car occupancy range in 1990 (persons), and range of alternative fuel consumption rate in 1990 (liter per 100 kilometers), own estimates.

	Estimated fuel consumption rate	Car occupancy range (assumed occupancy)	Fuel consumption rate range
NAM	13.8	1.1- 2.0 (1.6)	9.4-17.0
WEU	9.3	1.5-2.0 (1.9)	7.3-9.6
PAO	10.2	1.3-2.0 (1.4)	9.5-14.2
EEU	10.8	2.0-3.0 (2.0)	10.8-14.3
FSU	17.7	2.0-3.0 (2.0)	17.7-23.0
CPA	29.0	2.0-3.0 (2.0)	29.0-29.9
SAS	8.9	2.0-3.0 (2.7)	8.4-9.1
PAS	7.8	2.0-3.0 (2.3)	7.5-8.5
LAM	10.7	2.0-3.0 (2.0)	10.7-14.9
AFR	13.5	2.0-3.0 (2.5)	12.4-16.8
MEA	33.0	2.0-3.0 (2.0)	33.0-42.1
World (average)	**12.5**	**1.4-2.2 (1.8)**	**9.7-15.0**

Using these assumptions we calculated the average fuel consumption rates for 11 world regions. The results are presented in the first column of Table 6. As the estimated value of the fuel consumption rate is quite sensitive to the values of the car occupancy rates, we calculated the fuel consumption ranges that are associated with ranges of car occupancy rates that we found in the published literature. We note that when determining the car occupancy rate used in this study, we also considered the resulting range of the fuel consumption rate and found combinations of fuel economy and fuel consumption that are both within reasonable ranges when compared with the values found in the published literature. The second column of Table 6 gives the ranges of the occupancy rate, and the third column gives the corresponding ranges of the resulting ranges of fuel consumption rates.

Fuel consumption rates of some of the developing regions, such as SAS, PAS, LAM, and AFR are already at the same range of fuel consumption rates as those of industrialized countries in 1990. In fact, the fuel consumption rates for SAS and PAS are even lower than the leading regions. This is due to the fact that in the calculation we were not able to single out the transportation demand satisfied by two-wheeled vehicles, which are usually characterized by much lower fuel consumption rates than those of cars when in developing Asian regions, in particular in the SAS region, the reliance on the two-wheeled transportation is significantly high.

To evaluate the estimated fuel consumption rates for cars in 1990, we compared the results with other published estimations of the fuel consumption rates. Table 7 summarizes fuel consumption estimates that we collected from various sources for various years.

The differences among various estimates illustrate the difficulty in estimating the fuel consumption rates. Our estimates for the NAM, WEU and PAO regions are well in the range of estimates by other authors. Also, for EEU and FSU, our estimates appear reasonable. However, our fuel consumption rates estimated for CPA and MEA appear high in comparison with the numbers reported in Table 7. But note that there no data in the table that refer to countries or regions that are directly related to CPA or MEA. Also, since we have used assumptions on occupancy rates that are at the low end of the plausible range, we argue that these high rates are definitely defendable.

On the other hand, the fuel consumption rates for SAS and PAS are below the levels of the developed regions. For SAS, the estimated result was sensitive to the bus occupancy rate assumption, rather than car occupancy rate. With the bus occupancy rate assumed at 40 people for this region, it would give a fuel consumption rate of 9.7, instead of 8.9. Still, the number is comparatively low, given the state of the economic development of this region. This is accounted for by the fact that in this world region, in particular in India, the share of two-wheeled vehicles are non-negligible (the passenger travel demand for two-wheelers is almost as big as for cars; Bose and Sperling, 2001) and in our calculation, the fuels used by two-wheelers are not distinguished from fuel used by cars. For PAS, the same reasoning may apply for the rather low estimate of the fuel consumption rate. In addition, a different assumption on the bus occupancy rate again leads to a different fuel consumption rate; the bus occupancy rate of 20, instead of 18.3, would make the fuel consumption rate at 8.1 liters per 100 kilometer instead of 7.8 liter, and 25 would make it 9.6 liter per 100 kilometers.

Table 7: Fuel consumption rate estimates for light duty vehicles (on the road average) from other sources.

	1973	1975	1980	1985	1990	1995	2000	
US	19.8	19.3	17.7	16.1	14.3	14.0	13.9	EIA (2003a)
					13-14			Michaelis *et al*. (1996)
	17.7	17.4	15.4	14.1	12.4	12.1	11.9	IEA (2003a)
Japan	11.0				10.8			Davis and Diegel (2002)
	8.2	8.6	8.7	8.0	7.8	8.1	7.9	EDMC (2002)
	8.9	9.8	10.7	10.1	10.3	11.0	11.3	IEA (2003a)
(Japan and Korea)					10-11			Michaelis *et al*. (1996)
Australia		12.4	12.7	11.9	11.4	11.2	11.4	IEA (2003a)
Europe	10.2				9.4			Davis and Diegel (2002)
Europe 15			8.4	8.1	7.5	7.1		Samaras *et al*. (1999)
Western Europe					8-11			Michaelis *et al*. (1996)
Austria			10.7	10.0	9.2	9.0	8.5	IEA (2003a)
			9.5	8.6	7.8	8.0		Samaras *et al*. (1999)
Belgium			10.3	9.4	8.4	8.1		Samaras *et al*. (1999)
Canada				14.2	10.9	11.4	11.5	IEA (2003a)
Denmark	8.8	8.7	9.3	8.5	7.9	7.3	7.1	IEA (2003a)
			6.3	7.4	6.7	6.2		Samaras *et al*. (1999)
Finland	10.1	9.3	9.4	9.8	9.4	8.4	7.7	IEA (2003a)
			7.4	7.2	6.9	6.0		Samaras *et al*. (1999)
France	8.3	8.5	9.1	8.8	8.2	7.9	7.5	IEA (2003a)
			8.3	7.7	7.3	6.4		Samaras *et al*. (1999)
Germany	9.6	10.0	10.2	10.0	9.6	9.2	8.9	IEA (2003a)
			9.2	9.2	8.1	8.5		Samaras *et al*. (1999)
Greece			9.3	8.5	7.7	7.5		Samaras *et al*. (1999)
Italy	7.6	8.2	8.8	8.3	7.5	7.6	6.6	IEA (2003a)
			7.1	7.4	6.5	5.6		Samaras *et al*. (1999)
Ireland			8.2	7.7	6.0	5.6		Samaras *et al*. (1999)
Luxembourg			11.0	13.2	16.7	18.0		Samaras *et al*. (1999)
Netherlands	9.4	9.4	9.0	8.6	7.9	8.0	7.9	IEA (2003a)
			7.2	7.3	6.6	6.2		Samaras *et al*. (1999)
Norway	10.1	10.4	10.5	9.8	8.8	8.6	8.6	IEA (2003a)
Portugal			8.0	6.3	7.5	6.7		Samaras *et al*. (1999)
Spain	0.0	0.0	9.3	8.5	8.1	8.2	8.1	IEA (2003a)
			7.7	5.9	6.8	6.6		Samaras *et al*. (1999)
Sweden	10.0	10.0	9.8	9.4	9.2	9.1	9.2	IEA (2003a)
			9.1	9.3	7.9	8.2		Samaras *et al*. (1999)
UK	9.9	10.3	10.3	10.1	9.0	8.4	8.0	IEA (2003a)
			9.1	8.7	8.0	7.7		Samaras *et al*. (1999)
Singapore					9.0			Michaelis *et al*. (1996)
Poland					9.0			Michaelis *et al*. (1996)
Former USSR							12.0*	Michaelis *et al*. (1996)
Sub-Saharan Africa				20-25				Michaelis *et al*. (1996)
China, India and Thailand					11-14			Michaelis *et al*. (1996)

* Note to Former USSR data: highly uncertain.

3.4.2 Calculating fuel consumption rate targets

We calculated fuel consumption rate targets implied by our sustainable-development scenario by first estimating the fuel consumption rates for conventional cars (ICE engine using gasoline and diesel oil) and modifying these with the technology substitution effect calculated by MESSAGE.

Fuel consumption rate targets calculation for conventional cars (cars with ICE engine using gasoline and diesel oil)

In principle, the estimation of the fuel consumption rate targets for conventional cars was made using the following assumptions; by 2050, the average fuel consumption rates in industrialized regions (NAM, WEU, and PAO) will achieve the fuel consumption rates of the best available car in the market in the year 2000; by 2100, the average fuel consumption rate in industrialized regions will achieve the fuel consumption rates of cars with all currently (in the year 2000) foreseeable technological options implemented. According to our analysis, the best available cars in the current market have a 20% higher fuel economy than the average cars in the market. Likewise, according to the review of the published literature, we consider that currently implementable technology options would achieve the fuel economy improvements of about 50%. For developing world regions, it is assumed that each region would follow the pattern of fuel consumption rates improvement of one of the three industrialized regions[6]. A detailed description of the methodology is given in Appendix 8.3.

Table 8 summarizes the passenger cars' fuel consumption rate targets for gasoline/diesel-based cars. Table 9 shows the same results in terms of miles per gallon. Note that these targets are not for new cars but for the average cars on the road. The target calculated for NAM for 2050 is 10.7 liters per kilometer, which is about the current level of the fuel consumption rate in PAO. Targets for WEU, PAO, EEU, and LAM in 2050 are calculated at around 7 liters per kilometer. Targets for MEA and CPA, which are the two regions with much higher-than-average fuel consumption rates in 1990, are calculated around 17 liters per 100 kilometer which is about the current level of the FSU region. The target for SAS is set at the same level as the 1990 level because this relatively low fuel consumption rate in 1990 is likely due to the fact that the transportation demand for two-wheeled vehicles is included and it is expected that as more cars come in, the average fuel consumption rates will increase.

Table 8: Conventional (gasoline/diesel based) passenger vehicles' fuel consumption (on the road average) targets, liters per kilometer.

	1990	**2000**	**2020**	**2040**	**2050**	**2080**	**2100**
NAM	**13.8**	12.9	12.1	11.4	**10.7**	10.0	**9.4**
WEU	**9.3**	8.6	8.0	7.4	**6.9**	6.4	**5.9**
PAO	**10.2**	9.3	8.5	7.8	**7.1**	6.5	**5.9**
EEU	**10.8**	9.8	8.8	8.0	**7.2**	6.5	**5.9**
FSU	**17.7**	16.3	15.0	13.9	**12.8**	11.8	**10.9**
CPA	**29.0**	25.6	22.6	20.0	**17.7**	15.6	**13.8**
SAS	**8.9**	8.9	8.9	8.9	**8.9**	9.0	**9.0**
PAS	**7.8**	7.5	7.1	6.8	**6.5**	6.2	**5.9**
LAM	**10.7**	9.7	8.8	8.0	**7.2**	6.5	**5.9**
AFR	**14.7**	13.6	12.6	11.7	**10.8**	10.0	**9.3**
MEA	**33.0**	28.0	23.7	20.2	**17.1**	14.5	**12.3**

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[6] Here we assumed that FSU, MEA and CPA follow NAM; EEU, LAM, and AFR follow WEU; and SAS and PAS follow PAO. For detailed discussion, see Appendix 8.3.

Table 9: Conventional (gasoline/diesel based) passenger vehicles' fuel consumption (on the road average), miles per gallon.

	1990	**2000**	**2020**	**2040**	**2050**	**2080**	**2100**
NAM	**17.1**	18.2	19.4	20.7	**22.0**	23.5	**25.0**
WEU	**25.4**	27.4	29.5	31.8	**34.3**	37.0	**39.9**
PAO	**23.1**	25.3	27.7	30.3	**33.2**	36.4	**39.9**
EEU	**21.8**	24.1	26.7	29.5	**32.6**	36.1	**39.9**
FSU	**13.3**	14.4	15.7	17.0	**18.4**	20.0	**21.7**
CPA	**8.1**	9.2	10.4	11.8	**13.3**	15.1	**17.1**
SAS	**26.3**	26.3	26.3	26.3	**26.3**	26.3	**26.3**
PAS	**30.1**	31.5	33.0	34.6	**36.3**	38.0	**39.9**
LAM	**21.9**	24.2	26.7	29.6	**32.7**	36.1	**39.9**
AFR	**16.0**	17.2	18.6	20.1	**21.7**	23.4	**25.3**
MEA	**7.1**	8.4	9.9	11.7	**13.8**	16.2	**19.1**

By 2100, the fuel consumption rate targets for WEU and PAO, as well as PAS and LAM are calculated at 5.9 liters per 100 kilometer. For CPA, the target calculated the highest of all regions, at 13.8 liters per 100 kilometer which is about the level of the current average fuel consumption rate in NAM.

If one compares the results presented in Table 8 and the actual development of fuel consumption rates for the average gasoline/diesel-based cars on the road in the past 30 years presented in Table 7, the estimated targets do not appear ambitious. For example, in the US, the fuel consumption per 100 kilometers was reduced by 6 liters, from 20 liters to 14 liters, between 1973 and 2000. In comparison, fuel consumption rate improvement targets set for industrialized regions between 1990 and 2050 are to reduce fuel consumption per 100 kilometers between 2.4 liters and 3.1 liters. In Japan and Europe, the fuel consumption rates in the past have not decreased as drastically as in the US; the decrease was between 0.7 and 1.9 liters. For Japan, one source even shows an increased fuel consumption rate (IEA, 2003a). These are likely due to the change in consumer preference towards bigger cars. We note that our targets do not take such effects into consideration when calculating the target fuel consumption rates.

Also note that our target values reflect on-the-road average fuel consumption rates, which are often different from the cars' fuel consumption rates as announced by the manufacturers. For example, taking the case of the EPA's test rating, real-life fuel consumption is higher on the average than their driving cycles would indicate i.e., fuel economy calculated for US Federal urban and highway driving cycles; thus, fuel consumptions for different time points are best compared relatively (in percentage differences) rather than absolutely (fuel consumption per kilometer) (Weiss *et al.*, 2000). The difference between "official" and "on the road" fuel consumption rates mainly comes from higher consumption rates in city driving in comparison to highway driving, increasing congestion levels, and rising highway speeds. The value of the so-called "degradation factor" for cars (the ratio between official and on the road fuel consumption rates) in 1990 was estimated to lie somewhere between 0.85 and 0.75 for 2000 in the US case (EIA, 2003c). In other cases, differences can arise because, among other things, cars usually are not tested with auxiliary equipment, such as air conditioning in operation, and some tests do not include cold starts, which can results in excess fuel consumption as high as 50% for short trips in cold weather. In some regions, poor road qualities may also increase fuel consumption by up to 50% in Russia (Michaelis *et al.*, 1996).

Fuel consumption rate targets calculation for cars (including conventional and alternative cars)

Applying the efficiency improvement targets for the conventional technologies (Table 8) to the relative end-use efficiencies of alternative technologies to conventional technologies are presented in Table 2, and using the technology mix calculated in MESSAGE (Figure 7 and Figure 8)[7], we calculated the efficiency improvement targets for cars, including alternative technologies, such as fuel cell cars. Table 10 summarizes the results of the estimates of passenger cars' fuel consumption rate targets.

Table 10: Passenger vehicles' fuel consumption (on-the-road average) targets, including alternative vehicles, liter per kilometer.

	1990	**2000**	**2020**	**2040**	**2050**	**2080**	**2100**
NAM	**13.7**	12.5	8.2	6.0	**5.5**	4.6	**4.7**
WEU	**8.6**	6.9	5.4	4.0	**3.5**	2.9	**2.8**
PAO	**9.3**	6.5	4.9	3.7	**3.2**	2.9	**2.8**
EEU	**8.5**	7.9	6.1	4.4	**3.7**	3.4	**3.2**
FSU	**13.9**	10.8	10.7	8.9	**7.9**	6.4	**5.4**
CPA	**25.7**	22.2	17.8	13.6	**11.9**	8.3	**6.8**
SAS	**8.5**	8.0	7.9	5.9	**5.8**	4.3	**3.7**
PAS	**7.7**	7.1	5.0	4.4	**4.1**	3.6	**3.4**
LAM	**10.6**	9.5	6.9	5.3	**4.7**	3.9	**3.4**
AFR	**13.5**	10.9	9.9	7.2	**6.1**	4.5	**3.9**
MEA	**32.6**	26.7	19.5	11.4	**9.0**	7.3	**6.5**

Let us now, for comparison, present estimates and targets available from other published sources as to what fuel economy that a car with advanced feature could achieve. The United States initiated the Partnership for a new generation of vehicles (PNGV) with the "Big Three" (Ford, DaimlerChrysler, and GM) automobile manufacturers, to develop, by the year 2004, a prototype vehicle that would achieve a threefold (80 mpg, 2.9 liter per 100 kilometer) improvement in fuel efficiency while matching the affordability, safety standards, performance and comfort of current passenger cars (Sissine, 1996).

MIT's results of a vehicle computer simulation model (Weiss *et al.*, 2002) calculated a fuel consumption of 94.1 mpg (2.5 liter per kilometers) for hydrogen fuel cell cars (compared with 27.8 mpg, 8.5 liters per 100 kilometer, in 1996). This is assuming a significant improvement of on-board hydrogen storage systems, i.e., that hydrogen tanks can be developed with capacity, weight, volume, and shape that will permit competitive driving range without compromising other qualities such as passenger and cargo space.

In round numbers, an engine-driven vehicle that incorporates the essential elements of an ultra light-hybrid design synthesis would normally achieve a fuel economy of about 2-3 liter per 100 km (engine driven-liquid-fueled car), while a version with hydrogen fuel cells would achieve roughly 2 or fewer liter per 100 kilometer (Lovins and Williams, 1999).

OTA's technology assessment (OTA, 1995) estimates that by 2015, an aluminum-bodied mid-size PEM fuel cell vehicle with methanol fuel and a bipolar lead acid battery for high power need and cold start power might be capable of achieving about 80 mpg.

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[7] The technology mix calculated in MESSAGE includes not only automobile, but also other transportation modes such as bus, train, air, and ship. Since we are not able to disaggregate the technology mixes to each transportation mode, we used the aggregate MESSAGE technology mix for transportation sector as a proxy for the technology mix for passenger automobile.

3.5 The global car market

In this section, we estimate the size of the global car market (new car sales) that is consistent with the sustainable development future as is described by the PF scenario. The steps taken to calculate the car markets for the 11 world regions are as follows.

1. Calculate passenger transportation demands (for motorized transportation), in person-kilometers (pkm), from MESSAGE's final-energy use for passenger transportation using estimated EJ/pkm ratios. To disaggregate the MESSAGE's total final-energy use into energy use for passenger and freight transportation, we use the historical relationship between GDP and passenger/freight final-energy use ratio, which was also estimated.
2. Calculate the share of cars the in total passenger transportation demand using a modal split model developed by Schafer and Victor (2000). The model used the same GDP assumptions that we use in the PF scenarios.
3. Calculate the passenger transport demand for cars.
4. Estimate the average annual driving distances of a car in the initial year (1990) using the car transportation demand in terms of vehicle km (passenger transportation demand for a car divided by a car occupancy rate) and the number of cars estimated based on AAMA data (AAMA, 1997) for 1990. We use 15,000 km as a value for 2050 and interpolated the intermediate years.
5. Using the occupancy rate, an average annual driving distance by a car, and an average service life of a car (depreciation rate), calculate the size of new car sales.

Figure 9 presents the daily passenger travel demand by person, calculated in step 1. In the NAM region, a person travels the longest distance, 50 kilometers a day on average. In comparison, in the CPA region, a person travels only 1.8 kilometers a day. In other developed regions, the travel distances are generally short; 3.2 kilometers in AFR, and 4.9 kilometers in SAS. The world average daily travel distance is about 12 kilometers and there are notable inter-regional differences in the motorized-travel demand. The differences get smaller by 2050, mainly due to the increase of the motorized-travel demand in currently developing regions. The NAM region however keeps having the largest travel distance compared of all world regions even by 2050.

Figure 10 presents the shares of car travel in the total passenger travel demand calculated in step 2. The share that cars account for is substantially different from region to region. The share is outstandingly high in NAM and WEU, exceeding 75%. On the other hand, in SAS and CPA the share is insignificantly low, below 10%. The shares in industrialized countries decrease by 2050 due to the modal shift to faster modes of transportation (mainly airplanes). In most other world regions, the shares for car transport increase significantly, with the exceptions that in some of the world regions, the shares peak before 2050, again, due to the introduction of and shift to faster transportation modes.

Combining passenger travel demands (Figure 9) and shares of cars (Figure 10) gives a passenger transportation demands for cars as shown in Figure 11 (step 3).

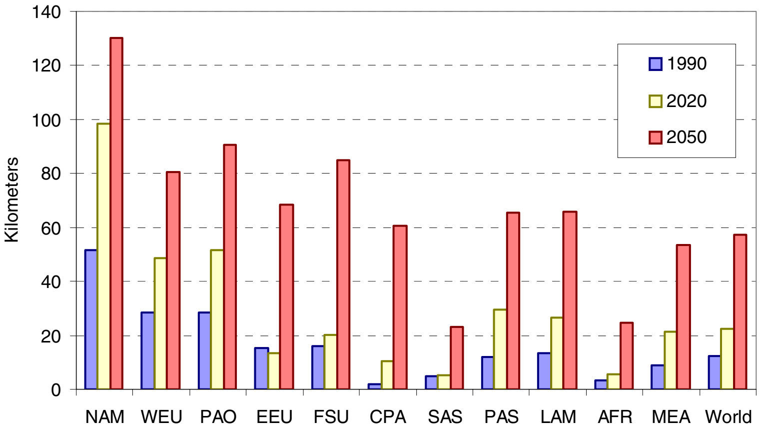

Figure 9: Daily passenger travel demand by person, in passenger kilometers per day.

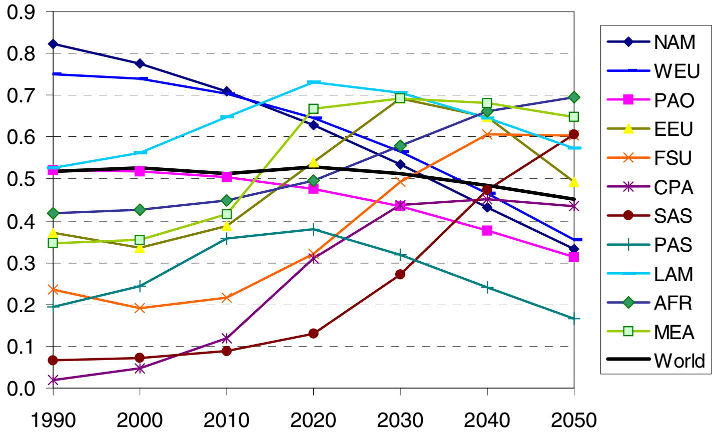

Figure 10: Shares of automobiles in passenger transport in the 11 regions in the PF scenarios, in percent of total passenger transportation demands, calculated based on Schafer and Victor (2000).

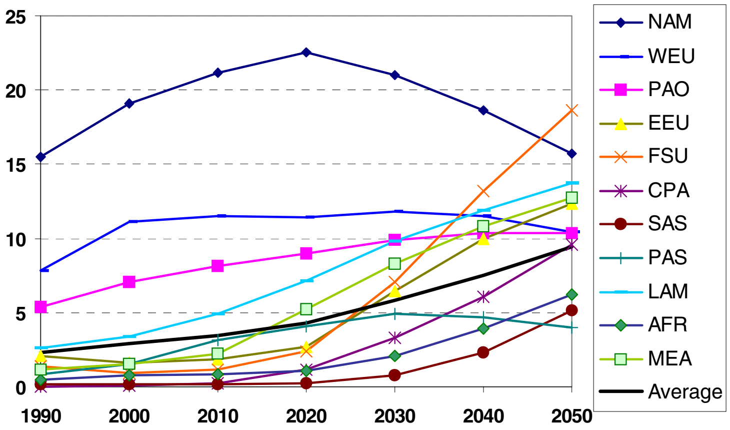

Figure 11: Daily passenger transportation demand for automobiles per person, passenger-km per person.

Reflecting the high passenger travel demand in NAM, the passenger transportation demand for cars in this region is also high. However, with a shift to faster transportation modes, the automobile passenger travel demand begins to decrease around 2020. A similar trend is found for WEU, but there it stabilizes rather than decreases. All other regions are characterized with increased passenger car demands. In particular, the increase in the FSU region is remarkable.

