Roadmap to deploying technologies for sustainable development

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Table of Contents

Table of Figures

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 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.

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.

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].

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

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.

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
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.

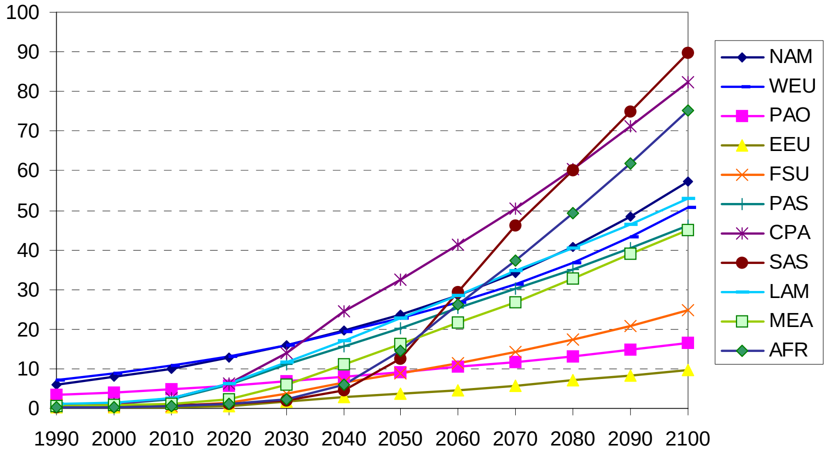

Figure 1: GDP assumptions used in the PF scenario, in trillion US1990 dollars.

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 million in 1990, 7.6 million in 2020, a peak in 2050 at 8.7 million and 7 million by 2100.

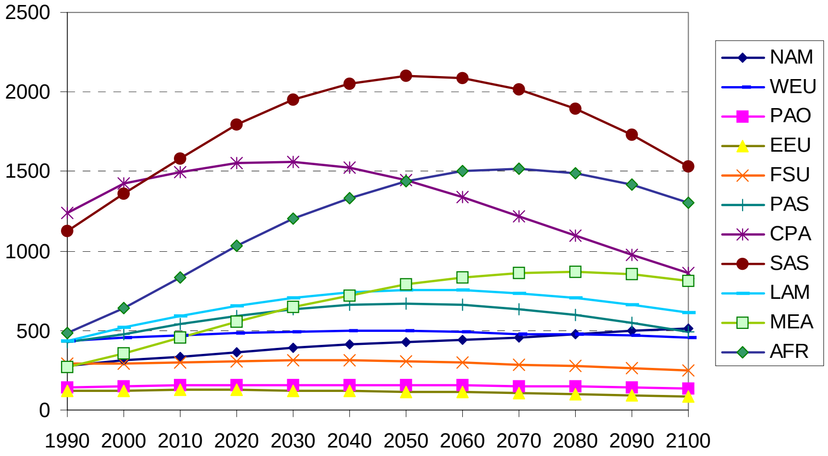

Figure 2: Population assumptions used in the PF scenario, in million people.

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.

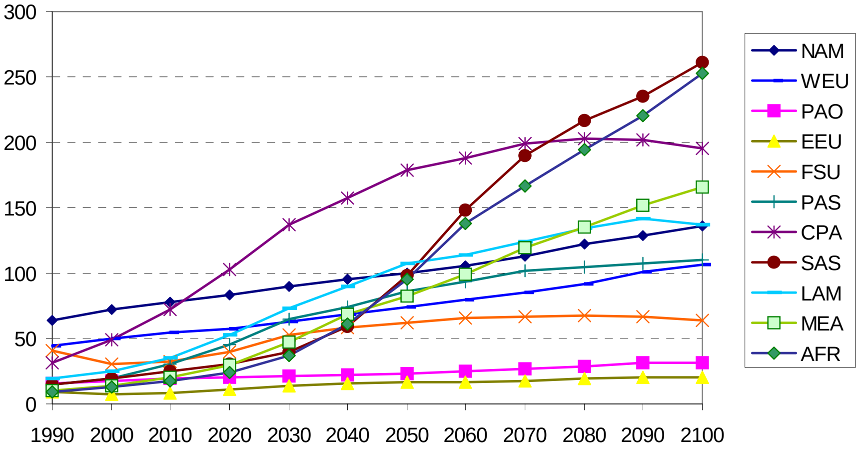

Figure 3: Final-energy demand assumptions used in the PF scenario, in EJ.