In Step 4, we estimated the average annual driving distance of a car in 1990. Such data are available from various sources, but no consistent, reliable data covering the whole world was found. Thus we estimated it by ourselves, using the passenger car demands calculated in Section 3.4 (in terms of vehicle kilometers) and the numbers of cars estimation based on data from American Automobile Manufacturers Association (AAMA, 1997).

We have estimated the number of cars in 1990 for 11 world regions, and compared the estimates for individual countries available from three sources; American Automobile Manufacturers Association (AAMA, 1997), International Road Federation (IRF, 2000), and EIA World Energy Projections System (EIA, 1999), and decided to use the AAMA as a main data source for our purpose since it is the most consistent dataset and since it covers the large number of countries. We first summed up for each region the numbers of cars in individual countries. Since not all countries are covered by AAMA data, we extrapolated the number in proportion to world-regional population. For a detailed discussion on this calculation, see Turton and Barreto (2004).

Table 11 presents the number of cars in 1990 in 11 world regions. Globally, it is estimated that there were 460 million cars as of 1990, 40% of which were owned in the NAM region, 33% in WEU and 10% in PAO. These three industrialized regions together thus account for 83%. Again, the regional difference is remarkable. In the NAM region, 65 cars were available for 100 persons. On the other hand, in the Asian developing regions, only 3 in 1000 persons (CPA) and 2 in 1000 persons (SAS) own a car. On the global average, 9.5 cars are available to 100 persons.

Using this data, we calculated average annual driving distances of cars for 1990, by dividing the passenger transportation demand in terms of vehicles kilometers with the number of cars (Table 11). The fist column of Table 12 shows the estimated average annual driving distance for 1990.

Table 11: Number of cars in million, and number of cars per 100 persons in 1990, estimated based on AAMA data.

	Number of cars	**Per 100 persons**
NAM	182.6	65.1
WEU	150.8	34.8
PAO	50.3	34.9
EEU	11.9	9.6
FSU	10.1	3.5
CPA	3.1	0.3
SAS	2.8	0.2
PAS	10.6	2.5
LAM	23.4	5.4
AFR	5.0	1.0
MEA	9.3	3.5
World	**459.9**	**9.5**

Table 12: Estimation and assumption on average annual driving distance.

	Estimation for 1990	Assumption for 2050
NAM	14,706	15,000
WEU	11,723	15,000
PAO	11,051	15,000
EEU	10,853	15,000
FSU	19,898	15,000
CPA	2,750	15,000
SAS	17,495	15,000
PAS	14,921	15,000
LAM	24,227	15,000
AFR	19,280	15,000
MEA	16,303	15,000

From the estimates for 1990, it is difficult to find a clear pattern regarding the relationship between the level of economic development and the average driving distance. Developing countries may have greater average driving distances, as is the case for CPA and LAM, but this is not always the case. Driving distance may decrease with better public transportation infrastructure, higher ownership of cars (if one person owns more than two cars, for example), and higher congestion in urban transportation, which often is associated with economic development. On the other hand, better highways and a shift from public transportation to private transportation, which too is often associated with economic development, may also lead to greater driving distances. Also, geophysical characteristics and population density of regions are highly influential to determine the driving pattern. For these reasons, making reasonable assumptions regarding the future development of the driving distances includes highly uncertain factors.

However, we needed some assumptions regarding future driving distances by a car for the calculation of the future global car market in step 5. The right-hand column of Table 12 shows assumed average annual driving distances of cars in 2050. For all world regions, we assumed that the average annual driving distances of cars converge at 15,000 kilometers. The choice of this value is based on an analysis done by Schafer (1995). For the intermediate years, we interpolated the estimated values for 1990 and the assumption for 2050. When calculating the global automobile market in step 5, we did some sensitivity analysis regarding alternative assumptions on the future average annual driving distances.

The number of cars in the future is calculated by dividing the car passenger transportation demand in terms of vehicle kilometers with the average driving distance (step 5). By dividing the number of cars with the average service life of a car (year), we can calculate the size of the car market for each world region. For the average service life of a car, we used 10 years uniformly for all regions and all time points.

Figure 12 shows the development of the numbers of cars per person in the 11 world regions. The values for 1990 correspond to the right-hand column of Figure 11. The developments over time look similar to the development of the passenger transportation demands for cars per person (Figure 11). Figure 12 also shows error bars which correspond to the results using alternative values for the annual average driving distance in 2050. The highest end of the estimation corresponds to the results using 10,000 kilometers, and the lowest end of the estimation corresponds to the results using 20,000 kilometers, instead of 15,000.

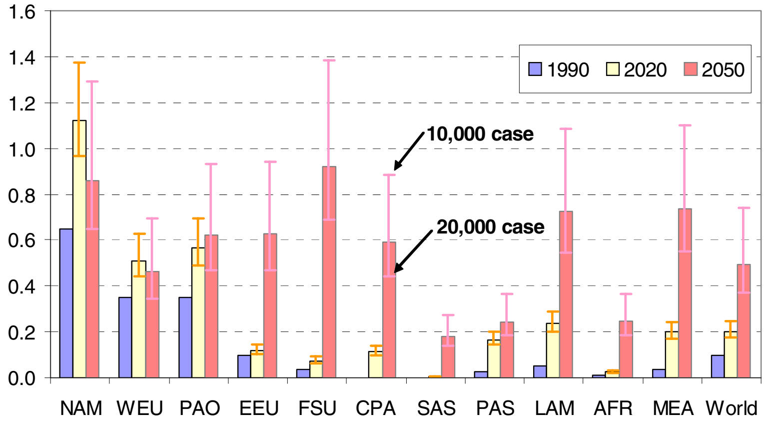

Figure 12: Number of cars per person in the 11 regions in the PF scenario, with uncertainty range.

By 2050 in the PF scenario, 50 cars are owned by 100 persons on the global average, which is less than the current level in NAM but much higher than the current levels in WEU and PAO. In most of the world regions, the car ownership in 2050 exceeds current levels of WEU and PAO. Three significantly delayed regions in terms of car ownership (SAS, PAS, and AFR) as of 1990 also achieve substantial increases of car ownerships, to about 20 cars per 100 persons.

Figure 13 shows the development of the global passenger car market in the PF scenario. Note that the numbers presented here are lower than those presented in the interim report to this collaboration project (Miketa and Schrattenholzer, 2002). This is the result of using the refined estimation methodology that we described above. In our new estimation, the market size increases from 50 million cars per year in 1990 to 400 million cars per year. The relative importance of the regions also changes substantially. In 1990, more than 80% of the car market was comprised from industrialized regions. By 2050, the share of the industrialized regions' market decreases to 20%. CPA will instead become a big market accounting for 20% alone. Other developing regions like MEA, LAM, SAS, and AFR will also turn into big car markets.

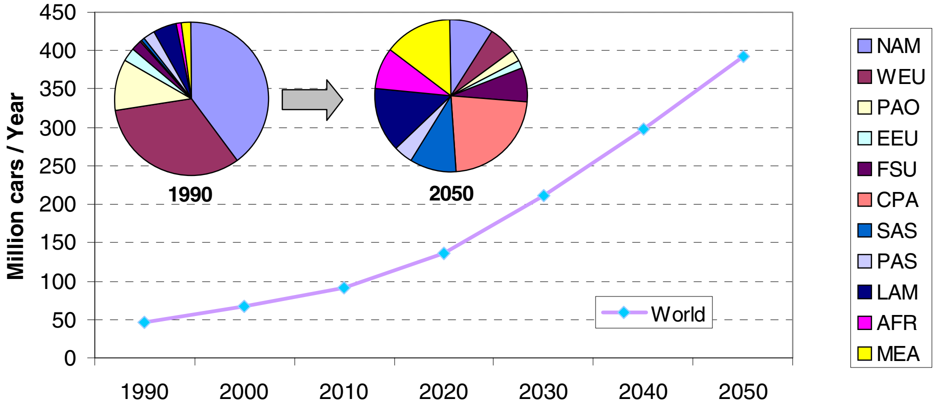

Figure 13: The development of the global passenger vehicle market in the PF scenario, in million cars per year.

Figure 14 illustrates the regional developments of the world-regional car markets in absolute terms. Emerging markets in CPA, MEA, and LAM each exceed even the size of the current global car market. Note that we consider the numbers presented here to be at the high end of plausible market sizes. This is particularly so for the developing regions because we used a 10-year as an average service life of a car uniformly to all regions, when in developing regions the service life of cars is expected longer due to limited financial means to buy new cars. Although it is difficult to obtain reliable estimates of the average service life of cars, there are some estimates that suggest a length of service between 20 and 25 years. If we were to use 25 years (instead of 10) as the average service life for the eight developing regions (all 11 world regions except NAM, PAO, and WEU), the new estimate of the market sizes would be 200 million instead of 400 million for the globe and 20-35 million instead of 55-85 million for CPA, MEA and LAM in 2050.

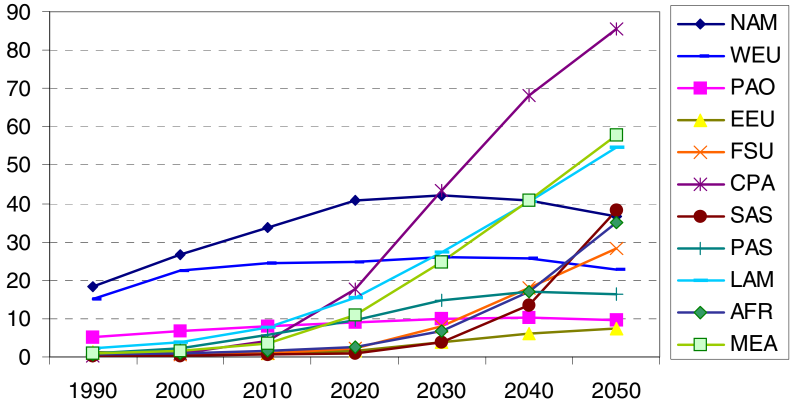

Figure 14: The developments of the passenger vehicle market in the 11 regions in the PF scenario, in million cars per year.

3.6 Demand-saving and carbon emission reduction potentials due to efficiency improvement in the transportation sector

MESSAGE calculates end-use efficiency (useful-energy demand divided by final-energy use) for the transportation sector in a way that is different from the other two sectors, industry and residential/commercial. It differs because this efficiency improvement does not include the efficiency improvement of the oil-based technology (because in MESSAGE the assumption is a constant efficiency for the oil-based technologies) and therefore this efficiency is solely due to the change in the technological composition as described in Section 3.3.

Figure 15 shows the end-use efficiency for the transportation sector in the PF scenario. It increases steadily over the century. The efficiency in 1990 was 15%, which is about the gasoline-based ICE's efficiency. Due to the introduction of more efficient technologies, such as fuel cell based electric motors, the efficiency reaches almost 23% by 2100.

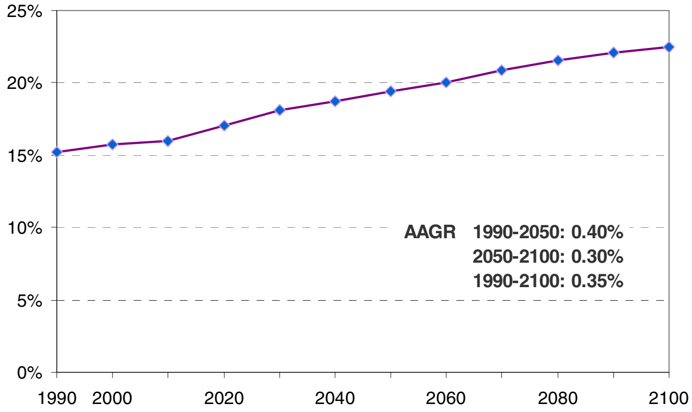

Figure 15: Final-useful energy efficiency in the transportation sector in the PF scenario, in percent.

Figure 16 shows the potential final-energy use reduction due to the end-use efficiency improvement as is described in the PF scenario. The potential reduction is calculated as the difference between would-be final energy use when there was no improvement of the end-use efficiency from 1990 and the final energy use calculated in the PF scenario. The potential reduction in the year 2100 is 240 EJ and corresponds to nearly 50% of the final-energy use in the transportation sector in 1990.

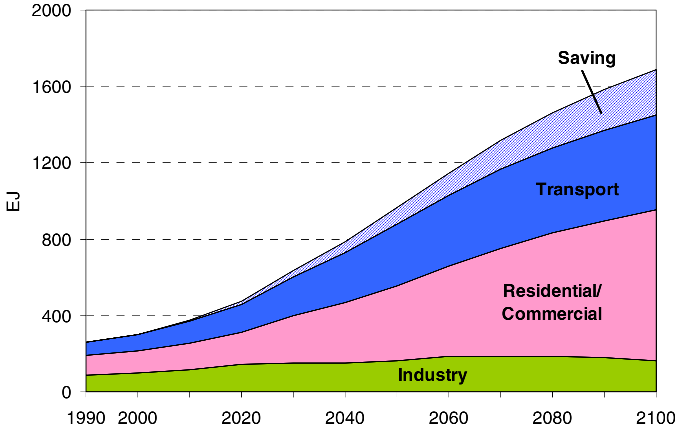

Figure 16: Global final energy use by sector in the PF scenario, and savings due to efficiency improvements in the transportation sector, in EJ.

A substantial shift from an oil-based to a fuel cell-based transportation system – as illustrated by the PF scenario – results in a thorough de-carbonization at the end-use level. Figure 17 shows the CO_2 emission reduction potentials due to decarbonization compared with those due to the end-use efficiency improvement described above. The orange line in the figure represents the development of CO_2 intensity of final-energy use in the transportation sector under the PF scenario. Only those CO_2 emissions are considered here that are directly emitted by the use of transportation technology at the end-use level. Since, in comparison with the other two sectors, technological change is the most drastic in the transportation sector, its de-carbonization effect and corresponding CO_2 reduction potentials are the most significant. The CO_2 intensity of transportation drops from 12 MtC/EJ in 1990 to 0.8 MtC/EJ by 2100, and this would contribute to a reduction of CO_2 emissions by nearly 6 GtC (90% reduction) relative to would-be emissions in 2100 if no technological change would take place after 1990. In comparison, the contribution of the end-use efficiency improvements to the CO_2 emission reductions is rather insignificant.

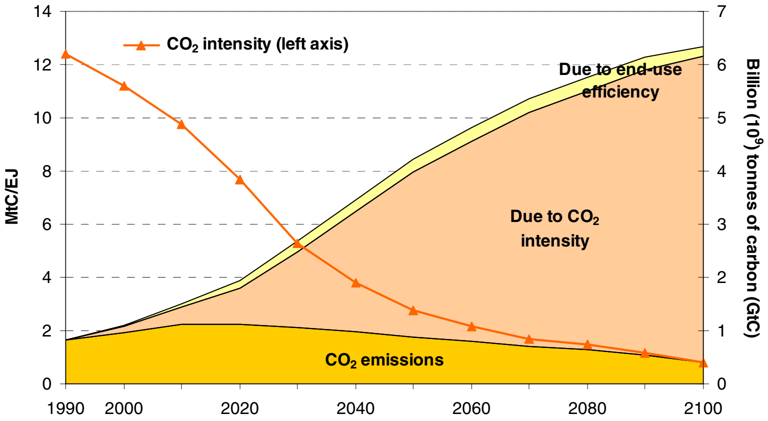

Figure 17: CO_2 emissions by the transportation sector (end-use only, right axis), CO_2 intensity development (left axis), and savings due to CO_2 intensity reduction (right axis)

Figure 18 shows a similar figure, but this time including *all* CO_2 emissions related to the transportation activities, i.e., including also emissions from producing and delivering the fuels or extracting the primary energy. The share of the direct CO_2 emissions from the transportation sector (CO_2 emissions in Figure 17 divided by ones in Figure 18) decreases from 53% to 19% by 2050, and stabilizes around that value by 2100. This indicates that the transportation end-use technologies achieve very low CO_2 emissions and the CO_2 emissions are mainly from the extraction, production, and delivery of transportation fuels. De-carbonization of transportation technologies and changes in the fuel production technologies have the potential of reducing 10 GtC of CO_2 emissions relative to would-be emissions without any technological progress since 1990.

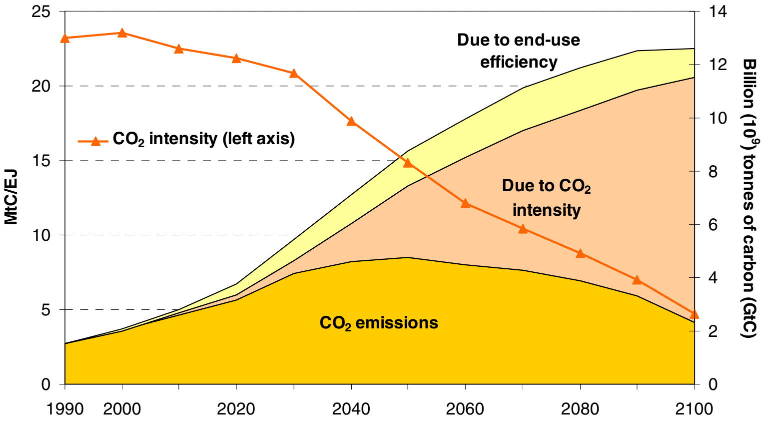

Figure 18: Total ("well-to-wheel") CO_2 emissions related to energy consumption in the transportation sector (right axis), CO_2 intensity development (left axis), and savings due to CO_2 intensity reduction (right axis).

3.7 Time targets for the introduction of fuel cell vehicles

The development of the technological mixes suggested by the PF scenario can provide an idea about time targets for the introduction of fuel cell cars. The fuel cell cars considered here use alcohol (ethanol or methanol) or hydrogen. Figure 19 shows the introduction of fuel cell cars calculated according to the PF scenario. These numbers could be interpreted as targets that could be achieved by successful technology policy aiming at the development and diffusion of fuel cell technologies and/or by generally favorable conditions. The target number for annual sales of fuel cell cars increases each decade and by 2050 it is about 1.7 billion (of which 25% are hydrogen-based cars) in comparison to the total number of cars at 4 billion. The choice of feedstock for fueling fuel cell cars reflects world-regional resource endowments.

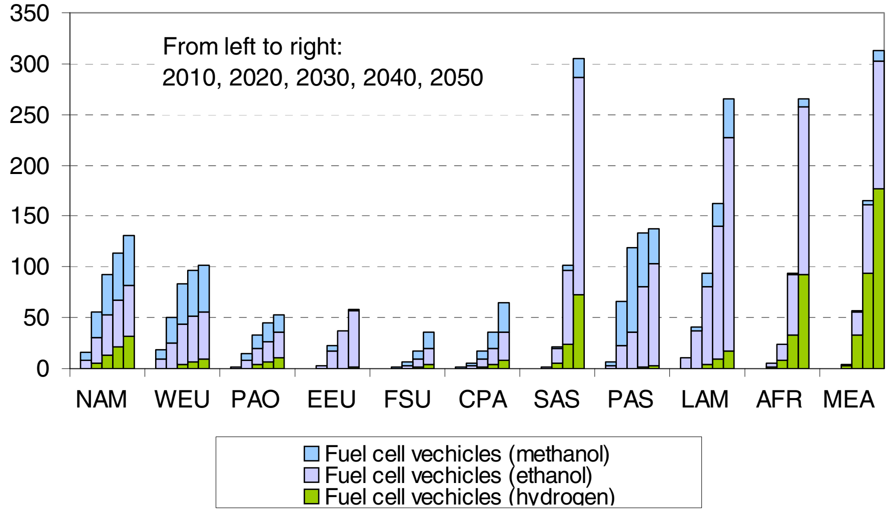

Figure 19: Target timing of introduction of low-emission vehicles

The use of methanol in fuel cell cars is rather limited with the exception of the industrialized regions (NAM, WEU, and PAO) and in some Asian regions (CPA and SAS) where the feedstock fuels are natural gas or coal. The massive introduction of ethanol-based fuel cell cars is possible under the PF scenario in other world regions, such as SAS, LAM, AFR, as well as in MEA. In LAM and AFR, ethanol is produced domestically, using indigenous biomass resources (see Section 6) and thus ethanol cars dominate the fuel cell car market. In MEA and SAS, where ethanol use depends on imports (nearly 90% for MEA, 30% for SAS in 2100), the use of hydrogen – produced domestically – is higher than in other world regions. Hydrogen-based fuel cell cars have a particularly high share in MEA.

The absolute numbers of hydrogen-based fuel cell cars that correspond to Figure 19 are given in Table 13. In the PF scenario, the total number of hydrogen cars sold annually by 2050 is 426 million, and annual sales increase sharply between 2020 and 2050. The pace of the introduction differs substantially among the world regions. In NAM, hydrogen fuel cell cars are introduced around 2010. Other regions follow; in particular AFR and MEA start to introduce the hydrogen fuel cell cars at a massive scale around 2020, with SAS following their pace at around 2030. In these three regions, the potential for the diffusion of the hydrogen-based cars are large because the market for cars using fossil fuels was small in 1990, and all the new infrastructure development could be geared towards fuel-cell cars. The rest of the world also introduces hydrogen-based fuel cell cars, but to a much lesser extent.

Table 13: Number of hydrogen-based cars, million (stocks).

	1990	2000	2010	2020	2030	2040	2050
NAM	0.0	0.0	0.4	5.8	13.8	21.7	**31.9**
WEU	0.0	0.0	0.0	0.0	3.4	6.2	**8.7**
PAO	0.0	0.0	0.0	0.0	3.7	7.2	**11.1**
EEU	0.0	0.0	0.0	0.0	0.0	0.0	**1.4**
FSU	0.0	0.0	0.0	0.1	0.6	2.0	**4.3**
CPA	0.0	0.0	0.0	0.5	1.9	4.3	**8.3**
SAS	0.0	0.0	0.0	0.2	5.0	24.2	**73.2**
PAS	0.0	0.0	0.0	0.0	0.0	1.2	**2.2**
LAM	0.0	0.0	0.0	0.0	4.0	8.9	**16.6**
AFR	0.0	0.0	0.0	1.5	8.2	32.7	**92.1**
MEA	0.0	0.0	0.0	2.7	32.9	94.2	**176.7**
World	**0.0**	**0.0**	**0.4**	**10.8**	**73.5**	**202.7**	**426.5**
(% of total vehicles)	**(0.0)**	**(0.0)**	**(0.0)**	**(0.8)**	**(3.5)**	**(6.8)**	**(10.9)**

The numbers of alcohol-based fuel cell cars introduced under the PF scenario are summarized in Table 14. The introduction of alcohol-based fuel cell cars precedes the introduction of hydrogen fuel cell cars in all regions. The absolute volumes of alcohol-based fuel cars are much larger than hydrogen-based fuel cell cars except in the MEA region. The total target number for alcohol-based fuel cell cars is 1.3 billion, of which the majority (1 billion) are ethanol-based cars.

Table 14: Number of alcohol-based cars, million (stocks).

	1990	2000	2010	2020	2030	2040	2050
NAM	0.0	0.0	15.6	50.2	79.0	91.8	**99.3**
WEU	0.0	0.0	18.9	50.4	79.5	90.4	**93.7**
PAO	0.0	0.0	1.9	14.1	29.6	37.2	**42.2**
EEU	0.0	0.0	0.0	3.0	23.1	37.3	**56.3**
FSU	0.0	0.0	0.2	1.1	5.4	15.7	**31.4**
CPA	0.0	0.0	0.7	5.2	15.3	30.7	**55.8**
SAS	0.0	0.0	0.0	1.1	16.3	77.2	**231.6**
PAS	0.0	0.0	7.1	66.2	119.2	132.7	**134.8**
LAM	0.0	0.6	10.1	41.0	89.3	153.9	**249.2**
AFR	0.0	0.0	0.6	3.4	15.3	61.5	**173.2**
MEA	0.0	0.0	0.0	1.6	23.3	70.7	**136.1**
World	**0.0**	**0.6**	**55.1**	**237.4**	**495.4**	**799.2**	**1303.7**
(% of total vehicles)	**(0.0)**	**(0.1)**	**(6.0)**	**(17.5)**	**(23.5)**	**(26.9)**	**(33.2)**

The introduction of fuel cell cars could be compared with the introduction of electric vehicles, which is currently taking place. The number of electric vehicles (EVs), including hybrid electric vehicles (HEVs), is estimated at 230,000 in 2002 in 11 major automobile market countries[8] that participate in the *Hybrid and Electric Vehicle Implementing Agreement* of the IEA (IEA/HEV, 2003). The average share of electric vehicles in total vehicles is about 0.07%, with Italy having the highest share of 0.14%. Note that this number is not directly comparable with our numbers because the IEA number includes also electric 2-3 wheelers as

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[8] These 11 countries are Austria, Denmark, Finland, France, Italy, Japan, Korea, Netherlands, Sweden, Switzerland, and USA.

well as industrial EVs, which we do not include. Also, their numbers include industrial use and freight transportation. If we were to limit the consideration to HEVs, we could say that most of the HEV's included in the IEA number are for passenger transportation. The number of HEVs in 2002 was 142.5 thousand, and its share in total vehicles was 0.04%. The first commercialization of the hybrid vehicle was Toyota's Prius in 1997, but despite five years of successful commercialization, the share of 0.04% is still rather insignificant. According to the analysis done by the USDOE, the time needed for hybrid vehicles to develop from concept vehicles to mass-produced vehicles was about five years in Japan (DOE, 1999). In the case of the Prius, it appeared as a concept vehicle around 1995, and in 1997, its mass production started.

Given the existing technical challenges for the fuel cell vehicles, the experts' consensus appears to be that they do not expect the commercialization of fuel cell vehicles before 2010. For example, the US Office of Technology Assessment considered it unlikely that a PEM fuel cell can be successfully commercialized for high-volume, light-duty vehicle applications by 2005, although fuel cell developers are hoping for early commercialization in larger vehicle applications (buses, locomotives). Thus, 2015 – or perhaps a bit earlier – seems a more likely date for commercialization, provided the remaining development challenges are successfully met (OTA, 1995).

For policy makers world-wide, it may be useful to closely watch developments in Iceland. There, the government is determined to establish the world's first "hydrogen society" by the year 2050. Although the situation of a country with a population of less than 300,000 and renewable energy sources abundant enough to make the generation of electrolytic hydrogen a promising proposition may not be comparable to most other countries, many pieces of Iceland's experience can be expected to provide ample "learning material" for the rest of the world.

4 The residential and commercial sector

The residential/commercial sector is the biggest sector of the three end-use sectors considered in this report. In 1990, approximately 40% of global final-energy use was consumed by the residential and commercial sector. Of this, electricity use was approximately 11% and the other 89% was energy for thermal purposes including non-commercial energy (37%).

Figure 20 shows the final-energy use for the residential and commercial sector for 11 world regions. Here, energy use is broken down into three energy use categories: non-commercial energy, thermal use, and specific use. Specific use refers to the use of electricity for non-thermal purposes. The given percentages depict the shares of the residential and commercial sector in total final-energy use in 1990. These shares were relatively higher in developing regions, suggesting that they will get smaller as their economic development proceeds.

In developing regions, such as PAS, SAS, CPA, AFR, and LAM, households still rely heavily on non-commercial bio-fuels, such as animal waste, firewood, charcoal, and other biomass, and they have limited access to modern sources of energy such as electricity and liquid fuels. They are mainly used for cooking.

In developed regions, thermal uses of energy account for more than 80% of the total use in the residential and commercial sector (with an exception of PAO, which has 58% due to higher shares for electricity use), in comparison to the global average of 53%.

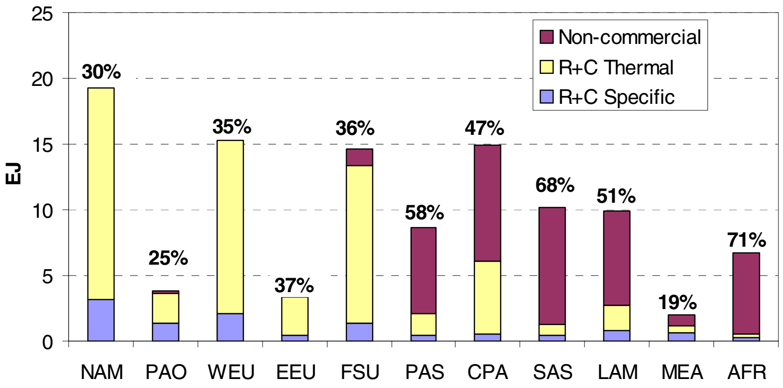

Figure 20: Final-energy use in the residential and commercial sector in 1990 in EJ. Percentages refer to the shares in total final energy consumed by the residential/commercial sector.

The major function of electricity use in the residential and commercial sector are electric lighting, low-temperature heat (for space heating, hot water, and cooking), compressors (mainly refrigeration and air conditioning), other motor-driven devices (such as ventilating fans, washers and dryers, dish washers, vacuum cleaners, mixers, lawn mowers, power tools, toys, record players and PCs) and electronic devices (radio, TV and information processing). Just to illustrate how much electric energy is used in each function, Figure 21 and Figure 22 show this disaggregation for the United States between 1902 and 2000.

When electricity was introduced of in the Unites States' residential sector in the early 1900s (Figure 21), it was used mainly to satisfy the lighting demand in the residential sector. In later years, the use of electricity for heating was established and since then, its share has increased steadily. The share of the refrigeration use of electricity grew rapidly in the late 1920's and early 1930's to reach 30% of electric-energy use. By around 1950, the share of refrigeration has reached 40%. Air conditioning was introduced around 1960 and its share increased incrementally since then until now. And as more and more appliances (i.e., other motors) were introduced into individual households, the electricity consumption in the residential sector grew dramatically. For example, the share of the other motor devices also accounts for nearly 30% of the total electricity consumption in 2000.

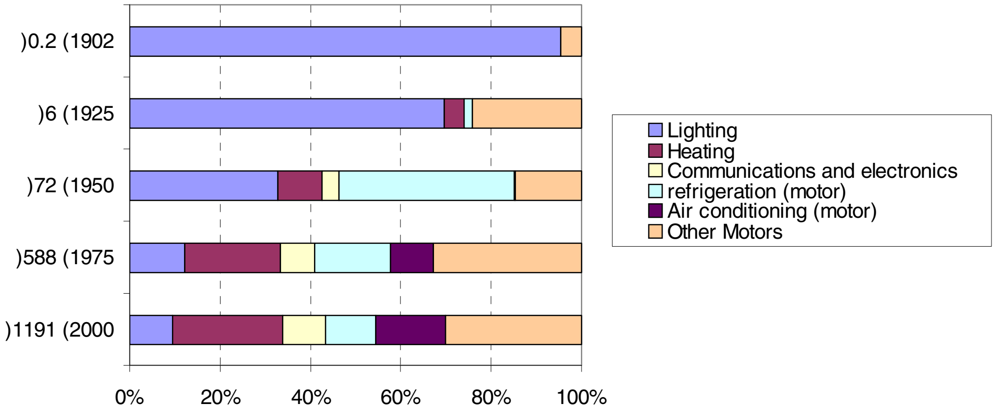

Figure 21: Electricity use by function in the United States in the residential sector (Ayres, *et al.*, 2004). Numbers in the parenthesis next to the years are the total electricity use in billion kWh.

In the United States commercial sector (Figure 22), lighting demand constitutes a large share of the total electricity consumption, similar to the residential sector. Heating demand is less significant. Note that electricity demands in the two parts of the United States' residential and commercial sector were more or less equal, with the residential sector slightly bigger than the commercial sector.

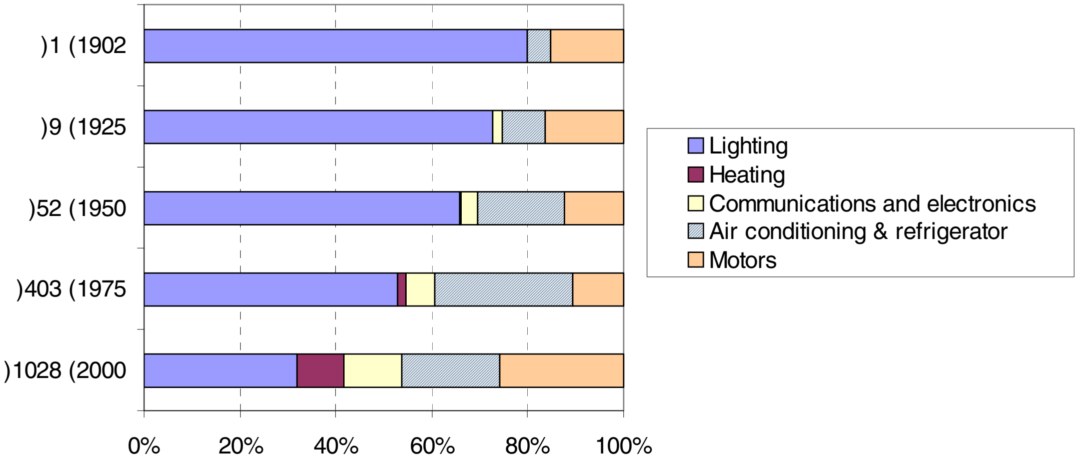

Figure 22: Electricity use by function in the United States in the commercial sector (Ayres *et al.*, 2004). Numbers in the parenthesis next to the years are the total electricity use in billion kWh.

4.1 World-regional final-energy use in the residential and commercial sector

Figure 23 and Figure 24 show the shares of fuels used in the residential and commercial sectors in the four aggregated world regions. Note that in 1990, in all these four regions and in contrast to the U.S. alone, energy demand in the residential sector was larger than in the commercial sector, and this is particularly pronounced in less developed regions.

In the residential sectors (Figure 23), the patterns of fuel use differ considerably across the regions, reflecting differences in resource endowments of each region. In the OECD region, petroleum products such as heating oil (used in central heating) and kerosene (used for stoves, mainly in the PAO region) as well as LPG (used for portable stoves and cooking) and natural gas (sold as city gas or compressed natural gas for homes in rural areas not connected to public utility system) are used as the main fuels for space heating and cooking. Electricity accounts for nearly 30% of the final energy use in this sector in the OECD region.

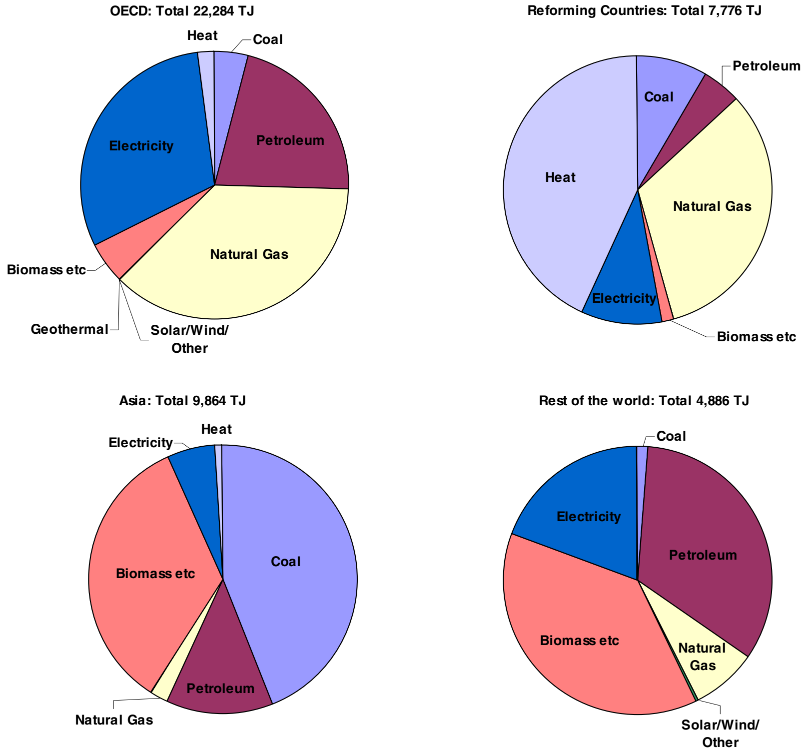

Figure 23: Final-energy use for the residential sector in 1990 for four aggregated world regions. Source: IEA (2002a, 2002b).

In the reforming countries, heat demand is particularly high, presumably due to poor insulation from planned-economy days. Eastern Europe is the main consumer of coal products in this region. On the other hand, natural gas is mainly used in the FSU area, where it serves as the main fuel source.

In Asia, coal and biomass dominate. Particularly in the CPA region, the use of hard coal (used for heating purpose) accounts for a large part of the energy consumption in the residential sector. In PAS, biomass use accounts for more than 40% and is the main fuel source. SAS also relies on biomass fuels, but the region also uses quite a significant amount of petroleum products, mainly kerosene.

In the LAM region, uses of petroleum and biomass dominate. In the LAM and AFR regions, biomass accounts for more than 30% of the fuels used in the residential sector. Oil products are also considered a major fuel source in LAM, in particular, LPG. In the MEA region, half of its fuel consumption in the residential sector are petroleum products, mainly by LPG and kerosene.

In the commercial sectors of all four world regions (Figure 24), the shares of electricity are higher than in the shares of electricity in the respective residential sectors. Non-electric uses of the fuels are mainly for space heating.

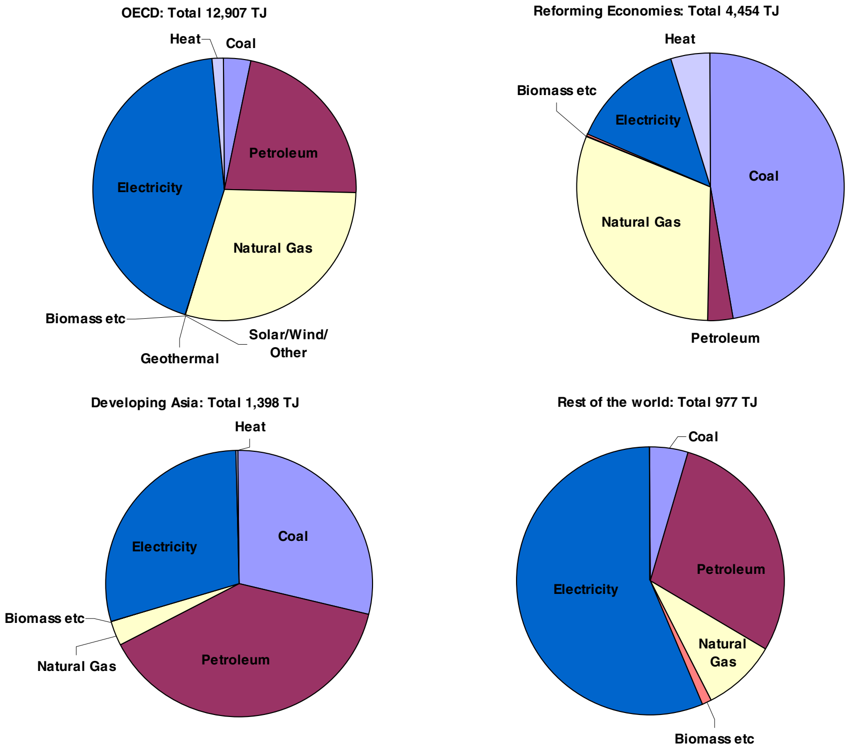

Figure 24: Fuel consumption for the commercial sector in 1990 for four aggregated world regions. Source: IEA (2002a, 2002b).

In the OECD region, electricity use has the largest share, followed by natural gas and petroleum. The use of natural gas is particularly high in the NAM region, whereas the use of petroleum products (mainly heating oil) is particularly high in the PAO region. In the reforming countries, the use of coal (mainly hard coal) has the highest share, in particular in FSU. In contrast, the residential sector of the same FSU region does not use coal. The use of natural gas is also high in FSU, even higher than electricity. In the Asia region, the use of petroleum products (mainly heating oil and kerosene) is particularly high in comparison to other regions. This is particularly so in the PAS region. In the CPA and SAS regions, coal accounts for the largest share. The LAM region has a high share of electricity; although the total demand for the commercial energy demand is small. The high share of electricity may be due to the limited demand for space-heating. In the MEA region, the use of oil products also has a significant share, e.g., mainly heavy fuel oil, LPG, and heating oil. In the LAM region, the main oil product used is heavy fuel oil, which is the cheapest liquid fuel available. In the AFR region, coal, followed by electricity, are the dominant fuel sources.

4.2 Description of key energy conversion technologies in the residential and commercial sector

4.2.1 Technologies for electricity supply to the residential and commercial sector

The MESSAGE model differentiates between electric and thermal uses of energy. MESSAGE calculates the optimal mix of technologies for each energy demand. For electricity generation, currently all electricity is supplied by central power plants, delivered to consumers by grid connections. For the future, there are additional technological options, such as electricity provided by on-site solar photovoltaic systems, by parked hydrogen cars, and by hydrogen-based-cogeneration systems. In the model, these three options are included to provide on-site services that are independent of the grid.

As discussed already, electricity is used in various electric applications in the residential and commercial sector. Assumptions on the efficiency of electric appliances used in MESSAGE are summarized in Table 15. In the following sections, we describe the new electricity supply options for the residential and commercial sector in more detail. Note that electricity use does not emit CO_2 at the end-use level.

Table 15: Efficiency assumptions of the electric appliances used in the residential and commercial sector in MESSAGE, in percent.

Regions	1990	2020	2050	2100
NAM, WEU, PAO	60	63	72	75
LAM, PAS	30	39	66	75
AFR, MEA, CPA, SAS	30	36	54	75
EEU, FSU	50	55	70	75

4.2.1.1 On-site solar photovoltaic system

A solar photovoltaic system is composed of solar cells, which convert sunlight into electricity using the photoelectric effect. Solar cells have been cost-effective for many years for satellites, earthbound signaling and communication equipment such as remote-area telecommunications equipment, off-grid installations such as remote homes and traffic signals, as well as low-power applications such as calculators and garden lighting. In order to use it as a stand alone-system, some means must be employed to store the collected energy for nights and clouded days. Possible storage systems include batteries and hydrogen (produced by the electrolysis of water). Excess electricity could also be fed into a utility grid system.


(http://www.nrel.gov/buildings/pv/basics_solarelectric_fs.html)

For accounting purposes, the “efficiency” of converting sun light to electricity is set at 100% in the PF scenario.

4.2.1.2 Electricity from parked fuel cell vehicles

Fuel cell vehicles (also electric vehicles) are capable of producing electricity for use in homes and buildings. Electricity can be generated using hydrogen stored on-board, or by using a stationary small reformer that could supply a continuous flow of hydrogen to vehicles. While parked, a fuel cell car could act as a power generator to supply local loads or other nearby power needs. The average American car is parked about 96% of the time, usually in places adjacent to residential or commercial consumers (Lovins and Williams, 1999). Kempton *et al.*,(2001) estimated the power generation capacity of a FC vehicle, using the Ford’s P2000 Prodigy, a fuel cell-powered sedan, running on hydrogen. Presently, this type of car can store 2 kg of hydrogen, and a 4-kg storage type is currently under development. The fuel economy of the version with 4-kg hydrogen storage is 0.227 kWh/km (2.6 liters per 100 kilometer)[9] and maximum vehicle range is 160 kilometers. With 1.6 kg of hydrogen (equivalent to 130 kilometers driving) it can produce 44 kWh. For comparison, the average household in Japan has an electricity consumption of about 10 kWh per day.

Household power could be drawn from a car, but the electricity produced in this way is most suitably used to provide peak power to an electricity grid (Kempton and Kubo, 2000). Such a system would make sense under an electricity pricing system that differentiates between peak and off peak times. During off-peak hours, the vehicle could use cheaper electricity to break the water up into hydrogen and oxygen, storing the hydrogen in its fuel tank. Then hydrogen is used to create electricity during peak demand, reducing the drain on the grid.

The technical requirements of such vehicles are on board-power electronics, plug-to-vehicle connections (power connection for electrical energy flow from vehicle to grid), and communication facilities (controllers to signal to the vehicle when powered is requested). For fueled vehicles, a third connection for gaseous fuel maybe added so that on-board fuel is not depleted. All of these are being produced commercially today or available as prototypes in vehicles although they have not yet been combined into one functional piece (Kempton *et al.*, 2001). Figure 25 shows an example design for a vehicle dashboard control for such FC vehicles as suggested by Kempton and Letendre (1997).

The conversion efficiency from hydrogen to electricity is assumed at 30% for all regions and for all time periods in the calculation of the PF scenario.

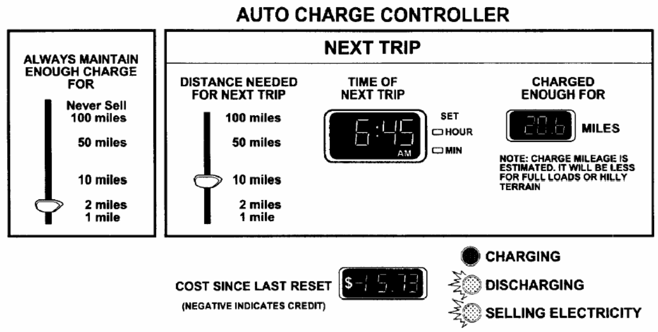

Figure 25: Example design of vehicle dashboard control for FCV with power generation capacity. Source Kempton and Letendre (1997).

4.2.1.3 Fuel cell cogeneration system

(Residential use-fuel cell system installation test: http://www.gas.or.jp /gasfacts_e/12_e.html)

A cogeneration system provides multiple energy forms such as heat and electricity from a single energy source. In conventional large-scale electricity-only generation, the primary-to-final efficiency is typically less than 35% due to waste heat and transmission loss whereas cogeneration systems achieve total efficiencies of 70-80% when utilizing the waste heat. Fuel cell technology is promising for electricity production at local sites as it can be utilized from a wide range of fuels and has a high efficiency rate. Fuel cells can turn 50% or more of the hydrogen's energy into a highly reliable, premium-quality

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[9] 1 kg of hydrogen produces 33kWh which is almost equivalent to the energy produced by 1 gallon of gasoline.

electricity, and most of the remainder into 70ºC pure water (Lovins and Williams, 1999).

One principal attractiveness of the fuel cell technology is that fuel cells can produce power with high efficiency in a wide range of system size. In general, stationary cells are expected to operate nearly continuously, and they also have the potential to act as co-generators, simultaneously producing electricity and useful waste heat (Lipman *et al.*, 2004).

Zero-carbon sources of energy generation, such as wind, geothermal and solar, are intermittent and the energy they produce cannot always be generated exactly on demand. Hydrogen can be used to utilize the full potential of renewable energy by offering the option to generate power exactly on demand. Hydrogen used for cogeneration in fuel cells is either delivered through a grid from a centrally produced hydrogen factory or using on-site reformers (using natural gas or electricity as inputs) integrated into the fuel cell cogeneration system.

The electric efficiency of hydrogen fuel cell cogeneration systems in MESSAGE is set at 80%. This is equivalent to conversion efficiency from an overall hydrogen input to electricity output at 55%[10].

4.2.2 Technologies for supplying the heat to the residential and commercial sector

The second category of energy use in the residential and commercial sector is heat. Heat is used for space heating, cooking, and supplying hot water in residential houses and commercial buildings including hotels and hospitals.

Figure 26 shows the distribution of fuels that provided heat in 1990 for the four aggregated world regions. Heat in both ASIA and ROW comes mainly from non-commercial biomass, such as wood collected in forestry by members of households. Coal also plays an important role in these regions. In the OECD, gas, electricity, and oil products provide more than 80% of all thermal energy to this sector. In the REFs region, unlike other regions, district heating (d_heat) accounts for nearly 25% of heat supplied.

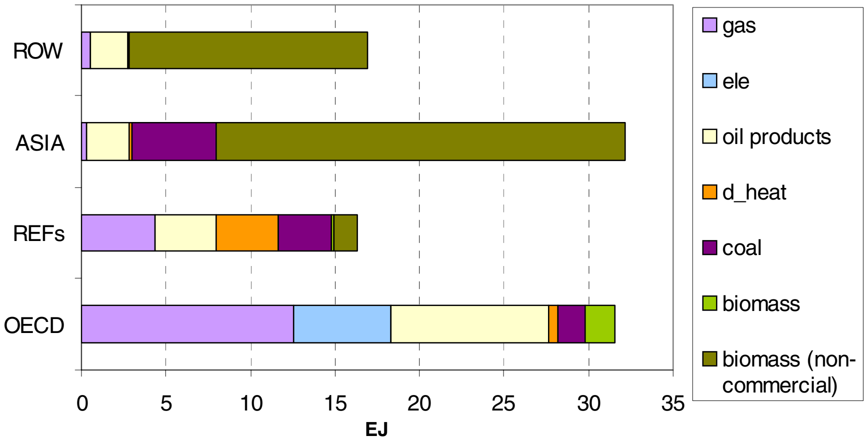

Figure 26: Thermal-energy use for the residential and commercial sector in four aggregated world regions in 1990, in EJ.