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 (7.5GtC).

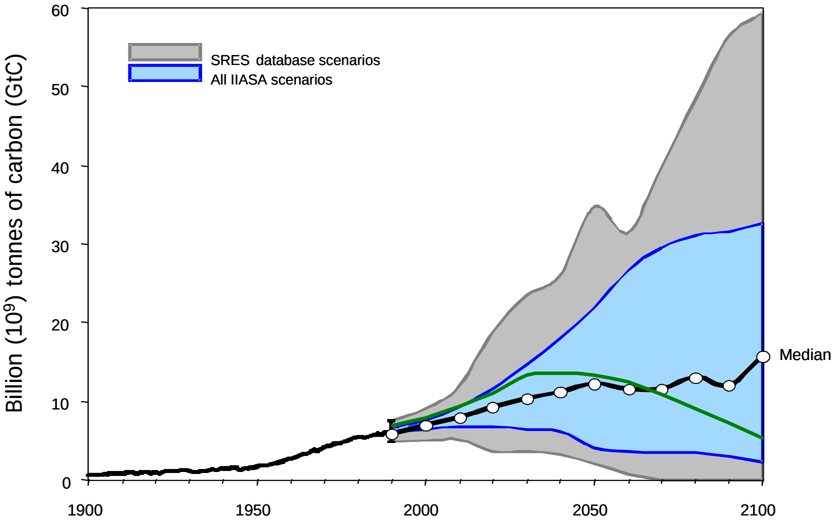

Figure 4: Global carbon dioxide emissions, actual development from 1900 to 1990 and PF scenario projections (green line) in comparison to other scenarios (140 of which from the SRES database) from 1990 to 2100. Historical data: Marland, 1994; Database: Morita and Lee, 1998.

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, special attention is therefore given to passenger road vehicle transportation.

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.

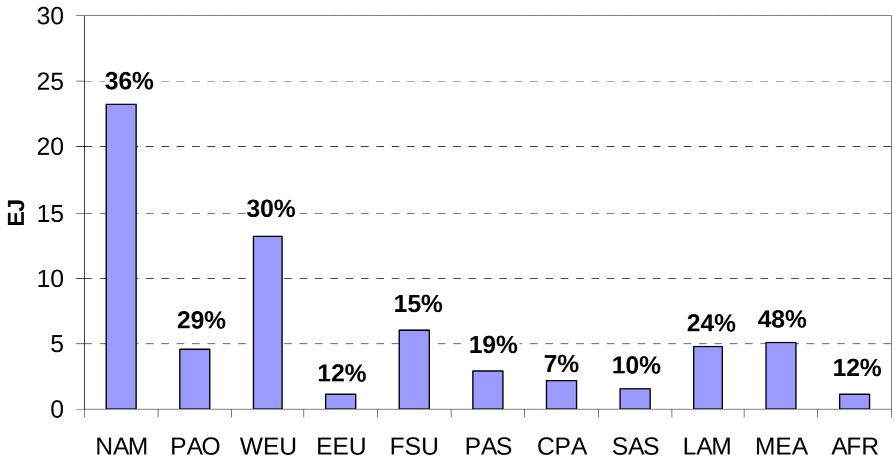

Figure 5: Global final-energy use in the transportation sector in 1990 in EJ. Percentages refer to the shares in total final energy consumed by the transportation sector.

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 and improves the emission quality of gasoline.