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[10] We assume 30% of the hydrogen input goes into thermal energy which produces thermal energy at 100% efficiency and 70% goes into electric energy which produces electric energy at 80%. On a total base, the output efficiency of electricity over the overall hydrogen input is thus calculated at 55%.

In addition to the conventional technologies providing heat, there are some promising key technologies that may be widely used in the future and that have the potential to both increase energy efficiency and reduce CO_2 emissions. These include heat pumps, solar thermal power systems, and fuel cell cogeneration systems, which we describe in detail in the following sections, together with the potential of conventional technologies. Table 16 summarizes assumptions regarding the thermal efficiencies used for the Post-Fossil scenario in MESSAGE. Likewise, Table 17 summarizes the CO_2 coefficient assumptions. Note that in our study, it is assumed that all (commercial and non-commercial) biomass is taken from sources cultivated in a sustainable manner (in other words, only the amount excess to the reproducible amount is assumed to be consumed). Although this might not necessarily be the case in some regions, we assumed that carbon emission from biomass use is therefore zero.

Table 16: Efficiency of heating appliances using different fuels assumed in MESSAGE.

Technology	Regions	Electricity generation efficiency			
		1990	2020	2050	2100
Non-commercial biomass	All regions	11	11	11	11
Biomass-based heating	NAM, WEU, PAO	60	62	68	70
	AFR, MEA, CPA, SAS, LAM, PAS	30	35	50	70
	EEU, FSU	50	54	66	70
Coal-based heating	NAM, WEU, PAO	60	63	72	75
	AFR, MEA, CPA, SAS, LAM, PAS	30	36	54	75
	EEU, FSU	50	55	70	75
Fuel oil-based heating	NAM, WEU, PAO	65	69	81	85
	AFR, MEA, CPA, SAS, LAM, PAS	40	45	60	85
	EEU, FSU	55	61	79	85
Light oil-based heating	NAM, WEU, PAO	70	73	79	85
	AFR, MEA, CPA, SAS, LAM, PAS	45	50	65	85
	EEU, FSU	60	65	80	85
Gas-based heating	NAM, WEU, PAO	75	78	87	90
	AFR, MEA, CPA, SAS, LAM, PAS	55	64	76	90
	EEU, FSU	65	70	85	90
District heating	All regions	100	100	100	100
Electric heat pump	All regions	250	250	250	250
Gas heat pump	All regions	150	150	150	150
Hydrogen-based co-generation	All regions	30	30	30	30

Note: see footnote 10 for detailed information on the hydrogen-based cogeneration.

Table 17: Specific CO_2 emissions of heating appliances using different fuels assumed in MESSAGE, ton C/TJ.

Technology	Specific CO_2 emissions 1990–2100
Non-commercial biomass	Zero emission (0.0)
Biomass-based heating	Zero emission (0.0)
Coal-based heating	25.8
Fuel oil-based heating	21.1
Light oil-based heating	20.0
Gas-based heating	15.3
Electric heat pumps	Zero emission (0.0)
Gas heat pumps	15.3
Solar thermal	Zero emission (0.0)
Fuel cell cogeneration system	Zero emission (0.0)

4.2.2.1 Combustion-based heating appliances

The most common residential and commercial space-heating system in use today is the furnace, including stoves and space heaters. When a furnace is a central heating unit, then the heat is distributed to the rooms of the building though ducts in the form of steam or in pipes in the form of hot water. Space heaters tend to heat the area in which they are located.

For hot-water supply, heat produced by furnaces, or more commonly called boilers for hot water supply, are distributed through pipes. For cooking, ovens and burners are commonly used heating appliances. Fuels for combustion in furnaces include biomass, coal, fuel oil, light oil, and gas.

As shown in Table 16, the current efficiency (75% for industrial regions) as well as potential efficiency (90% for all regions) for gas is the highest. Potential improvement for the oil products (85% for all regions) is also high given the current world-regional differences in the efficiencies.

4.2.2.2 District heating

District heating systems distribute steam or hot water to many buildings. The heat can be provided by a variety of sources, including geothermal, cogeneration plants, waste heat from industry, and purpose-built heating plants. A recent census by the US Department of Energy found that there are more than 30,000 district heating systems in the United States and there are thousands more throughout the world (Pierce, 2003). In Japan, a plant or complex of plants that produces heat at a rate of at least 21 gigajoules per hour is considered district heating according to a law. Such plants usually cover business complexes or big residential towns (The Japan heat Service Utilities Association, 2003).

The production and use of combined heat and power is only possible when there is an area near the plant that has a need for the heat – a downtown area, a college campus or an industrial development. Some of the world's largest heating systems are found in the former Soviet Union, i.e., St. Petersburg (237 PJ/yr), Moscow (150 PJ/yr), Prague (54 PJ/yr) and Warsaw (38 PJ/yr) (Pierce, 2003). District heating is also provided by power plants by recovering the wasted heat from power plants. Standard power plants effectively use just 40% of the fuel they burn to produce electricity. Sixty percent of the fuel used in the electric production process ends up being rejected or "wasted" up the smokestack. Combined heat and power systems use this rejected heat to heat buildings in a surrounding area through a district energy system.

The thermal efficiency of the district heating is assumed 100% in the PF scenario, because when thermal energy is provided to buildings, the energy is already in a directly usable form.

4.2.2.3 Heat pumps

Heat flows naturally from a higher to a lower temperature. Heat pumps, however, are able to force the heat flow in the opposite direction, using a relatively small amount of high-quality driving energy (electricity, fuel, or high-temperature waste heat). Although this is usually not explicitly pointed out to consumers, the most popular application of heat pumps (in the technological sense) is in refrigerators. There, the heat extracted from the refrigerated items is transferred to the outside of the refrigerator. Sometimes this excess heat from cooling is considered as a waste, but sometimes, it meets a simultaneous heat demand.

Using the term in the more common way, heat pumps are the most energy-efficient way to provide heating and cooling in many applications, as they can use renewable heat sources in our surroundings. Even at temperatures normally considered low, air, ground, and water contain useful heat that is continuously replenished by the sun and/or geothermal sources. By applying a little extra energy, a heat pump can raise the temperature of this heat energy to the level needed for room conditioning. Similarly, heat pumps can also use waste heat sources, such as from industrial processes, cooling equipment or ventilation air extracted from buildings

In order to transport heat from a heat source to a heat sink, external energy is needed to drive the heat pump. Theoretically, the total heat delivered by the heat pump is equal to the heat extracted from the heat source, plus the amount of drive energy supplied. Electrically-driven heat pumps for heating buildings typically supply 100 kWh of heat with just 20-40 kWh of electricity. Many industrial heat pumps can achieve even higher performance, and supply the same amount of heat with only 3-10 kWh of electricity (IEA Heat Pump Programme, 2002).

Both electric and gas-driven heat pumps thus achieve “efficiencies” that in effect are higher than 100%. As summarized in Table 16, in the PF scenario we used 150% for gas heat pump efficiency and 250% for electric heat pump efficiency as input assumptions.

Because heat pumps consume less primary energy than conventional heating systems, they are an important technology for reducing pollutant emissions that harm the environment, for example carbon dioxide (CO_2), sulfur dioxide (SO_2) and nitrogen oxides (NO_X). However, the overall environmental impact of electric heat pumps depends very much on the way the electricity is produced. Heat pumps driven by electricity from, for instance, hydropower or renewable energy reduce emissions more significantly than if the electricity is generated by coal, oil or gas-fired power plants (IEA Heat Pump Programme, 2002).

4.2.2.4 Solar thermal

Solar thermal systems convert sunlight into heat. “Flat-plate” solar thermal collectors produce heat at relatively low temperatures (30 to 70 ºC). They are generally used to heat air or a liquid for space and water heating or to dry agricultural products. Concentrating solar collectors can produce higher temperatures. A concentrating collector system can have a fixed collector which can be placed in an area directly facing south or it can track the sun.

Tracking devices shift the position of the reflector and the receiver to maximize the amount of sunlight concentrated on the receiver (Office of Energy Efficiency and renewable Energy, 2003).

Solar domestic water heating systems can meet up to 60% of the water heating needs of typical households in Northern Europe and up to 90% of the water heating needs of households in Southern Europe. In 1994, 28 million square meters of solar thermal collectors have been installed worldwide, and 5.6 million square meters in the EU (ATLAS Project, 2003).

4.2.2.5 Fell cell co-generation system

As noted in Section 4.2.1.3, cogeneration systems can provide heat and electricity from a single energy source. For all regions and for the entire time period, the thermal efficiency for heat production of fuel cell-based cogeneration system is set at 30%[11] in the MESSAGE PF calculation.

4.3 Demand-saving and carbon emission reduction potentials due to efficiency improvement in the residential and commercial sector

The PF scenario illustrates the emergence of on-site electricity production, as well as a drastic transition from furnace-based technologies to solar and fuel cell-based technologies in the residential and commercial sector. The potential contributions of the key technologies discussed above to the global energy supply in the residential and commercial sector are discussed, first in terms of electricity supply, and then in terms of thermal energy supply.

The PF scenario illustrates the drastic shift from reliance on centrally produced and grid-connected electricity supply to on-site production of electricity. This is a major change from 1990, when electricity supply by centralized power plants delivered though grids accounted for virtually all electricity supply in this sector. In the long run, decentralized systems using the clean and efficient electricity produced by solar photovoltaic and fuel cell cogeneration system and fuel cell vehicles could supply electricity to the residential and commercial sector. Figure 27 illustrates the potential contributions of these technologies to the global electricity supply in the residential and commercial sector. Grid-independent electricity production technologies could cover nearly 40% in 2050, and up to 75% by 2100. In particular, fuel cell cogeneration systems will be a crucial technology in providing electricity, accounting for nearly 60% of total electricity provided to the sector.

Figure 28 illustrates the development of the supply mix for meeting global heat demand in the residential and commercial sector and the potential contribution of advanced technologies to the global residential and commercial thermal energy mix under the PF scenario.

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[11] See Footnote 10.

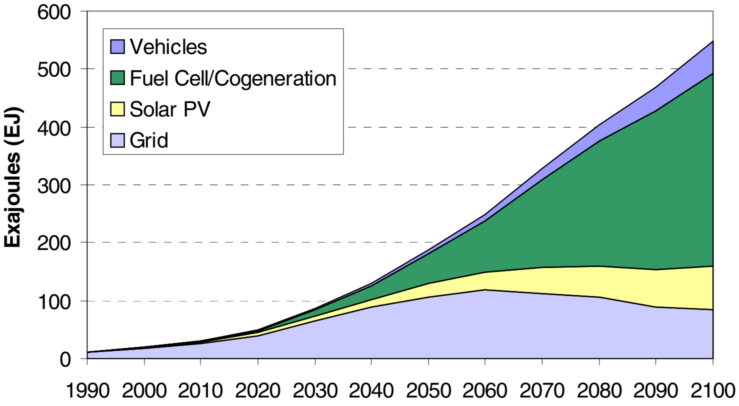

Figure 27: Development of final-energy (specific) use in the residential and commercial sector in the MESSAGE PF Scenario, in EJ.

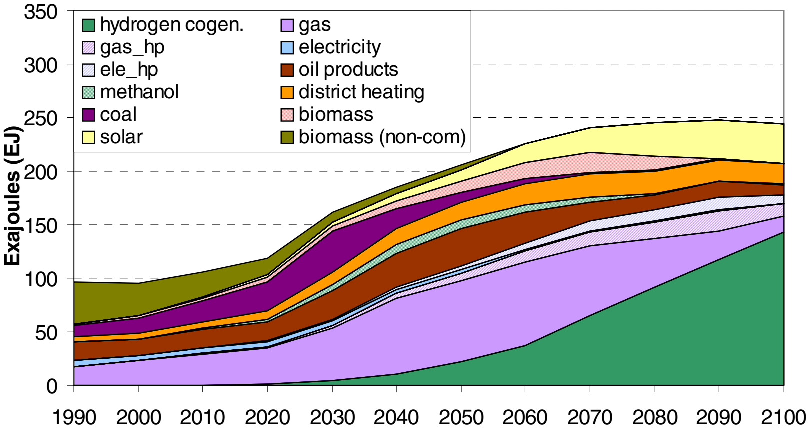

Figure 28: Development of final-energy (thermal) use in the residential and commercial sector in the MESSAGE PF Scenario, in EJ.

In 1990, the share of non-commercial biomass provided as much as 40% of the global thermal energy demand. As we have seen earlier (Figure 26), they are mainly used in developing regions. As these regions keep developing, non-commercial energy will be more and more substituted by commercial fuels. By the year 2020, in Asia, it will have been replaced by mainly coal, and in LAM region oil products will be used as main alternatives. In the reforming regions, the reliance on district heating will increase, accounting for nearly half of thermal energy demand there. In the OECD, gas-based furnace systems will further develop as an important supplier (70%) of thermal energy, replacing oil products. By 2050, the importance of gas will have increased further worldwide, due to the further replacement of the non-commercial biomass with natural gas in the LAM region regions, as well as substitution of coal with gas in the Asian regions. Methanol also begins to play an important role in the LAM region around the year 2030, but on a global basis, its contribution is limited.

At the same time, hydrogen-based cogeneration systems are introduced around 2020 and expand rapidly from then on. In the OECD regions, hydrogen-based cogeneration systems they have shares of up to 11% by 2030, and will reach 20% by 2050. On the global scale, hydrogen-based co-generation systems provide 10% of world thermal energy demand by 2050 and by 2100, their share increases to 60%, reaching 70% in the OECD. Solar technology also plays an important role, providing 15% of the thermal demand on global basis by the year 2100. Solar thermal energy becomes particularly important in the Asian regions in the long term.

The introduction and penetration of fuel-cell based cogeneration systems in the PF scenario for the 11 world regions of our study is illustrated in Figure 29. Accordingly, fuel cell-based cogeneration systems are first introduced in the developed regions (NAM, PAO, WEU, FSU and EEU) around 2010, but penetration potentials in these regions are rather limited compared with late-comers. By 2040 and onwards, the developing regions provide bigger markets than the developed regions. By 2100, 80% of the global hydrogen consumption for the fuel cell cogeneration system in the residential and commercial sector is in developing regions. Penetration potentials in AFR, SAS, and CPA are particularly high in the long run.

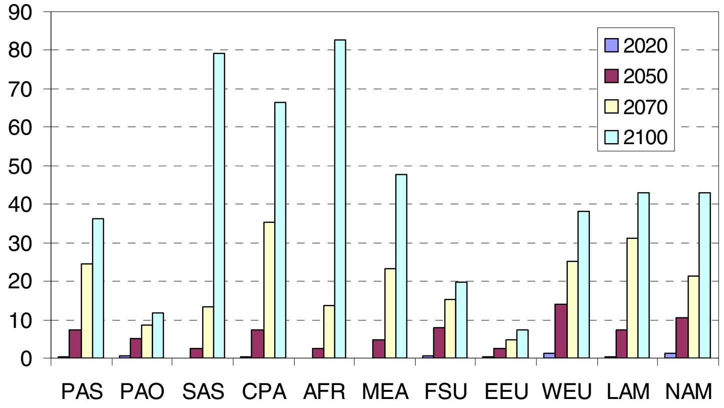

Figure 29: Introduction and penetration of fuel cell-based cogeneration system in MESSAGE global regions, in EJ (of hydrogen input).

4.4 Potential energy demand savings and emission mitigation

The massive introduction of new technologies to the residential and commercial sector as is described by the PF scenario improves final-to-useful energy efficiency as well as CO_2 emission coefficients, both leading to a reduction in energy use as well as in CO_2 emissions. Figure 30 illustrates the resulting final-to-useful energy efficiency improvement, drawing on the technological change described the PF scenario for the residential and commercial sector, separately presented for electricity and thermal-energy demand. End-use efficiency is defined as the useful-energy demand divided by the final demand. The efficiency of the hydrogen-based cogeneration systems is included with 80% for electrical efficiency and 100% for thermal efficiency. On average, efficiency for the energy use in the residential and commercial sector is at 85%.

The change in the supply structure of the residential and commercial electricity could result in an increase of the final-to-useful efficiency of the electricity use in the sector from 50% in 1990 to 81% in 2100 This increase is mainly due to the higher efficiency improvement potential of the currently developing regions, who are currently lagging behind the developed regions in terms of the efficiency.

The final-to-useful efficiency of the thermal energy demand, including non-commercial biomass, was 44% in 1990 (without non-commercial biomass, it was 67%). Due to the disappearance of non-commercial biomass use, which is characterized by low efficiency (about 12%) during the first half of the 21st century, as well as due to the dissemination of efficient technologies (such as heat pumps and solar thermal) in the second half, the efficiency improves steeply over the century. The drop of the efficiency at the very end of the time horizon is due to the wider introduction of solar technologies, which substitute heat pumps (which have higher efficiency than solar thermal). The efficiency for total residential and commercial energy demand increases from 45% in 1990 to around 90% by 2070.

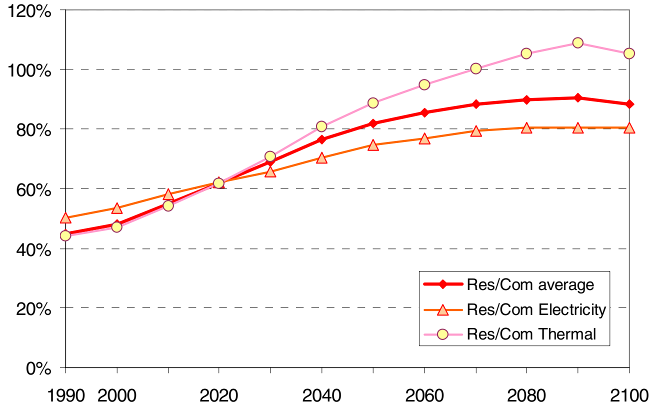

Figure 30: Global final-to-useful energy efficiency in the residential/commercial sector in the PF scenario, including non-commercial biomass, in percent.

This energy efficiency improvement shown in Figure 30 could bring a potential energy demand saving of 671 EJ (Figure 31) in 2100. This is calculated as a hypothetical energy demand that would arise additionally if the energy efficiency remained constant at the 1990 level. Note that the saving is not calculated relative to an assumed business-as-usual development of energy efficiency, but rather relative to the 1990 level. The saving effect corresponds to about 30% reduction from the would-be energy demand in 2100 (or 45% more than the actual final-energy use under the PF scenario). In terms of cumulative emissions, the saving effect corresponds to 25% of would-be final energy consumed between 1990-2100 (or 34% more than the cumulative final energy use under the PF scenario). Non-commercial energy use is included in the thermal category and large demand saving potential for thermal sector for the first half of the century is, again, due to the substitution of non-commercial energy with more efficient technologies.

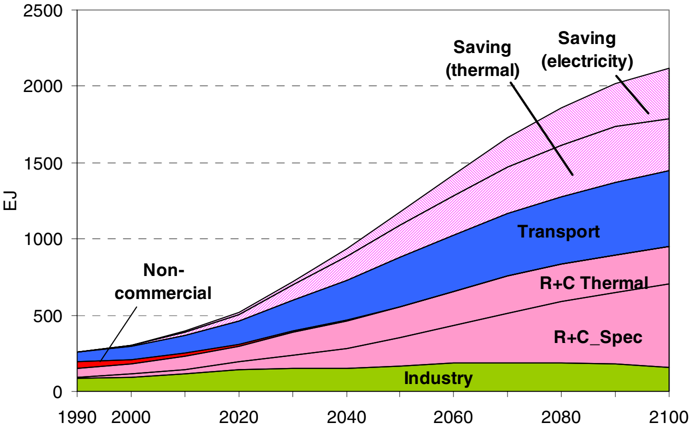

Figure 31: Global final-energy use by sector in the PF scenario, and savings due to efficiency improvements in the residential/commercial sector (electricity and thermal use).

Figure 32 illustrates the evolution of the sectoral carbon intensity due to the energy end-use in the residential and commercial sector and its potential CO_2 emission reductions in the PF scenario. Potential CO_2 emission reductions due to the end-use efficiency (i.e., the useful demand divided by the final use) improvement presented above are also presented for comparison. CO_2 emissions here include only those that are directly emitted by the residential and commercial sector. Since the end-use of electricity does not emit CO_2, CO_2 emissions are due to the use of fossil fuels for thermal purposes. In the PF scenario, the increase in the share of electricity use, together with the reduction of biomass and coal use replaced by the cleaner hydrogen cogeneration system bring substantial de-carbonization effect as is illustrated by the CO_2 intensity development depicted by the orange line in Figure 32. CO_2 intensity here is defined as CO_2 emissions from the energy use in the residential and commercial sector, divided by the final-energy use of that sector. This represents the de-carbonization effect due to end-use technology changes. This effect amounts to a potential reduction of CO_2 emissions of 4.7 GtC by 2100. This means that if the CO_2 intensity of the final energy were to remain constant at its 1990 level, this would give extra annual CO_2 emissions that are equivalent to 65 times the projected CO_2 emissions in 2100 and 6 times the cumulative CO_2 emissions between 1990-2100 under the PF scenario. In comparison, the effect of the end-use efficiency improvement to the CO_2 emission reduction is limited. If the final-to-useful efficiency were to remain at the 1990 level, final demand would have been just 45% more than in the case with technological change described under the PF scenario (Figure 31). This additional final energy would give an extra emission of 50% of cumulative CO_2 emissions under the PF scenario (light yellow area in Figure 32).

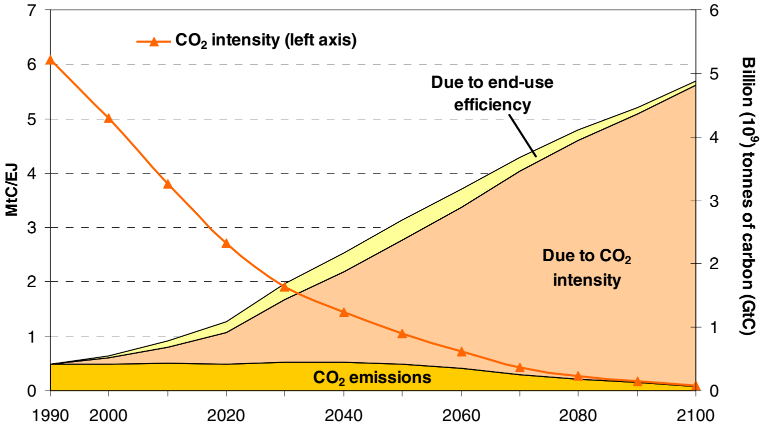

Figure 32: CO_2 emissions by the residential/commercial sector (end-use only, right axis), CO_2 intensity development (left axis), and savings due to CO_2 intensity reduction (right axis).

Figure 33 shows a similar analysis as Figure 32, with a difference of including all CO_2 related to the production and distribution of energy to be used in the residential and commercial sector. CO_2 emissions related to energy consumption in the residential and commercial sector in 1990 was 1926 MtC (corresponding to CO_2 emissions in Figure 32), with 419 MtC (22%) directly emitted in the sector (corresponding CO_2 emissions in Figure 33). The rest are CO_2 emissions which occur during the production of the energy to be delivered to the residential and commercial sector. It includes CO_2 emissions from power plants and from resource extraction, for example. The share of CO_2 emissions related to the direct use of energy in the end-use sector decreases to 6%. This is because the end-use technologies that are used to supply the major part of energy in the residential and commercial sector by 2100 will be non-carbon emission technologies. The CO_2 intensity presented here is defined as CO_2 emissions related to the production and distribution of the energies used in the residential and commercial sector divided by final energy use by residential and commercial sector.

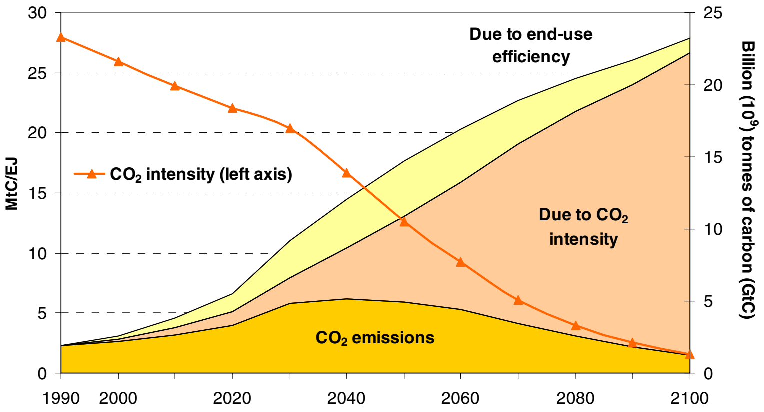

Figure 33: Total CO_2 emissions related to energy consumption in the residential/commercial sector (right axis), CO_2 intensity development (left axis), and savings due to CO_2 intensity reduction (right axis).

5 The industry sector

Global final-energy use by industry in 1990 was approximately 37% of total final energy. Of this, electricity use (excluding electricity for thermal use) consisted of 20%, and the other 80% was energy used for industrial thermal purposes (heat and steam production).

Figure 34 shows the final-energy use for the industry sector in 1990 for the 11 world regions of our study. Here, energy use is broken into two broad energy-use categories: thermal and specific use. As mentioned in the section on residential/commercial sector, the specific use refers to the use of electricity for non-thermal purposes. Electricity used for the thermal purposes, for instance in electric furnaces, is classified under thermal use in our study. The given percentages depict the shares of the industrial sector in total final-energy use of each world region.

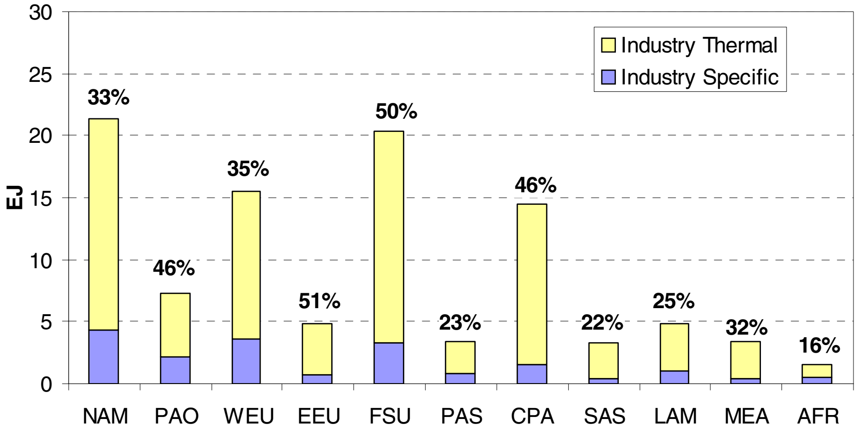

Figure 34: Final-energy use in the industry sector in 1990 in EJ. Percentages refer to the shares in total final energy consumed by the industry sector.

Energy use in the industry sector of a region largely reflects the economic structure of the region. Regions whose economic structures depend on manufacturing industries, in particular energy-intensive ones, tend to have high industrial shares in the total energy use. For example, EEU, FSU, CPA and PAO have rather high energy shares in the industry sector. NAM and WEU consume large amounts of energy in the industry sector in absolute terms reflecting the size of their economies, but the relative shares of the industry sector are not as high as the four aggregated world regions mentioned above. In the future, the shares of the industry sector are expected to increase in particular in regions like PAS, SAS, LAM and AFR, which are currently characterized by lower shares of the industry sector as they continue their industrialization processes.

The major functional uses of electricity in the industry sector are electric lighting, electric furnace applications (using high-temperature heat), electrolysis (electrolytic and electro-chemical processes) and electric-motor use. High-temperature heat is needed to melt certain metals. It is also used in processes for producing acetylene from calcium carbide in electric furnaces, producing phosphoric acid by the electric furnace process, and for steel making from scrap iron in electric-arc furnaces. In the United States, electric heat has been substituting the steam process throughout the chemical industry. The electrolytic processes are utilized in a number of manufacturing sectors. Their main uses are production of chlorine, copper and aluminum. Motors are used in a variety of applications, including (1) pumps, fans, and compressors used in fluid processing, heating, ventilation and air conditioning (41% of electricity used for motor use is derived from US manufacturing firms), (2) materials processing equipment used for crushing, grinding, cutting, mixing and forming (32%), and (3) material handling machinery tools such as cranes, conveyors, elevators, and robotics (27%) (OTA, 1993). To give a rough idea about how much electric energy is used by each function, Figure 35 shows shares of the functions for the United States between 1902 and 2000.

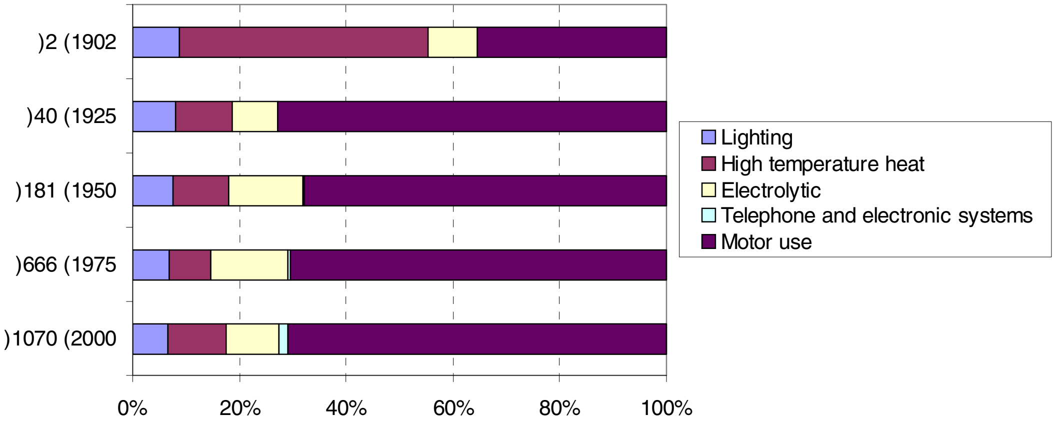

Figure 35: Electricity use by function in the United States in the industry sector (Ayres *et al.*, 2004). Numbers in parentheses next to the years are the total electricity use in billion kWh.

The figure shows that the share of lighting has been rather stable at around 8% total industrial electricity use. The biggest share of electricity use was for driving motors, accounting for approximately 70% throughout the period. Electrolysis and high-temperature heat account for the rest. This particular pattern of electrical energy use in the US does not necessarily represent a general picture of the industrial energy use in other countries and regions because a pattern of electricity use in the industrial sector reflects an economic structure of industrial activities which are particular to each country or region.

As far as thermal uses of energy in the industry sector are concerned, fuels are converted to heat or steam to provide thermal-energy services, which include heating, drying, and cooling of fluids as well as of materials. Heat is primarily used for process heating, that is, to heat fluid and materials directly using furnaces or ovens. Process heat is vital to nearly all manufacturing processes that produce basic materials or commodities. The biggest share of heat is generated by the combustion of fossil fuels and the rest is from electricity (Capital Surini Group International and Energetics, 2001). Steam is also used throughout the industrial sector for heating fluids and materials. Steam is typically generated in boilers, some of which are linked to turbine and generator sets in order to generate electricity at the same time. Smaller quantities of heat and steam are also used for space heating.

5.1 World-regional final-energy use in industry and its major sectors

Figure 36 shows final-energy shares in the industry sector in the four aggregated world regions. Note that this figure does not include feedstock use of primary-energy carriers.

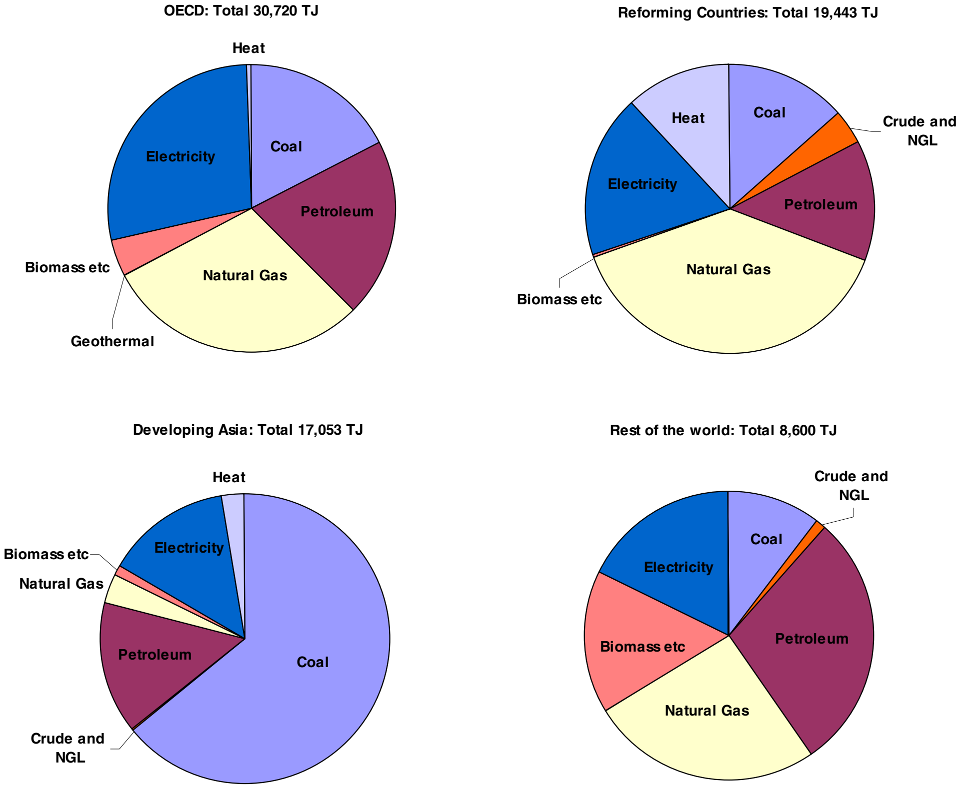

Figure 36: Final-energy mix in the industry sector in 1990 for four aggregated world regions. Source: IEA (2002a, 2002b).

In the OECD region, the shares of coal, petroleum, natural gas and electricity are quite similar. Natural gas is extensively used in the reforming economies, whereas coal use dominates in the developing countries of Asia. In the LAM region, the share of biomass in industrial final energy is higher than in other regions. On a global scale, this means that coal and natural gas are the most important fuels used in the industry sector, each accounting for 25% of the global industrial final-energy use.

Half of the world's industrial coal consumption is used in developing Asia. Coal is mainly used in the iron and steel sector (25% of world consumption), non-metallic minerals sector (22%), and chemical sector (11%).

50% of the industrial natural gas is consumed by the OECD regions and 40% by the reforming regions. Gas is used in various sectors, with chemical, iron and steel, and non-metallic ferrous, machinery each accounting for about 10% of the global gas consumption in industries.

Oil products and electricity are used widely in all regions and in various industrial sectors. Construction, non-metallic minerals, and the chemical sector each account for 10% of global petroleum consumption. Regarding electricity, 18% is used in the chemical sector and the rest is used in a variety of sectors such as iron and steel, non-ferrous metals, machinery, and pulp and paper.

Figure 37 illustrates the structures of the final-energy use by major industrial sectors for the four aggregated world regions. The economic structures of regions do not seem to differ significantly. In particular, energy-intensive sectors such as iron and steel, chemical, and non-ferrous metals have quite similar shares across the regions. "Non-metallic minerals" is also energy-intensive, but the share of this sector is exceptionally high in Asia. The "non-specified" sector, which comprises any manufacturing industry not named here, accounts for quite substantial shares in all regions. It also includes fuels that are not attributed to any sector.

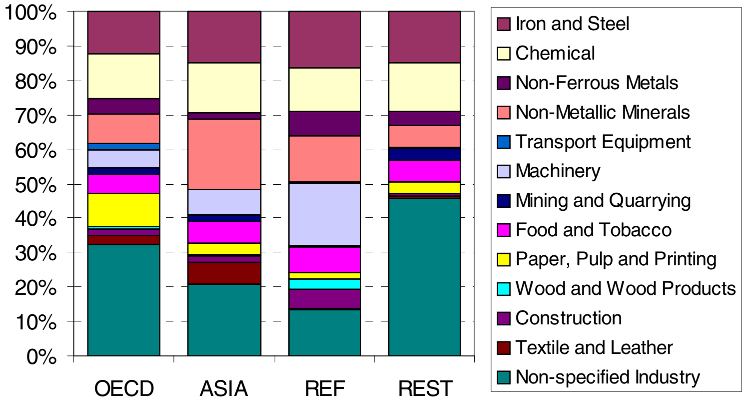

Figure 37: Sectoral final-energy use by industry in four aggregated world regions, in 1990. Source: IEA (2002a, 2002b)

5.2 Description of key energy conversion technologies in industry

There are many energy-efficient technologies and practices that could save energy while achieving lower CO_2 emissions. Technologies in the industry sector are sometimes specific to certain industries, but there are also some technologies that are commonly applied throughout industries. Our focus here is on such generic technologies.

As explained in Section 4.2 on the residential and commercial sector, the MESSAGE model differentiates between non-thermal/electric (specific) and thermal uses of energy. However, the distinction between non-thermal and thermal energy use is somewhat arbitrary because many industrial applications have cogeneration capabilities, i.e., they co-generate electricity and heat. The main combined heat and power (CHP) technologies in industry are boilers with steam turbines, reciprocating (i.e., piston) engines (mainly fueled with diesel) with heat recovery, gas turbines (including micro gas turbines), combined-cycle gas turbines, and fuel cells. In MESSAGE, fuel inputs to diesel engines are treated as "specific use" of energy, fuel inputs to gas turbines are treated as "thermal use" of energy, and fuel input to a fuel cell cogeneration system is treated explicitly under both specific use and thermal use. Steam turbines are modeled as additions to boilers or gas turbines (combined cycle) and do not require fuel input as itself.

5.2.1 Electricity supply technologies for the industry sector

Currently, electricity used in the industry sector is either purchased from utility companies and delivered through an electricity grid or generated by a factory's own power plant, which may or may not include the capability of cogeneration. The main on-site power generation system is the diesel engine, using "light oil" as a main fuel. The steam turbine and gas turbine cogeneration systems also provide electricity. In the future, solar power generation, hydrogen-based power generation, and hydrogen-based fuel cell cogeneration are expected to become important technologies to generate on-site electricity for industrial use.

In MESSAGE, the efficiency of the industrial use of electricity is given as an average of electric appliances used in industry. As we discussed at the beginning of Section 4, electricity is used in various non-thermal appliances such as electric motors, light bulbs, and electrolysis process. It is therefore difficult to estimate average efficiencies of industrial electric appliances even for industrial countries, let alone for 11 world regions. The efficiency assumptions of electric appliances in the industry sector used for the calculation of the PF scenario by MESSAGE for the 11 world regions are therefore only rough estimates. They are summarized in Table 18.

Table 18: Efficiency assumptions of the electric appliances used in the industry sector in MESSAGE, in percent.

Regions	1990	2020	2050	2100
NAM, WEU, PAO	80	81	84	85
MEA, CPA, SAS	75	76	80	85
LAM, PAS, EEU, FSU	75	77	83	85

MESSAGE also assumes efficiencies of on-site electricity generation by industrial factories for their own purpose. MESSAGE considers five technological options for such electricity generations. A conventional technological option is a diesel engine using light oil as an input fuel[12]. Alternatively, methanol can be used as an input to the diesel engine. As for future options, fuel cells, solar photovoltaic systems, and fuel cell cogeneration systems are considered in addition. In Table 19 and Table 20, we summarize efficiency assumptions and CO_2 coefficient assumptions used in MESSAGE for the PF scenario.

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[12] Note that MESSAGE does not model the CHP capability explicitly except for the fuel cell cogeneration system. Electricity generated by steam turbines (which are added to the boilers) and by gas turbine CHP system (which we discuss in Section 5.2.2 since their main use is in general steam production) are implicitly included in MESSAGE's "electricity" category.

Table 19: Efficiency assumptions of the on-site electricity generators for the industry sector used in MESSAGE for the calculation of the PF scenario, in percent.

Technology	Regions	Electricity generation efficiency			
		1990	2020	2050	2100
Light oil-based power generation (diesel engines)	NAM, WEU, PAO	40	40	40	40
	AFR, MEA, CPA, SAS, LAM, PAS	30	32	36	40
	EEU, FSU	30	32	38	40
Hydrogen fuel cell-based power generation	NAM, FSU, LAM, PAS	60	64	76	80
	WEU, PAO, EEU	55	60	75	80
	AFR, MEA, CPA, SAS	60	63	72	80
Methanol-based power generation (diesel engines)	NAM, FSU, PAS, LAM, MEA, CPA	60	60	60	60
	WEU, PAO, EEU	50	52	58	60
Solar photovoltaic power generation	All regions	100	100	100	100
Hydrogen fuel cell cogeneration system[13]	All regions	90	90	90	90

Table 20: Specific CO_2 emissions of on-site electricity generators using different fuels assumed in MESSAGE, ton C/ TJ.

Technology	Specific CO_2 emissions, 1990–2100
Light oil-based power generator	20.0
Hydrogen fuel cell based power generator	0
Specific use of methanol	17.4
Solar photovoltaic power generator	0
Fuel cell cogeneration system	0

5.2.1.1 Industrial electric appliances

Efficiencies of electric appliances in the industry sector can be improved by switching to higher efficiency appliances as well as improved housekeeping and maintenance practices. Minor changes in such practices are typically the cheapest and the easiest measures to implement but usually (but not always) yield the smallest energy savings. Some factories employ energy management systems to ensure efficient use of electricity, for instance, by systematically turning off or turning down process equipment, lights and fans (OTA, 1993)

As we discussed at the outset of Section 5, consumption by motors accounts for the largest functional use of electricity in the industry sector. Standard motors convert electricity input into mechanical output with average efficiencies between 77 and 94%, depending on their size. High-efficiency motors operate at 84% to 96% efficiency. High-efficiency motors use improved design and better materials to decrease losses. They typically cost 30% more than standard motors (OTA, 1993).

Assumptions of the efficiency developments of average electric appliances in industry for 11 world regions are summarized in Table 18 above.

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[13] We assume that 30% of the hydrogen input goes into thermal energy production with an efficiency of 100% and that 70% goes into electricity production with an efficiency of 90%. Therefore, electricity output is 60% of the hydrogen input.

5.2.1.2 Diesel engines

Diesel engines have long been used for electricity generation, originally to counter high expenses, poor reliability, and (temporary or permanent) unavailability of electricity provided by utilities. With utility service improving, electricity purchases from utilities grew faster than on-site generation. As a result, diesel engines used merely for on-site generation declined in importance (OTA, 1993). To compensate however, the diesel engine is increasingly used for the cogeneration of heat and electricity (CHP). Diesel engine CHP systems in the industrial sector can be designed to produce steam, hot water, or hot air. Hot-water systems are by far the most common type (Resource Dynamics Corporation, 2003). According to the OTA's comparison of the state-of-the-art cogeneration systems (OTA, 1993), the diesel engine's steam efficiency (with a steam-to-electricity ratio of 1-3 lbk (liquid bulk)/kWh was much lower than that of other cogeneration systems[14].

5.2.1.3 Hydrogen fuel cell-based power plant

Fuel cells are an emerging small-scale power generation technology, using hydrogen or hydrogen-rich fuels as input fuels. Stationary power is the most mature application for fuel cells. Most fuel cell applications have capacities of less than 1 MW, although larger applications exist. There are several types of fuel cells. Fuel cells primarily used for power generation are phosphoric acid, solid oxide, and molten carbonate, and they are generally not suited for transportation use[15] (Resource Dynamics Corporation, 2003).

5.2.1.4 Solar photovoltaic power generation system

Solar photovoltaic (PV) systems, which were already discussed in Section 4.2.1.1 for residential and commercial applications, can be also applied in a power generation system for industrial use. PV systems are flexible in the size of operation, and they can provide tiny amounts of power for watches, large amounts for the electric grid and, of course, everything in between. In industry, today's uses range from supplying electricity for a factory's building lighting (with PV modules mounted onto the roof of the factory) to providing electricity at a much larger scale using factories' on-site power plant consisting of many PV arrays installed together.

5.2.1.5 Hydrogen-based fuel cell cogeneration system

The phosphoric-acid fuel cell can be used in two different types of industrial cogeneration applications: to produce just hot water at around 60ºC or together with low-temperature steam around 120ºC (Resource Dynamics Corporation, 2003).

5.2.2 Technologies for supplying industrial heat

The second category of energy use in industry is heat. Heat is used for heating materials, to process materials and commodities, as well as for space heating and hot-water supply. The main use of heat in industry is process heat and steam generation. Process heat systems usually include a heating device that generates and supplies heat; heat transfer devices for transferring heat from the source to the product being heated; heat containment in the form of

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[14] Steam-to-electricity ratios were between 0 and 30 for steam turbines and between 2.5 and 10 lbk/kWh for gas turbines.

[15] For transportation use of fuel cells, current efforts focus on the proton exchange membrane (PEM) type.

a furnace, heater, oven etc; and a heat recovery device (Capital Surini Group International and Energetics, 2001).

Steam is typically generated in boilers. The steam produced by boilers is piped directly from the boiler to its point of use. Some boilers are linked to steam turbines to cogenerate electricity. In that case, the steam from the boiler is expanded in a steam turbine that turns a generator to produce electricity. Steam is also co-produced by gas turbines (referred to equivalently as combustion turbines in some publications). A gas turbine system relies on heat recovery units rather than boilers to produce steam. In a gas turbine system, the fuel is burned in a turbine to turn an electricity generator, and the exhaust gases are run though a heat recovery unit to generate steam. Gas turbine systems can also be linked to steam turbine to produce additional electricity (such a system is referred to as combined cycle cogeneration). Some industrial facilities installed dual- and multi-fuel steam systems for boilers. In the United States, for example, approximately 50% of boilers are now capable of using more than one fuel, giving industry's main fuel switching capabilities (OTA, 1993). Steam systems are the most common type, because of the high-quality waste heat available and the high demand for steam in many industries. Traditionally, gas turbine applications have been limited by lower electrical efficiencies[16] to combined heat and power uses in industrial settings. Some applications use gas turbines solely for power generation when emissions from engine-based power generation are seen as a disadvantage (Resource Dynamics Corporation, 2003).

For any application, the optimization of the combustion system, improvement of the heat recycling system, and the advancement of material resistant to high temperatures are essential for energy efficiency improvement in the industry sector. For furnaces, the installation of properly designed and applied sensors and control systems and other auxiliary systems can also lead to energy savings. For boilers, reducing leaks of steam is also important for improving energy efficiency.

In MESSAGE, technologies for the generation of thermal energy are not categorized by applications, such as furnaces, boilers, and gas turbines, but by fuels used for the appliances. Furnaces and boilers are fueled by several kinds of fuels, such as coal, biomass, oil products, natural gas, electricity, methanol, gaseous hydrogen, etc. Gas turbines are fueled mainly with natural gas and oil products. In general, the thermal efficiencies of fuels used in the thermal applications can be ranked from high to low in the following order: gaseous hydrogen, electricity, natural gas, oil products, coal, and biomass. The assumptions on the thermal efficiency for heat appliances that are used in MESSAGE for the calculation of the PF scenario are summarized for each fuel in Table 21. Likewise, Table 22 summarizes CO_2 emission assumptions used for the PF scenario.

Heat generated by reciprocating engines (diesel and gas engines) is not explicitly treated in MESSAGE. It is included implicitly under heat generated by oil products and by natural gas respectively.

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[16] See Footnote 14.

Table 21: Efficiency of heat appliances using different fuels assumed in MESSAGE.

Technology	Regions	Thermal efficiency, %			
		1990	2020	2050	2100
Biomass-fired boilers/furnaces	NAM, WEU, PAO, FSU	65	67	73	75
	EEU	60	63	72	75
	LAM, PAS	50	55	70	75
	AFR, MEA, CPA, SAS	50	53	62	75
Coal-fired furnaces/boilers	NAM, WEU, PAO	65	68	77	80
	EEU, FSU	60	64	76	80
	LAM, PAS	45	56	74	80
	AFR, MEA, SAS, CPA	45	49	64	80
Light fuel oil-fired furnaces/boilers/turbines	NAM, WEU, PAO	75	77	83	85
	EEU, FSU	65	69	81	85
	LAM, PAS	55	61	79	85
	AFR, MEA, CPA, SAS	55	59	71	85
Natural gas-fired furnaces/boilers/turbines	NAM, WEU, PAO	80	82	88	90
	EEU, FSU	70	74	86	90
	LAM, PAS	65	70	85	90
	AFR, MEA, CPA, SAS	65	68	77	90
Methanol-based furnaces/boilers	All regions	75	77	83	85
Gaseous hydrogen-based furnaces/boilers	All regions	95	95	95	95
Electricity-based furnaces	NAM, WEU, PAO	95	95	95	95
	EEU, FSU	90	91	94	95
	LAM, PAS	85	87	93	95
	AFR, MEA, CPA, SAS	85	87	91	95
District heating in industrial boilers	NAM, WEU, PAO, LAM	95	100	100	95
	EEU, FSU, PAS, AFR, MEA, CPA, SAS	90	100	100	90
Electric heat pump	All regions	300	300	300	300
Gas heat pump	All regions	200	200	200	200
Hydrogen-based co-generation[17]	All regions	100	100	100	100

Table 22: Specific CO_2 emissions of heating appliances using different fuels assumed in MESSAGE, ton C/TJ.

Technology	Specific CO_2 emissions, 1990-2100
Biomass-based heating	0
Coal-based heating	25.8
Fuel oil-based heating	21.1
Light oil-based heating	20.0
Gas-based heating	15.3
Electric heat pumps	0
Gas-based heat pumps	15.3
Solar thermal	0
Fuel cell cogeneration system	0

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[17] Overall, the output efficiency of heat over the overall hydrogen input is calculated at 30%. See also Footnote 13.

5.3 Demand-saving and carbon emission reduction potentials due to efficiency improvement in the industry sector

Technological change as described by the PF scenario for the industry sector is by far less dynamic than that in the other two end-use sectors. Figure 38 shows the development of electricity supply technologies to the industry sector according to the PF scenario. Electricity use in the industry sector increases steeply between 1990 and 2060, and it stabilizes after 2060. Also the electricity supply structure changes in the first half of the century, remaining rather constant later. The change in the first-half century is characterized by the replacement of diesel engines by solar PV as well as fuel cell systems. The share of purchased electricity (provided through grids) and electricity produced by CHP turbines remains high, and the introduction of on-site systems is limited. Such limitation in the industry sector is due to the fact that the need for the on-site electricity production is limited when electricity from utility companies can offer reliable service.

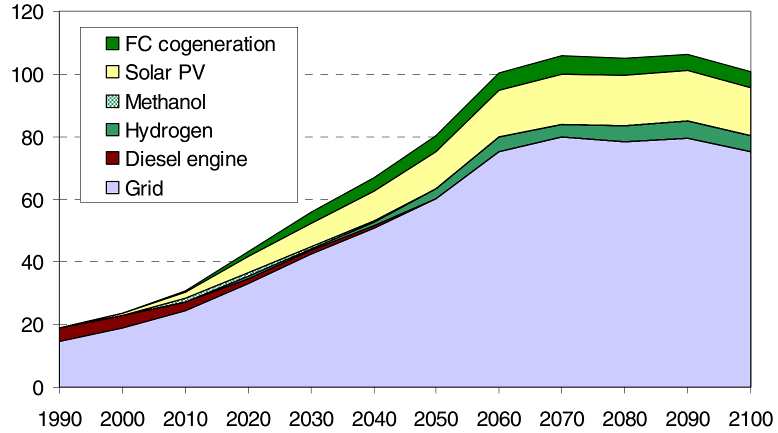

Figure 38: Development of final-energy (specific) use in the industry sector in the MESSAGE PF scenario, in EJ. Note: "Grid" includes electricity produced by CHP turbines.

Figure 39 illustrates the development of the mix of heat generation technologies for meeting global heat demand in the industry sector under the PF scenario. The global energy demand first increases, peaks around 2020, and steadily decreases thereafter. The increase in thermal-energy use is due to the increase in developing regions (developing Asia and the LAM region). This increase is in fact partly offset by the decrease in developed regions (OECD, reforming economies). After 2020, some developing regions also begin to lower their energy demand. CPA and LAM peak their thermal energy use in the industry sector in 2020, PAS in 2030 and SAS in 2080. Figure 40 gives regional details of the thermal energy use and supply mix development.

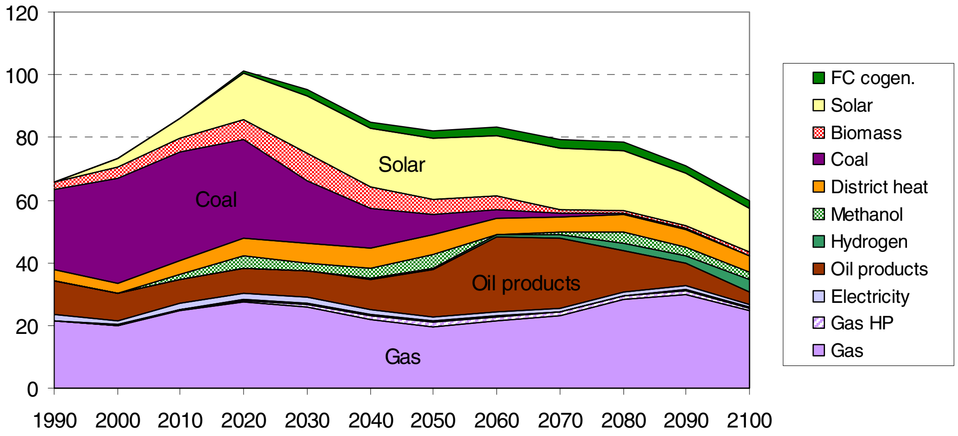

Figure 39: Development of final-energy (thermal) use in the industry sector in the MESSAGE PF scenario, in EJ.

The main industrial fuels used globally in 1990 were coal, gas and oil products. The PF scenario illustrates a smooth transition from coal to oil and solar-based technologies in the developing regions, and from oil to gas in the developed regions. The global use of coal decreases significantly as the CPA region, which relies heavily on coal resources, reduces its thermal energy use after 2020. With that region's shift to more efficient fuels, the use of coal for industrial thermal purposes nearly disappears globally around 2070. On the other hand, gas and oil products remain to be important fuels throughout the century. This is due to an increase of energy use by developing regions, which rely heavily on natural gas and oil products. Towards the end of the century, as both regions, in particular the developing Asia region, shift from oil products to gas, the global use of oil products for industrial thermal uses declines substantially. Solar thermal is the new technology that increases its significance in the course of this century. The introduction of this technology proceeds at a rapid pace in the first half of the century, reaching a share around 25% by 2050 globally and keeps this share almost constant afterwards.

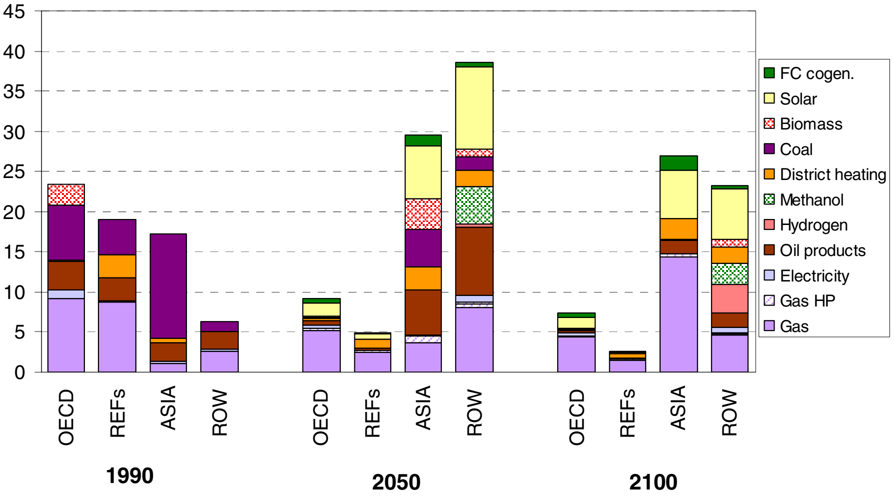

Figure 40: Development of final (thermal) use in the industry sector for the four aggregated world regions in the MESSAGE PF Scenario, in 1990, 29050, and 2100.

5.4 Potential energy demand savings and emission mitigation

The development of final-to-useful efficiency can be calculated as a result of the technological composition of the PF scenario discussed in the previous sector. Figure 41 illustrates the development of final-to-useful energy efficiency for the industry sector under the PF scenario, separately presented for the specific (non-thermal) and the thermal demand. The share for the thermal energy in the total industrial energy use is also presented.

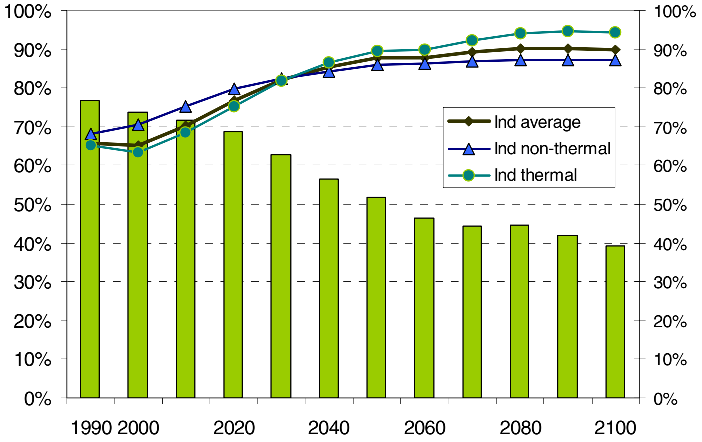

Figure 41: Global final-to-useful energy efficiency in the industry sector in the PF scenario, in percent (lines) and share of thermal energy (in total useful) demand (bars).

Under the PF scenario, the efficiency improvement for non-thermal uses of energy in the industry sector is rather limited compared with the other two end-use sectors. In particular, the technical potentials for efficiency improvement of the non-thermal energy use appear to be exhausted before 2050, when the efficiency reaches a value as high as 87%. The efficiency for thermal energy uses increases more steeply than the non-thermal use case, from 65% in 1990 to as high as 94% by 2100. On average, the industry sector achieves relatively high efficiency (90% by 2100).

The introduction of more efficient and new technologies described in the earlier section (Section 5.2) would help reducing final-energy use. In addition, the introduction of renewable and hydrogen-based applications in the industry sector achieves CO_2 emission reduction. As to the energy demand saving, due to the limited prospects for energy efficiency improvement illustrated by the PF scenario, the demand-saving potential is also limited compared with the demand saving potential from technological progress in the other two end-use sectors, residential/commercial and transport. Figure 42 depicts the potential energy saving due to the technological development under the PF scenario in the industry sector. Like the calculation of the potentials for the other two end-use sectors, the potential energy saving is calculated as a difference between the final-energy use under the PF scenario and a hypothetical would-be final-energy use with the 1990 level end-use efficiency to satisfy the given end-use energy demand.

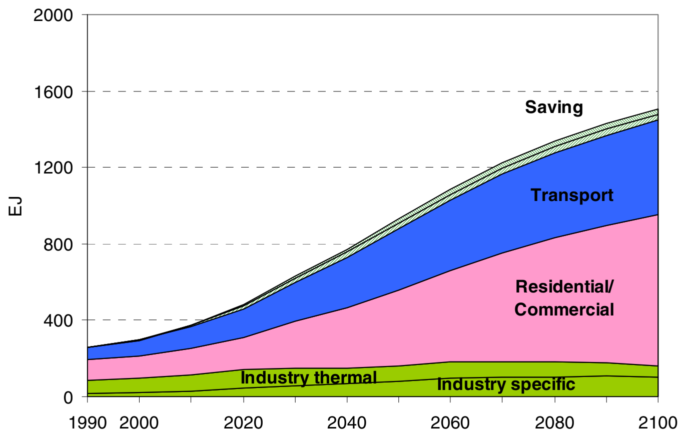

Figure 42: Global final-energy use by sector in the PF scenario, and savings due to efficiency improvements in the industry sector (electricity and thermal use).

The potential energy saving was calculated as 6% of the total would-be global energy demand. This contribution to the "total" energy saving is rather low compared with the other two end-use sectors and this is due to the relatively small size of the industrial energy use. If one looks at the industry sector alone, it corresponds to 26% of the would-be "industry sector" energy demand. Within the industry sector, the potential is quite substantial but its impact on the total energy use saving is limited due to the small size of the industry's energy demand.

Figure 43 illustrates potential CO_2 emission reductions due to the end-use efficiency (i.e., the useful-energy demand divided by the final-energy use) improvement under the PF scenario as well as to CO_2 intensity improvements calculated in a similar manner to Figure 42. CO_2 emissions here include only those emissions that are directly emitted by the industry sector. CO_2 emissions come from various combustion processes incorporated in the electricity generations as well as heat and steam productions. The orange line in the figure depicts CO_2 intensity, defined as CO_2 emissions from the activities in the industry sector, divided by final-energy use of the sector. As shown here, the CO_2 intensity steeply decreases in the first half of the century. Such a decline of the CO_2 intensity leads to a significant potential reduction of CO_2 emissions. The potential mitigation effect amounts to 90% of the would-be CO_2 emissions. In other words, without the CO_2 intensity improvements since 1990, the CO_2 emissions would have been more than 11 times the CO_2 emissions calculated under the PF scenario. Within the industry sector, the CO_2 mitigation effect of the de-carbonization seem profound, but again, given the relatively small size of CO_2 emissions from this sector, the impact of technological change in this sector on the total CO_2 mitigation is comparably quite limited. As far as the effect of the end-use efficiency improvement to the CO_2 emission mitigation is concerned, it is insignificant as it was the cases for the other two end use sectors.

Figure 44 shows a similar analysis to Figure 43, the difference being that here, all CO_2 emissions related to the production/distribution of energy to be used in the industry sector are included. CO_2 emissions related to energy consumption in the industry sector in 1990 is 3 GtC, including 0.4 GtC (15%) directly emitted from the activities in the sector. Similar to the trend in the other two end-use sectors, this share decreases to 6%. The industry sector achieves higher efficiency with the introduction of advanced technologies, but still substantial fossil fuel is used, in particular natural gas. Thus the CO_2 reduction effect is rather limited on the overall basis compared with the other sectors.

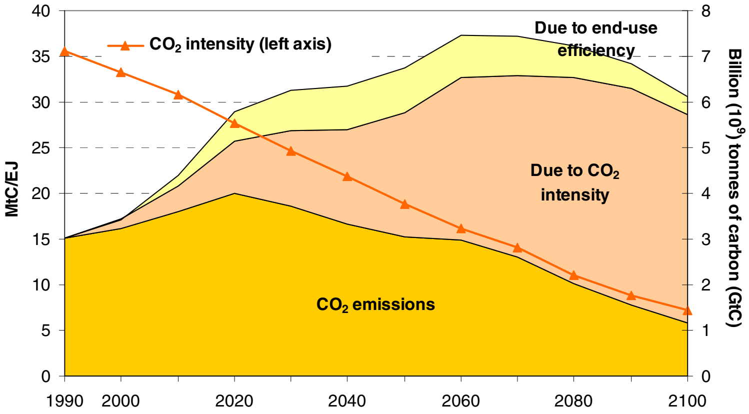

Figure 43: CO$_2$ emissions by the industry sector (end-use only, right axis), CO$_2$ intensity development (left axis), and savings due to CO$_2$ intensity reduction (right axis).

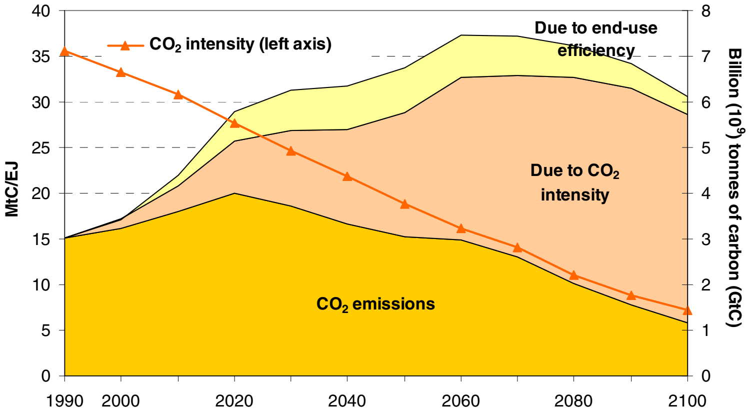

Figure 44: Total CO$_2$ emissions related to energy consumption in the industry sector (right axis), CO$_2$ intensity development (left axis), and savings due to CO$_2$ intensity reduction (right axis).

6 Synthetic fuel production

The PF scenario describes a world with a maximum introduction of renewables-based technologies as well as fuel cells in the end-use sectors. Fuel cells are applied to power vehicles and to providing electricity as well as heat in cogeneration applications. As fuels to fuel cells, hydrogen, ethanol, and limited amounts of methanol are introduced in PF. Hydrogen necessary for the end-use amounts to 1,000 EJ globally by 2100. Alcohol fuels (ethanol and methanol) are mainly used to fuel fuel-cell vehicles and its production rises to over 300 EJ by 2100.

Renewables-based technologies are mainly solar photovoltaic (PV) to generate on-site electricity and solar thermal systems to provide heat at the point of the end-use. The potential usefulness of renewables-based technologies for clean energy is more important for the production of synthetic fuels and electricity production rather than for use at the end-use level.

The focus of this report has been the end-use sector, but the technological change in the end-use sector is strongly interlinked with the technological change in the whole energy supply chain. The prerequisite for a successful introduction of new technologies using new type of energy carriers is an infrastructure that supports the generation and distribution of such fuels. Also, to have a sustainable future, the whole reference energy system, not only at the end-use level, must rely on efficient and clean technologies. The sustainability of the PF scenario is ensured by the fact that electricity and hydrogen are generated to a major extent by renewable technologies. For this reason, this section examines issues related to the supply of new energy carriers. We start with hydrogen production, and then proceed to alcohol fuels production.

6.1 Hydrogen productions

One of the advantages of using hydrogen as an energy carrier is that it can be produced from variety of fossil and non-fossil primary-energy sources. Thus, it can be produced according to the feedstock available in different world regions, which can bring concrete energy security benefits and which could facilitate the transition to a sustainable energy system (Barreto *et al.*, 2003). In the PF scenario, the hydrogen production is initiated with diversified indigenous resources, which are different across regions, but later, the production systems evolve very rapidly to a predominantly solar-based hydrogen production structure in all regions.

Figure 45 shows the world-regional hydrogen production in the PF scenario. The production begins in the developed regions, but later, developing regions become the major producers. In particular in the very last decades of the 21st century, hydrogen production in SAS and AFR grows exceptionally fast. Note that in the PF scenario, hydrogen trade among world regions is virtually zero, which means that hydrogen is produced close to where it is demanded. Current and foreseeable cost trends indicate that several of the feedstock used to produce hydrogen can be transported over long distances cheaper than hydrogen itself, which requires either hydrogen pipeline or transporting liquefied hydrogen in ships (Barreto *et al.*, 2003).

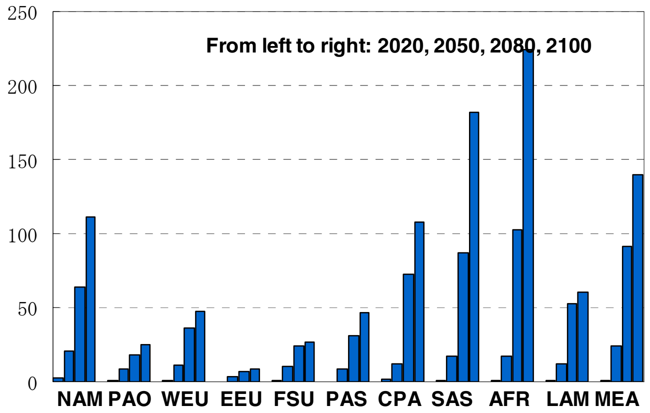

Figure 45: World-regional hydrogen production, in EJ/yr.

Globally, hydrogen production reaches 1,000 EJ by 2100 in the PF scenario. Figure 46 illustrates the global hydrogen production and its methods. The PF scenario describes that in its early stages, the hydrogen is mainly produced from the currently available fossil fuels. In particular, natural gas plays a crucial role in initiating the successful penetration of hydrogen.

Steam reforming of natural gas produces hydrogen either at a large scale and feeds it into a hydrogen distribution system or at smaller scale which can be applied in distributed production sites. In any case, a natural gas-based hydrogen production system would benefit from the existing natural gas distribution system (Barreto *et al.*, 2003).

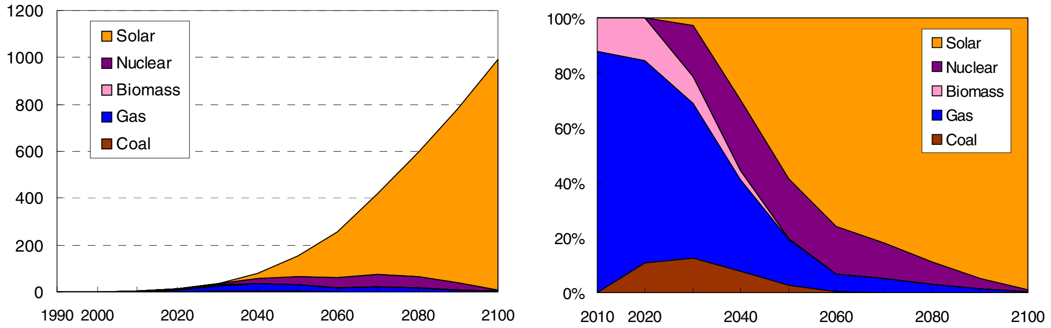

Figure 46: Global hydrogen production in EJ (left) and its methods (right).

In the PF scenario, biomass (biomass gasification) as well as coal (coal gasification) also contribute to the hydrogen production, although only at the beginning and to a limited extend. This mainly reflects the economic availability of these resources in developing regions. In the last decades of the 21st century, hydrogen production by electrolysis based on non-fossil primary energy becomes dominant. In particular, solar thermal systems rapidly increase their share and by the end of the century, virtually all hydrogen is produced by this method at the global scale. The use of solar energy for hydrogen production makes hydrogen a convenient medium to overcome the problems posed by the intermittence of this primary-energy source (Barreto *et al.*, 2003). In the transition from natural gas- to solar-based hydrogen production, electrolysis with high-temperature nuclear reactors also contributes, but to a lesser extent.

Figure 47 illustrates the hydrogen production methods deployed in the 11 world regions. In the early stages of the introduction of the hydrogen, production methods differ among regions, reflecting different availabilities of primary resources. In the OECD (NAM, PAO, plus WEU), natural gas accounts for most of the hydrogen production in 2020. Also in the reforming regions as well as in LAM and MEA, natural gas is the main source of the hydrogen production in 2020. In comparison, coal and biomass-based hydrogen dominate in Asia, whereas all hydrogen is produced from biomass in AFR in 2020. Particularly in SAS and CPA, which are represented respectively by India and China, where significant gas resources are lacking, natural gas reforming never develops into an option at any time of the century. By 2050, nuclear energy becomes the important source of hydrogen production, particularly in the NAM region. It is introduced also in reforming countries to some extent. In some regions, solar begins to have major shares of the hydrogen production. After 2050, solar thermal systems become the main production method in all world regions and by 2100, solar becomes the only primary-energy source used for hydrogen production in many regions. Even in FSU – where natural-gas resources are abundant – steam reforming of natural gas accounts only 13% of the total hydrogen production and the rest is produced by solar thermal.

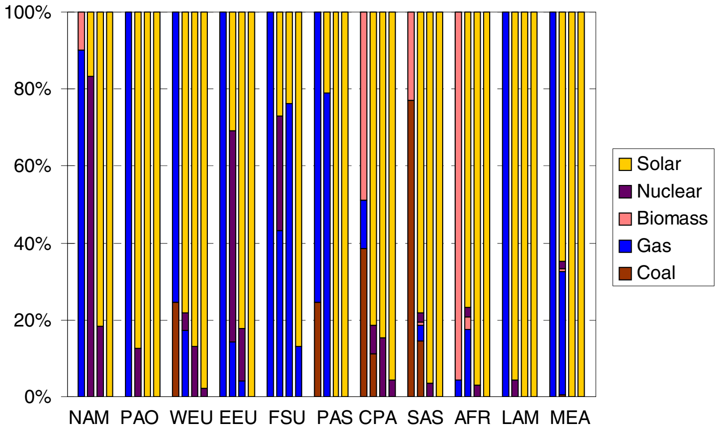

Figure 47: World-regional hydrogen supply mix (shares) for 2020, 2050, 2080 and 2100 (from left to right).

6.2 Methanol and ethanol production

Methanol and ethanol could become strategically important energy carriers for the realization of a sustainable energy system such as the one described by the PF scenario. Under the PF scenario, methanol and ethanol are used in the transportation sector as inputs to fuel cell cars. Unlike hydrogen, which requires new production and supply infrastructures, methanol and ethanol have an advantage of easier handling because of their liquid nature, and their suitability to utilize existing infrastructure. However, this advantage comes at a price as fuel cell cars using methanol or methanol need a chemical on-board reformer. Still, methanol and ethanol are very important for advancing the diffusion of fuel cell technologies before an appropriate hydrogen supply infrastructure is in place.

In the PF scenario, ethanol produced from biomass is the main alcohol fuel used in the fuel cell car applications. Methanol produced from natural gas or coal also makes limited contributions. By 2100, global ethanol production reaches 220 EJ and methanol production 40 EJ annually in the PF scenario. Methanol production is limited, but methanol plays an important role in some world regions where natural gas and coal are more easily available than bio-feedstocks.

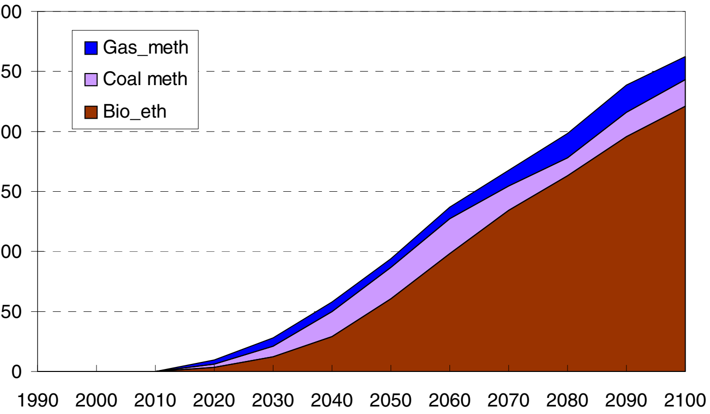

Figure 48: Global methanol and ethanol production, in EJ.

Figure 49 shows the use of alcohol fuels in different world regions in the PF scenario. Methanol is used in some regions to a limited extent. Ethanol use is particularly high in LAM, AFR, and SAS region. In the two reforming regions (EEU and FSU), demand is rather low due to diffusion of natural-gas cars instead of fuel cell cars. In MEA, due to the lack of available feedstocks, both ethanol and methanol have to be imported and their demand is therefore low.

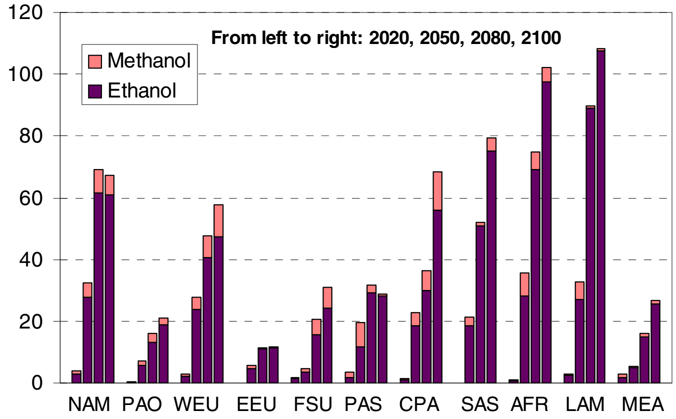

Figure 49: World-regional methanol and ethanol use, in EJ.

Figure 50 illustrates the methanol and ethanol supply mixes of the 11 world regions. In the OECD90 region (NAM, PAO and WEU), methanol made from natural gas and ethanol made from biomass are the main alcohol fuels. In the reforming regions (EEU and FSU) and in Asia (PAS, CPA, SAS), mainly coal is used as a feedstock to produce methanol, but in FSU, natural gas is also used for producing methanol. In Asia, biomass is the main feedstock for producing ethanol, but ethanol imports are also substantial, particularly in SAS. In AFR, coal-based methanol is the main alcohol fuel supply in the early stages, but later, ethanol production from biomass becomes dominant. MEA is exceptional as it relies to a major extent on imports of alcohol fuels rather than on its indigenous production.

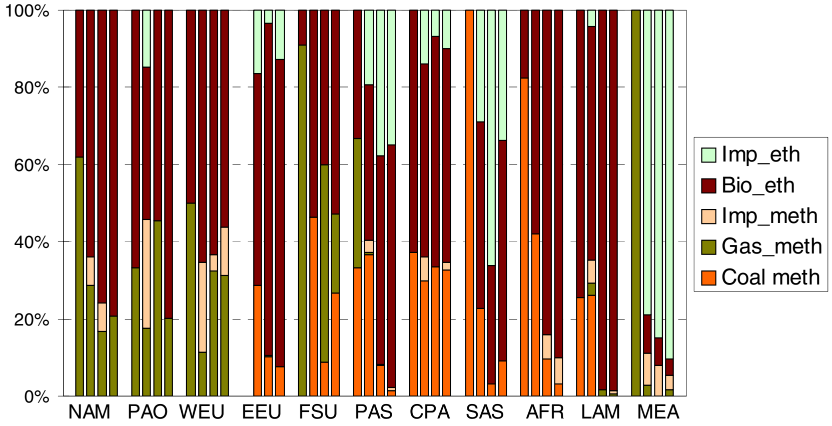

Figure 50: World-regional methanol and ethanol supply mix (shares) for 2020, 2050, 2080 and 2100 (from left to right).

7 Conclusions: Policies for sustainable development

In this report, we presented the results of an analysis of a global sustainable-development scenario that would, if implemented, successfully address the climate change challenge. Our presentation focuses on the technologies that would be required for following a path to the sustainable development of the global energy system. Amending earlier, more aggregate descriptions, we here aimed at describing this technological path in concrete terms and quantified how such a technological solution could contribute to a realization of the sustainable development. We present the required technology development from a normative perspective, highlighting the importance of technologies based on renewable energy and fuel cells. We showed that such a transformation from the current energy system based on predominantly fossil fuels is feasible at least from technical point of view.

It is clear that such a technological solution cannot be expected to develop automatically. Rather, technological policy must be in place to support the development of technologies included in the scenario that can keep the global energy system on a sustainable-development path as described by the PF scenario. In this concluding section, we would like to discuss policy implications of our study.

The PF scenario outlines the potential contribution of renewable energy to the global energy supply in the 21st century if favorable conditions for its penetration were in place. An energy system with a maximum contribution of renewable resources is consistent with long-term sustainability: locally, it reduces hazardous emissions, on the global level it reduces carbon emissions, and it conserves primary energy resources. Clearly, substantial technological changes are required to achieve such a renewable-based energy system, and policies will be called upon to bring them about.

In the PF scenario, a rapid decrease of specific investment cost of advanced – in particular renewable – technologies is assumed. More specifically, in MESSAGE, the costs of technologies are specified exogenously for over 400 technologies, and the PF scenario assumes particularly rapid cost reduction for renewable and fuel cells. This drives the penetration of technologies based on renewable energy as is described in the PF scenario. This kind of technology progress is assumed to be the result of cumulative experience with the production and use of these technologies (technological learning) and of technology policies.

In addition, general economic conditions must provide a suitable environment for technology development. Accordingly, the PF scenario assumes rapid economic growth, which in turn generates a rapid growth of new and a fast turn over of existing technology stock. This high demand for investments in energy conversion technology allows for massive R&D investment in advanced technologies. From a policy perspective, government R&D and procurement policies would be the obvious way to promote the cost reduction as well as the penetration of energy conversion technologies.

IIASA-ECS uses various approaches to study effective technology policy making. A detailed description of these studies is beyond the scope of this report, but we introduce here some results of the work that we have done in this area.

In the very early phases of technological development, when technology research is mainly focused on prototypes, R&D is known to have substantial effects on reducing technology cost down to the order of magnitude of the cost of established technologies. Later, at the beginning of a technology's commercialization phase, government procurement policy is effective to bring technology costs down to a competitive level.

In the past, technology policies such as procurement, subsidies, and public R&D support have played a key role in achieving cost-reductions of environmentally friendly technologies. Examples of technology policies on wind technology and their effect can be found in Klaassen *et al.* (2003). We now give a brief summary of that study.

The progress of wind technology can be attributed to R&D programs and accumulated experience with producing wind turbines (Klaassen *et al.*, 2003). In Denmark, for instance, a coordinated R&D support in the field of energy technology started in 1976, and 10% of the total energy research program was spent on wind energy projects in a constant way. The Danish experience suggests that their R&D resulted in technically reliable wind turbines thus establishing a market for wind turbines by the end of the 1970s. A successful market introduction of wind technologies was accomplished also with the help of various procurement policies, mainly in form of investment subsidies (1979-1989). Since the mid-1980s, the Danish government has guaranteed a tariff to be paid to the wind farm operators by the energy supply companies for selling electricity to the electricity companies.

In Germany, a first phase of public R&D support for wind started in 1974, and the second one in the mid-1980s. After an unsuccessful first phase, which focused on large wind turbines, a second phase focused on manufacturing prototypes for small wind turbines, and a modified prototype was launched in the market successfully. Policies helping the rapid diffusion of wind power in Germany included investment subsidies and a feed-in law that regulates the purchasing of renewable electricity by public energy supply companies, combined with low-interest loans for the construction of the wind turbines.

In the United Kingdom, over 10 million US dollars (1998 purchasing power) were spent annually for R&D projects on wind technology between mid-1980 and mid-1990. As a procurement policy, since 1989, the UK government introduced the so-called non-fossil obligation, which requires regional electricity companies to purchase specified amounts of electricity generated by non-fossil sources at a premium price from specified producers for a fixed long-term period, with the difference between competitive price and the premium price being reimbursed by the government to the regional electricity company.

The policy efforts in three countries contributed to the significant cost reduction as well as to higher market shares of wind turbines. This is conceptualized in a concept known as "technological leaning", which explains the phenomenon decreasing technology cost as the result of an increasing cumulative installation of the technology. To initiate such a process, policy intervention can be effective because without it, established technologies would maintain their competitive price advantage. An energy system could therefore remain locked into the use of technologies that are not environmentally friendly.

To deal with this phenomenon analytically, the concept of "learning curves" was used. A learning curve depicts an empirical relationship between specific-cost reduction and cumulative capacity of a technology. The postulated relationship is based on the empirical observation that for each doubling of cumulative capacity, there is a constant percentage decrease, called the learning rate[18], of technology price (specific investment cost of the technology). Typical learning rates calculated for studies on wind turbines range from 4 to

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[18] See McDonald and Schrattenholzer (2002) for a compilation and discussion of learning rates of energy technologies.

32% depending on the country or region studied and the indicator used (investment cost or production cost).

Klaassen *et al.* (2003) integrated the effect of R&D investment on the cost reduction into the learning-curve framework. They used the so-called two-factor leaning curve concept and estimated the effectiveness of R&D and procurement policies in a form of learning rate using the data for the above mentioned three European countries. Their estimation result suggested a robust learning rate of 5.4% for procurement and 12.6% for the R&D[19].

In general, wind and solar photovoltaic technologies are two typical examples of successful technology learning in the energy area, and accordingly, they are studied intensively. Past experience on the cost development can give useful information for the technology policy making in the policy area. One example is a study published by Miketa and Schrattenholzer (2004), which used the optimization model ERIS by Barreto and Kypreos (2003) to explore the usefulness of the learning-curve concept for policy making. ERIS is an optimization model of the global electricity supply system and incorporates the learning-curve concept in a form that separately includes the impact of R&D on technology development. ERIS was used to analyze the optimal research and development support for wind and solar photovoltaic technologies. The study is methodologically oriented and cannot yet reliably produce concrete policy recommendations. Still, it supports the idea that higher upfront costs of introduction of technology could be recovered in the long-run after technological learning, combined with support by public R&D. In addition, it approximately quantifies the effect of public R&D support.

Based on this experience with the analysis of the optimal R&D, IIASA-ECS has participated in several projects, sponsored by the European Commission (EC) – on the allocation of energy R&D to different power generation technologies. In these projects, the stochastic multi-objective model ISPA (Kouvaritakis, 2001) was used to calculate the optimal allocation of R&D, which is defined as maximizing the probability of reaching the aspirations formulated as the main indicator of sustainable development while keeping the achievements in terms of other indicators above specified probability levels. The application of this model is also mainly at a methodological level, but is planned to be introduced to policy makers to test its applicability in the real world.

Currently emerging technologies such as fuel cell does not have experience enough to reliably estimate a quantitative relationship between the development of specific technology cost, cumulative capacity, and R&D. Still, these technologies can be analyzed with the learning-curve framework in a scenario-like (i.e., parametric) way.

Our studies of optimal R&D strategies were driven by the motivation that their quantitative results could, in the future, provide a solid ground for policy to target R&D at technologies that have been shown to lead to sustainable development. For R&D policy to be getting more attention, research on its effectiveness is essential and research development in this regard is behind various procurement policies that has been studied by far the most intensively in the economic literature.

If successful, these policies could lead to a path towards sustainable development that does not restrict deteriorate life style, allows more cars, permits the world population to travel

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[19] The learning rate for R&D, sometimes also referred to as learning-by-searching rate (LSR), is defined in complete analogy to the more conventional learning-by-doing rate, i.e., as the reduction of specific technology cost that accompanies a doubling of cumulate R&D of the technology.

more and more, lets everyone enjoy high-quality energy service, and, generally, is consistent with ever-increasing economic prosperity. In our opinion, such a future is possible and achievable, provided an appropriate targeted policy effort is made.

The sprit of our study was to portray a picture of a technically plausible global energy system in the sustainable-development PF scenario and to arrive at policy-relevant targets for the technological development that is needed to achieve it. Our study undertook to translate such a technology development into concrete "milestones" for each of three aggregated economic sectors (transport, industry, and residential/commercial). Passing these milestones at the suggested times may keep us on a path to sustainable development of the global energy sector.

8 Appendix

8.1 Appendix to Section 3.2

Table 23 and Table 24 are taken from Nakićenović *et al.* (1996), who presented end-use efficiency data for different transportation modes using different fuels in European OECD as well as LAM region. The efficiencies of fuels for transportation sector total have been calculated by the authors of this study using the updated weights for different transportation modes based on the fuel consumption in 1990 taken from the recent IEA database (IEA, 2002a, IEA 2002b). Based on Table 23 and Table 24, we calculated the global average of end-use efficiencies presented in Table 3 in the main text.

Table 23: End-use efficiency for European OECD in 1990 (calculated based on Nakićenović *et al.*, 1996).

	Coal	**Renewable Fuels**	**Oil**	**Gas**	**Electricity**
Transportation sector total	**6.9**	**29.9**	**15.3**	**12.1**	**83.2**
Bus and Truck	---	---	13.5	13.5	---
Car and Truck	---	---	10.9	10.4	---
Airplanes	---	---	26.2	26.2	---
Ship*	15.9	15.5	31.8	31.8	---
Rail	6.6	5.0	31.8	31.8	82.7
Other	54.7	44.2	57.7	60.6	88.8

* "Ship" here refers to fuel consumption by ships engaged in transport in inlands and coastal waters and does not include international marine bunkers which is delivered to sea-going ships of all flags, including warships.

Table 24: End-use efficiency for the rest of the world (rest of European OECD) in 1990 (calculated based on Nakićenović et al, 1996).

	Coal	**Ren. Fuel**	**Oil**	**Gas**	**Electricity**
Transportation sector total	**6.3**	**44.2**	**15.0**	**12.3**	**74.1**
Bus and Truck	---	---	13.9	13.5	---
Car and Truck	---	---	11.0	10.4	---
Airplanes	---	---	26.3	---	---
Ship*	---	---	30.4	31.8	---
Rail	6.0	0.0	25.0	---	72.9
Other	45.8	44.2	53.1	---	88.8

* "Ship" here refers to fuel consumption by ships engaged in transport in inlands and coastal waters and does not include international marine bunkers which is delivered to sea-going ships of all flags, including warships.

8.2 Appendix to Section 3.4.1.

Followings are the details of the numbers presented in Table 4. The data sources are presented together with some remarks on the data.

NAM: The occupancy rate of 1.6 used for NAM was taken from the *Transportation energy data book (ORNL)*, "average vehicle occupancy rate for passenger cars in the United States". Time-series from 1970-2000 are given in Table 25 Table 21-4 of Michaelis *et al.* (1996) gives an alternative value, 1.5, for 1991. Nakićenović *et al.* (1993) give a smaller value, 1.15.

WEU: European Average of 1.9 was calculated by the authors as population weighted averages based on individual country data for 1990 taken from Eurostat (2002). The time series of available counties are presented in Table 25. IEA (1997b) gives an alternative estimate for early 1990s, 1.5-1.6, for Europe as a whole. Michaelis *et al.* (1996) give 1.5-1.8 for Western Europe in 1991.

PAO: The occupancy rate of 1.4 used for PAO is a Japanese data for 1991 taken from Michaelis *et al.* (1996). Newman and Kenworthy (1989) also gives 1.4 as a value for Tokyo. For Australia, authors' own calculation based on Australian Bureau of Statistics (2001) gives 1.33.

EEU: Michaelis *et al.* (1996) present 2.0 as an occupancy rate for Poland in 1991. Since no other estimate was available, we used this value to represent the EEU region.

FSU: The occupancy rate of 2.0 is taken from Soviet Union Data (for 1988) given in Michaelis *et al.* (1996).

CPA: Michaelis *et al.* (1996) present an occupancy rate for China as 2.0, although they note that their value is highly uncertain. We used this value to represent the CPA region.

SAS: Michaelis *et al.* (1996) present an occupancy rate for India as 2.0, although they note that their value is highly uncertain. Bose (1998) reports occupancy rates for cars/jeeps in Delhi, Calcutta, Mumbai, and Bangalore as 2.7, 2.6, 1.6, and 2.7, respectively. We used 2.0 as a load factor for the SAS region.

PAS: Michaelis *et al.* (1996) present 2.0 as an occupancy rate for Thailand, although they note that their value is highly uncertain. It also gives 1.7 for Singapore (in 1992), and 1.4 for Korea (in 1991). However, to also account for the less developed countries in this world region, we used 2.3 as an occupancy rate to represent PAS.

LAM: For LAM, we had no estimate available. We used 2.0 as an occupancy rate.

AFR: Estimate for Accra (Ghana) was available and it was 2.3. We used 2.5 as an occupancy rate for the AFR region.

MEA: For MEA, we had no estimate available. We used 2.0 as an occupancy rate.

Table 25: Development of passenger car occupancy rates in selected countries. Source: see the text.

	1960	1970	1980	1990	1995	1998	2000
USA	1.95	1.91	1.81	1.62	1.59	1.59	1.6
Belgium			1.8	1.5			
Austria			2	2			
Denmark			1.8	1.7	1.7	1.7	
Finland			1.5	1.5	1.4	1.4	
France			1.8	1.9	1.8	1.8	
Germany			1.8	1.6	1.4		
Greece							
Ireland				0.9	0.9		
Italy			1.7	1.9			
Luxembourg			1.4	1.3			
Netherlands			1.7	1.8	1.6		
Portugal			2.4	2.5	2.6	2.4	
Spain			3.2	3	3		
Sweden				1.6	1.5	1.7	
UK			1.9	1.8	1.5	1.5	

8.3 Appendix to Section 3.4.2.

As discussed in the main text, for the three industrial regions (NAM, PAO, WEU), the assumptions of fuel economy of cars on the road in 2050 are given as the fuel economy of the best available cars in the market in 2000. For the 2100, it was assumed that on the road fuel economy is about the best technically available cars foreseeable in 2000. US data, Japanese data, and EU data were used to represent the NAM, PAO, WEU region, respectively.

Based on all the estimates of the future values of fuel economy are the current average fuel economies in the markets. There are some estimates available from several data sources. Table 26 summarizes available estimates for selected countries for selected years. This table reveals technical difficulties underlying such estimates. For some countries, different sources report different values. One has to note that these numbers are not necessarily comparable given the fact that test practices of different countries are not done under the comparative conditions (IEA, 2003b).

Table 26: Fuel consumptions of new cars, weighted by sales volume, liter per 100 kilometers.

	1970	1975	1980	1985	1990	1995	2000	Sources
US (including light trucks)		18.0	12.3	11.0	10.9	11.1	11.4	Hellman and Heavenrich (2003)
Australia			10.1	9.5	9.2	9.0		IEA (2003a)
Japan	9.3	10.2	8.0	7.5	8.0	8.4	7.1	EDMC (2002)
Japan			8.3	8.1	8.8	9.1		IEA (2003a)
Germany		10.3	8.9	7.4	7.7	7.4	6.7	IEA (2003a), ECMT
Austria			8.7	7.3	7.3	7.0		ECMT (2000)
Belgium			8.0	7.0	6.8	6.7		ECMT (2000)
France		8.7	7.6	6.7	6.5	6.5	5.9	IEA (2003a), ECMT (2000)
Italy			7.7	6.5	6.7	7.0	6.0	IEA (2003a), ECMT
UK			8.8	7.4	7.3	7.3		ECMT (2000)
UK			8.8	7.4	7.2	7.3	6.8	IEA (2003a), ECMT (2000)
Sweden			9.4	8.2	8.5	8.5		ECMT (2000)
Sweden			9.0	8.2	8.4	8.5	7.5	IEA (2003a)
EU 7 average			8.3	7.1	7.1	7.1		ECMT (2000)

For the calculations of the fuel consumption rates of the best available cars in the markets of the three industrialized regions in 2000, we used results of "best-in-class analysis" done by the U.S. EPA (Hellman and Heavenrich, 2003). The best-in-class analysis is based on an assumption that an average fuel economy of each vehicle class could eventually reach the level of the best vehicle, or several top vehicles, currently in that class. Using model year 2003 as a reference, their result was that the best-in-class cars have fuel economies of 20% higher than the market average of new cars in the US market in 2003. Although this analysis was originally done for the US market, we also assumed a 20% higher fuel economy than the current average fuel economies of new cars in the Japanese (in 2000) and European (in 1995) markets to represent the best-in-class cars in the respective markets. For the average fuel economy in 2003 in NAM region, we used the American data estimated by Hellman and Heavenrich (2003). For PAO, we used Japanese data estimated by IEA (2003a), and for WEU we used data estimated by ECMT (2000).

To calculate the fuel consumption rates of technically advanced cars, which are to be used as assumptions of the fuel economy in 2100, we first reviewed various estimates of the potential of fuel economy increase of the gasoline/diesel-based cars from available literature sources. Table 27 gives the summary of our literature survey. Since all studies reviewed were from US, we summarized results both in miles per gallon (conventional in the U.S.) and litter per 100 kilometers. We made our own assumption on the fuel consumption rate improvement, which we think is approximately consistent with the PF scenario. Note that we excluded efficiency improvement estimates of hybrid-cars, because in MESSAGE, efficiencies of all technologies based on different fuels are defined relative to the conventional gasoline/diesel-based technologies (see the discussion related to Table 2 on page 10), and an inclusion of the hybrid technology would overestimate the entire efficiency improvement potential of the transportation sector as whole.

The first study that we reviewed was from the US Energy Information Administration (EIA, 2003b), who forecasted that for the United States, advanced technologies such as variable valve timing and direct fuel injection, as well as electric hybrids for both gasoline and diesel engines, are to decrease average fuel consumption of new light duty vehicles to 8 percent (to achieve 9.0 liters per 100 kilometer compared with 9.8 litters per 100 kilometers) by 2025 for the reference case. Under the reference case, it is assumed that the fuel efficiency standards for new light-duty vehicles stay at current levels and projected low fuel prices and higher personal income expected to increase the demand for larger and more powerful cars, which put the brakes on the fuel efficiency improvement. Note that this estimate includes the introduction of electric hybrid-vehicles.

The second study that we reviewed was from Massachusetts Institute of Technology (Weiss *et al.*, 2002). MIT's results are based on a vehicle computer simulation model, which showed that the fuel consumption rate for gasoline/diesel cars would decreases by 35% in the reference case by 2020; in the advanced technology case, it argues that additional 9% (for gasoline car) and 15% decrease (for diesel car) is achievable. The difference between the reference case and the advanced technology case is that in the reference case efficiency improvement is limited to the improvements with the engine, whereas in the advanced technology case, further improvements related to the introductions of advanced body designs with lighter-weight materials and further (but modest) improvement of ICEs are taken into consideration.[20]

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[20] Including hybrid-cars, the fuel consumption rate reduction is of course higher; in that case, it has been calculated that by 2020, the fuel consumption rate could reach 70.8 mpg (3.3 liter per 100 kilometers) for the

Table 27: Summary of published estimates of potential improvements of fuel consumption rates for passenger light-duty vehicles (cars and light trucks). Fuel efficiencies are in mpg (in parentheses, fuel consumption rate expressed in terms of liter per 100 km).

	Fuel efficiency at the reference year	**Reference year**	**Fuel efficiency at the end year**	**End year**	**% increase, fuel efficiency**	**% decrease, fuel consumption rate**
EIA (2003b), reference case	24.1 (9.8)	2001	26.1 (9.0)	2025	8%	7.7%
Weiss *et al* (2002), reference case	27.8 (8.5)	1996	43.2 (5.5)	2020	55%	36%
Weiss *et al* (2002), advanced technology case	27.8 (8.5)	1996	49.1 / 56.0 (4.8 / 4.2)	2020	78% / 101%	45% / 51%
NAS (2002), Path 1		2000		-2010	14% (cars only: 8%-13%)	12% (cars only: 7.4-11.2%)
NAS (2002), Path 2		2000		-2010	37% (cars only: 18%-39%)	27% (cars only: 15.5-28.8%)
NAS (2002), Path 3		2000		2010-2015	54% (cars only: 39%-28%)	35% (cars only: 27.9-36.7%)
OTA (1995), Advanced conventional	27.5 (8.4)	1995	53-63 (3.7-4.2)	2015	42%	50%-56%
NRC (1992), Shopping cart projections	23.7-31.2 / 19.5-25.2 (7.5-9.9 / 9.3-12.1) (cars / light trucks)	1991	31.9-40.7 / 25.4-27.5 (5.8-7.4 / 7.2-9.3)	2006	27-35% / 30-36%	22-25% / 23-26%
Lightfoot and Green (2003)	27.5 (8.4)	1988 (peak year)	60 (4.0)	2100	117%	54%
IEA (1997)					20%	
Shafer *et al* (1999), Moderate vehicles	24.8 (9.5)	1995	43.2 (5.5)	2010	74%	42%

The third study that we reviewed was from the National Academy of Science (NAS, 2002), who assessed fuel economy improvement potentials for the next 10-15 years for three cases (Path 1 to Path 3), based on detailed lists of fuel economy improving technology options. Path 1 assumes likely market-responsive or competition-driven advances in fuel economy using technologies that may be possible under current economic and regulatory conditions and could be introduced within the next 10 years. Path 2 assumes more aggressive advances in fuel economy that employ more costly technologies but that are technically feasible for an introduction within the next 10 years if economic and/or regulatory conditions justify their use. Path 3 assumes even greater fuel economy gains, which would necessitate the introduction of emerging technologies that have the potential for substantial market penetration within 10-15 years. It estimated the fuel consumption rate improvement for passenger cars to be 7.4-11.2% reduction for Path 1, 15.5-28.8% reduction for Path 2, 27.9-36.7% reduction for Path 3 depending on car types.[21] The average fuel consumption rate improvement (weighted by new sales of passenger vehicles in 2000) would be 10% for cars and 12% for all passenger light vehicles (including cars, SUVs, mini-vans, and pickup trucks) in Path 1. Likewise, for Path 2, 21% reduction was found for cars and 27% was for all passenger vehicles, and for Path 3, 32% was for cars and 35% was for all vehicles.

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case of gasoline plus electric hybrid car, and 82.3 mpg (2.9 liter per 100 kilometers) for the diesel plus electric hybrid car.

[21] The analysis was done separately for 10 weight classes, including not only cars but also SUVs, mini-vans, and pickup trucks.

The fourth study that we reviewed was from the US Office of Technology Assessment (OTA, 1995). OTA's technology assessment of advanced vehicles to be introduced during the next 10 to 20 years identifies the technical potentials for fuel efficiency improvement (and its cost) among other technical characteristics of such cars in the future. Their analysis is based on a wide-range review of literature sources and interviews with car manufactures regarding technical potentials. The average estimate of car manufacturers regarding the future fuel efficiency of advanced ICE vehicle in 2015 was 53.2 mpg (4.2 liter per 100 kilometers) and the most optimistic estimate was 63.5 mpg (3.7 liter per 100 kilometers, 56% reduction of fuel consumption rate compared with the current average fuel consumption rate of new cars of 8.4 liter per 100 kilometers). These numbers are considered as maximum potentially achievable while maintaining interior space and performance constant at 1995 levels. To achieve this fuel economy, vehicles would combine optimized aluminum body, continuously variable transmission, advanced low rolling resistance tires with advanced ICE technology.

The fifth study that we reviewed was from the US National Research Council (NRC, 1992), who projected the future fuel economies using three different methods. The first method is "historical trend projections" using regression analysis of past data on fuel economy development between 1975 and 1991. The second one is "best-in-lass projections" similar to the one used in the above-mentioned U.S. EPA study (Hellman and Heavenrich, 2003). The third one is called "shopping cart projections" (or "technology-penetration projections"). This method is based on an explicit consideration of the potential fuel economy contributions of specific, well-established technologies and this is indeed the method used by the most of the studies reviewed here. Here we only report the result of shopping cart approach since this is the most appropriate one in the light of this study. One characteristics of NRC's study is that it includes only proven technologies and thus it assumes that only technologies can be implemented by manufacturers in the normal process of replacing manufacturing equipment, that is, in 15 years or less. In their calculation, vehicle performance was held constant at 1990 level. They estimate the fuel economy improvement potential for 8 vehicle classes including both cars and light trucks. It projects that for cars, the fuel consumption rate improves about 22% to 25% depending on the size of cars, and for light trucks by about 23% to 26%.

These five studies are based on a detailed technology reviews. There are also a number of rather rough estimate of fuel efficiency improvement potential. Lightfoot and Green (2002) gave a rough expert estimate of fuel economy improvement potential. They estimate that a further increase of 115% (equivalent to a specific-fuel consumption decrease by 54% given the peak of fuel consumption rate at 8.6 liter per 100 km in 1988) may be possible by improvements to current four stroke engines, continuously variable transmissions, light weight materials, reduced rolling resistance and improved aerodynamics.

The IEA (1997) also gives rough estimate of maximum potential efficiency improvement of ICE engine's efficiency. They report that 20% of efficiency improvement could be achieved with improved exhaust treatment, improved combustion, and fast warm-up.

Schafer *et al.* (1999) characterized four types of future cars, of which two are based on improved ICE technology. "Evolutionary vehicles" incorporate a direct-injection gasoline engine and a standard auto body and they are to be introduced by 2005; and "moderate vehicles" represent a 4-valve low-friction port-injected engine integrated in a first generation aluminum space frame body and they are to be introduced by 2010. They characterize evolutionary vehicles to have 30% lower fuel consumption rate, and 42% lower in the case of moderate vehicles.

Based on our review, we select 50% as the assumption for currently foreseeable fuel economy improvement rate by 2100. We applied this improvement to the average fuel economies of new cars in 2000 to calculate the technically foreseeable fuel economies in absolute term in three industrialized regions. We used these fuel economies as assumptions for average fuel economies of on the road cars in 2100.

For developing regions we assume that each region follows one of the three industrialized regions fuel economy development paths. We associate each region with region's "leader" as summarized in Table 28. We assume that a leader and a follower achieve the same level of fuel economy at the point where a follower's per-capita GDP level reaches 85% of the leader's per-capita GDP level. For example, we assume that CPA's fuel economy level in 2050 is equal to NAM's fuel economy in 2000 because in 2050 CPA's per-capita GDP level reaches 85% of per-capita GDP level of NAM in 2000. The year in which 85% of the per-capita GDP of a leader corresponds to the 2050 level of a follower is given in the second column of Table 28. Likewise, the third column shows the year that 85% of the per-capita GDP of a leader corresponds to the 2100 level of a follower. In a case where a follower takes over the 85% of the leader's GDP level before 2100, the year in which a region takes over is used as a year that the fuel economy of the leader and the follower equalized.

The SAS and AFR world regions refer to the past (before 2000) fuel economy of the corresponding leaders (PAS and WEU). The past data for PAS is taken from IEA (IEA, 2003), and for WEU, Samaras *et al.* (1999) was used after scaled-up so that their time-series and our estimated 1990 data become consistent.

Table 28: Assumed development paths for non-industrialized regions used in our calculation.

	Regions to follow (leader)	85% of 2050 GDP corresponds to…	85% of 2100 GDP corresponds to…
EEU	WEU	**2050**	**2100 (take over in 2060)**
FSU	NAM	**2020**	**2100 (take over in 2090)**
CPA	NAM	**2000**	**2100**
SAS	PAO	**1972**	**2085**
PAS	PAO	**2040**	**2100 (take over in 2080)**
LAM	WEU	**2040**	**2100 (take over in 2080)**
AFR	WEU	**1991**	**2080**
MEA	NAM	**2000**	**2060**

References

American Automobile Manufacturers Association (AAMA), 1997: *World Motor Vehicle Data*, Washington, DC.

Alternative Fuels Data Center (AFDC), 2003: Alternative Fuels, Information and Comparisons, U.S. Department of Energy. <http://www.afdc.doe.gov/altfuels.html> (October, 2003).

The ATLAS Project, 2003, Solar Thermal Heating Overview. <http://europa.eu.int/comm/energy_transport/atlas/htmlu/solhover.html>, (11 November, 2003).

Ayes, R., Ayres, L.W. Pokrovsky, V., 2004: On the Efficiency of Electricity Usage Since 1900, IR-04-027, IIASA, Laxenburg.

Barreto, L., and S. Kypreos, 2003: Endogenizing R&D and Market Experience in the Bottom-up Energy-systems ERIS Model. *Technovation* (in print).

Barreto, L., A. Makihira, and K. Riahi, 2003: The Hydrogen Economy in the 21st Century: A Sustainable Development Scenario. *International Journal of Hydrogen Energy* 28 (3), pp. 267-284.

Bevilacqua Knight, Inc., 2001: *Bringing Fuel Cell Vehicles to Market: Scenarios and Challenges with Fuel Alternatives*. Consultant Study Report prepared for California Fuel Cell Partnership (CaFCP), California, US.

Bose, R. K., 1998: Automotive Energy Use and Emissions Control: A Simulation Model to Analyze Transport Strategies for Indian Metropolises. *Energy Policy* 26 (13):1001-1016.

Bose, R.K. and D. Sperling, 2001: Transportation in Developing Countries: Greenhouse Gas Scenarios for Delhi, India. Pew Center on Global Climate Change and Institute of Transportation Studies, California, US.

Capital Surini Group International, Inc. and Energetics, Inc., 2001: *Roadmap for Process Heating Technology*, prepared for US Industrial Heating Equipment Association and U.S. Department of Energy Office of Industrial Technologies. Washington, DC, US.

Davis, S.C. and S.W. Diegel, 2002: *Transportation Energy Data Book: Edition 22*, Oak Ridge National Laboratory, ORNL-6967, Tennessee, US.

Department of Energy, DOE Annex V Team, 1999: Introduction of Hybrid Electric Vehicles. <http://www.nrel.gov/china/pdfs/annex5/introduction_of_hybrid_electric_ vehicles.pdf> (December 1, 2003).

Doyle Thomas A., 1998: Technology Status of Hydrogen Road Vehicles, IEA Agreement on the Production and Utilization of Hydrogen, IEA/H2/TR1-98. <http://www.eere.energy.gov/hydrogenandfuelcells/hydrogen/iea/pdfs/tech_status.pdf> (December 1, 2003).

The Energy Data and Modeling Center (EDMC), 2002, エネルギー経済統計要覧, Tokyo.

Energy Efficiency and Renewable Energy (EERE), 2003: Hydrogen, Fuel Cells and Infrastructure Technology Program, US Department of Energy <http://www.eere.energy.gov/hydrogenandfuelcells/> (October 21, 2003).

Energy Information Administration (EIA), 2003a: EIA Monthly Energy Review, Table 1.9 on Motor Vehicle Mileage, Fuel Consumption, and Fuel Rates. <http://www.eia.doe.gov/emeu/mer/txt/mer1-9> (January 12, 2004).

Energy Information Administration (EIA), 2003b: Annual Energy Outlook 2003, with Projections to 2025, US Department of Energy, DOE/EIA-0383(2003), Washington, DC. US.

Energy Information Administration (EIA), 2003c: The Assumptions to the Annual Energy Outlook 2003, with Projections to 2025, US Department of Energy, DOE/EIA-0554(2003), Washington, DC, US.

Energy Information Administration (EIA), 2003d, Form EIA-886, Annual Survey of Alternative Fuel Vehicles Suppliers and Users, available at Alternatives to Traditional Transportation Fuels 2002 (Table 14). <http://www.eia.doe.gov/cneaf/alternate/page/ datatables/atf14-20_02.html> (December, 1, 2003).

Energy Information Administration (EIA), 1999: A Model Documentation Report: Transportation Sector Module of the World Energy Projection System, US Department of Energy, DOE/EIA-M072(99), Washington, DC, US.

European Conference of Ministers of Transport (ECMC), 2000: Monitoring of CO_2 Emissions from New Cars, Updated with Data to 1999, ECMT, Paris. <http://www1.oecd.org/cem/topics/env/CO2Cars.pdf> (December 1, 2003).

Eurostat, 2002: Transport and Environment: Statistics for the Transport and Environment Reporting Mechanism (TERM) for the European Union, data 1980-2000, European Commission in cooperation with Eurostat, Luxembourg 2001 (Unpublished electronic update, January 2002) <http://themes.eea.eu.int/Sectors_and_activities/transport/indicators/

technology/occupancy/TERM_2002_29_EU_Occupancy_rates_of_passenger_vehicles.pdf> (December, 2003).

Gilli, P.V., N. Nakićenović, and R. Kurz, 1996: First- and Second-Law Efficiencies of the Global and Regional Energy Systems, RR-96-2, IIASA, Laxenburg

Hellman, H.K. and R.M. Heavenrich, 2003: Light-Duty Automotive Technology and Fuel Economy Trends: 1975 Through 2003, US Environmental Protection Agency, EPA420-R-03-006

International Energy Agency (IEA), 2003a: Unpublished data. Personal communication with Alan Meier (alan.meier@iea.org).

International Energy Agency (IEA), 2003b: Based on unpublished IEA Analysis. Personal communication with Lew Fulton (lew.fulton@iea.org).

International Energy Agency (IEA), 2002a: Energy Balances of Non-OECD Countries, 2002 edition, Paris.

International Energy Agency (IEA), 2002b: Energy Balances of OECD Countries, 2002 edition, Paris, France.

International Energy Agency (IEA), 1997a: *Energy technologies for the 21st Century*. Paris, France.

International Energy Agency (IEA), 1997b: *Indicators of Energy Use and Efficiency*. Paris, France.

International Energy Agency Heat Pump Programme, 2002: More about heat pumps <http://www.heatpumpcentre.org/tutorial/home.htm> (March 2002).

International Energy Agency, Implementing Agreement Hybrid and Electric Vehicles (IEA/HEV), 2003: Information Exchange on Hybrid and Electric Vehicle Technologies and Programmes < http://hevannex1.vtt.fi/index.htm> (November 2003).

International Road Federation, 2000: *World Road Statistics 2000*, Geneva.

The Japan Heat Service Utilities Association, 2003, The Role of District Heating and Cooling in Japan. <http://www.jdhc.or.jp/0002/p0002.html>, (4 August, 2003).

Kempton, W. and T. Kubo, 2000: Electric-drive Vehicles for Peak Power in Japan. *Energy Policy* 28(1): 9-18.

Kempton, W. and Letendre, S., 1997: Electric Vehicles as a New Source of Power for Electric Utilities *Transportation Research* 2(3): 157-175.

Kempton, W., J. Tomić, S. Letendre, A. Brooks, and T. Lipman, 2001: *Vehicle-to-Grid Power: Battery, Hybrid, and Fuel Cell Vehicles as Resource for Distributed Electric Power in California*. Institute of Transportation Studies, University of Davis. UCD-ITS-RR-01-03.

Klaassen, G., A. Miketa, K. Larsen and T. Sundqvist, 2003: The Impact of R&D on Innovation for Wind Energy in Denmark, Germany and the United Kingdom, Interim Report, IIASA, Laxenburg.

Kouvaritakis, N., 2001: *First runs with the ISPA meta-Model in the context of the SAPIENT project*, internal report for the EC-supported SAPIENT project, NTUA, Athens.

Lightfoot, H.D., and C. Green, 2002: Energy Intensity Decline Implications for Stabilization of Atmospheric CO_2 content, Report No. 2001-7, October 2001, McGill Center for Climate and Global Change Research, Canada.

Lipman, E. Timothy, Jennifer L. Edwards, and Daniel M. Kammen, 2004: Fuel Cell System Economics: Comparing the Costs of Generating Power with Stationary and Motor Vehicle PEM Fuel Cell Systems. *Energy Policy*, 32, pp. 101-125, forthcoming.

Lovins, B.A. and B.D. Williams, 1999: A Strategies for the Hydrogen Transition, 10th Annual U.S. Hydrogen Meeting, National Hydrogen Association.

Marx, T.G., 2000: The role of technology in responding to concerns about global climate change. In: *The Kyoto Commitments: Can Nations Meet Them with the Help of Technology?* ACCF Center for Policy Research, Washington, DC.

McDonald, A. and Schrattenholzer, L., 2002: Learning curves and technology assessment, *International Journal of Technology Management* 23(7/8):718-745.

Messner, S., and M. Strubegger, 1995: User's Guide for MESSAGE III, WP-95-69. International Institute for Applied Systems Analysis, Laxenburg, Austria.

Michaelis, L., D. Bleviss, J-P. Orfeuil, R. Pischinger, J. Crayston, O. Davidson, T. Kram, N. Nakićenović, and L. Schipper, 1996: Mitigation Options in the Transportation Sector. In Climate Change 1995: Impacts, Adaptation and Mitigation of Climate Change: Scientific-Technical Analyses. Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK.

Miketa, A., and L. Schrattenholzer, 2004: Experiments with a methodology to model the role of R&D expenditures in energy technology learning processes; first results, *Energy Policy* 32(15):1679-1692.

Ministry of Environment, Japanese government, 2003: 中核的温暖化対策技術検討会, 民生・運輸部門における中核的対策技術に関する中間報告, Tokyo.

National Academy of Sciences, Transportation Research Board (TRB), 2002: *Effectiveness and Impact of Corporate Average Fuel Economy (CAFÉ) Standards*. Washington, DC, US.

National Research Council, 1992: Automotive Fuel Economy, How Far Should We Go? Committee on Fuel Economy of Automobiles and Light Trucks Energy Engineering Board, commission on Engineering and Technical Systems, National Academy Press, Washington, DC, US.

NEDO (2002) 水素利用国際エネルギーシステム技術（WI-NET）第 II 期研究開発, NEDO-WE-NET-0101.

Nakićenović, N., J. Alcamo, G. Davis, B. de Vries, J. Fenhann, S. Gaffin, K. Gregory, A. Grübler, T.Y. Jung, T. Kram, E.L. La Rovere, L. Michaelis, S. Mori, T. Morita, W. Pepper, H. Pitcher, L. Price, K. Riahi, R.A. Roehrl, H.-H. Rogner, A. Sankovski, M. Schlesinger, P. Shukla, S. Smith, R. Swart, S. van Rooijen, N. Victor, and Z. Dadi, 2000: Special Report on Emissions Scenarios (SRES), A Special Report of Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK.

Nakićenović, N., P.V. Gilli, R. Kurz, 1996: "Regional and Global Exergy and Energy Efficiencies. *Energy-The International Journal*, 21(3):223-237.

Nakićenović, N., A. Grübler, A. Inaba, S. Messner, S. Nilsson, Y. Nishimura, H. Rogner, A. Schafer, L. Schrattenholzer, M. Strubegger, J. Swisher, D. Victor, and D. Wilson, 1993: Emission Reduction at the Global Level, Special Issue of *Energy*: *Long-Term Strategies for Mitigating Global Warming*, Vol.18, Number 18.

Office of Energy Efficiency and Renewable Energy, 2003, Consumer Energy Information: EREC Reference Briefs. <http://www.eere.energy.gov/consumerinfo/refbriefs/ac5.html>, (5 November, 2003).

Office of Technology Assessment (OTA), 1995: *Advanced Automotive Technology: Visions of a Super-Efficient Family Car*. OTA-ETI-638, Washington, DC, US.

Office of Technology Assessment (OTA), 1993: *Industrial Energy Efficiency*, OTA-E-560, Washington, DC, US.

Pierce, Morris A., 2003, the District Energy Library. <http://www.energy.rochester.edu/dh/> (31 May 2003)

Riahi, K., G. Klaassen, A. McDonald, R.A. Roehrl, and L. Schrattenholzer, 2000: Review of Energy-Economic GHG Emissions Scenarios, Interim Report to the Millennium Project, Laxenburg, Austria.

Resource Dynamics Corporation, 2003: *Cooling, Heating, and Power for Industry: A Market Assessment*, Prepared for Energy Efficiency and Renewable Energy US Department of Energy and Oak Ridge National Laboratory, Virginia.

Samaras, Z., T. Zachariadis, A. Babajimopoulos, D. Hassel, F.-J. Weber, K.-S. Sonnborn, and T. Meretei, 1999: *Study on transport related parameters of the European road vehicle stock*, Final Report to the European Commission, Study B98-27040-SIN 6516-ETU, Thessaloniki.

Schafer, A., 1995: Trends in Global Motorized Mobility, The Past 20 Years and Implications for the Next Century. IIASA Working Paper, WP-95-49, Laxenburg, Austria.

Schafer, A., S. Kypreos, L. Barreto, H. Jacoby, P. Dietrich, 1999: Automobile Technology in a CO_2-constrained World. In B. Eliasson, P. Riemer, A. Wokaun (Editors), Greenhouse Gas Control Technologies, Proceedings of the 4th International Conference on Greenhouse Gas Control Technologies, Interlaken, Switzerland. pp 911-916.

Schmied, Martin, EM Generic Database Documentation for Transport Processes: Emission Factors and Fuel Consumption Data for Motorized Road Traffic in Developing Countries. Öko Institute, Germany. <www.oeko.de/service/em/docu/data/emda0038.htm> (August, 2003)

Sissine, F., 1996: The Partnership for a New Generation of Vehicles, SRD Report for Congress, 96-191 SPR.

Turton, H., and L. Barreto, 2004: Automobile Technology, Hydrogen and Climate Change: A Long-Term Modelling Analysis, International Institute for Applied Systems Analysis, Laxenburg, Austria.

US Department of Energy (USDOE) and US Environmental Protection Agency (USEPA), 2003a: *Fuel Economy Guide Model Year 2004* < http://www.fueleconomy.gov/feg/ FEG2004.pdf> (December, 1, 2003).

US Department of Energy (USDOE) and US Environmental Protection Agency (USEPA), 2003b: Fuel Cell Vehicles <http://www.fueleconomy.gov/feg/fuelcell.shtml> (November, 4, 2003).

Weiss M.A., J.B. Heywood, E.M. Drake, A. Schafer, and F.F. AuYeung, 2000: On the Road in 2020, A life-cycle analysis of new automobile technologies. Energy Laboratory Report MIT EL 00-003, Energy Laboratory, Massachusetts Institute of Technology, Massachusetts.