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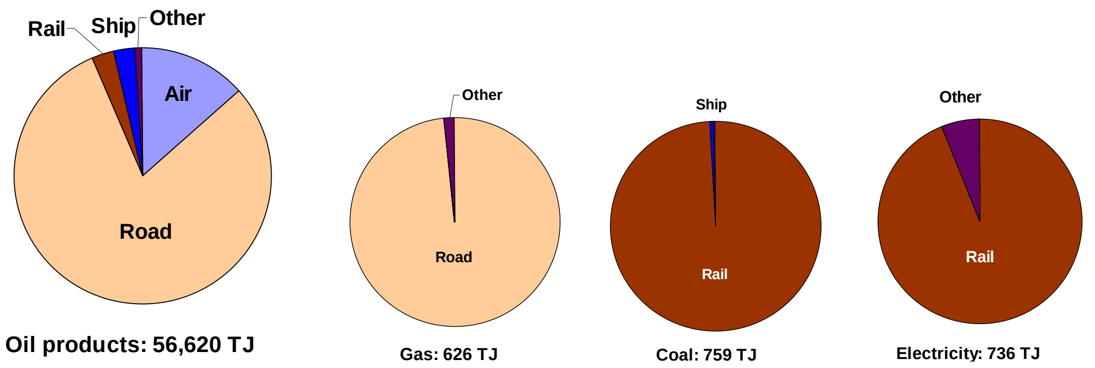
[2] In this figure, liquefied petroleum gas (LPG) is included under gas and not under oil products, although IEA’s statistics classify LPG as an oil product to make it consistent with the MESSAGE’s definition of gas.



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, 10^{12} 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, 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-based 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 produced by fermenting and distilling starch crops that have been converted

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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).

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. Particulate emissions are very low with ethanol. Adding ethanol to gasoline would also increase the octane number of gasoline and improve the emissions quality of gasoline, 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, 10% of ethanol is added to gasoline (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, India, and Australia 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, 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 the use of methanol is that it produces a high amount of formaldehyde in emissions. 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 produce 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 to 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 preferable.

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 fuels in that mechanical power is derived directly from it. Whereas the other alternative fuels release stored chemical energy through combustion to provide mechanical power, motive power is produced 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 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 liter to 4.3 liter 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

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

FCVs could exceed 60% (IEA, 1997a) – compared with 20% for gasoline-based internal combustion engines and may also incorporate other advanced technologies to increase efficiency.

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.

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

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 national energy security by reducing our dependence on oil from foreign countries. 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, petroleum distillates, or even 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.

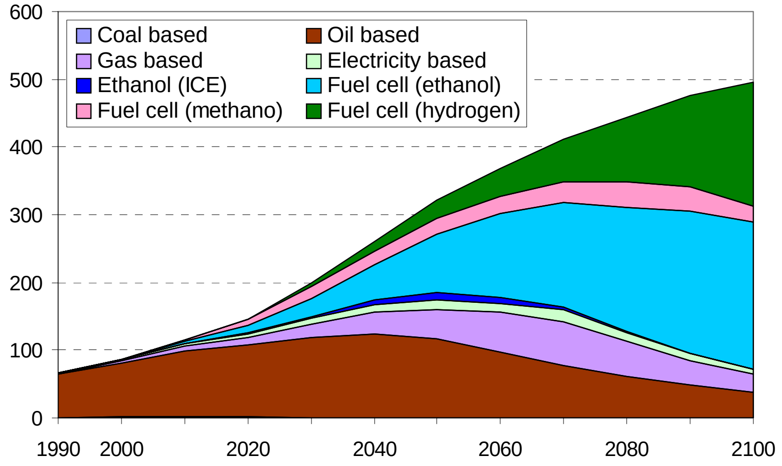

Figure 7: The development of technology mix in the transportation sector of the PF scenario, in EJ.

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 may be more suggestive. The pie charts show clearly that the transportation sector in the PF scenario undergoes a major structural change. 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%.

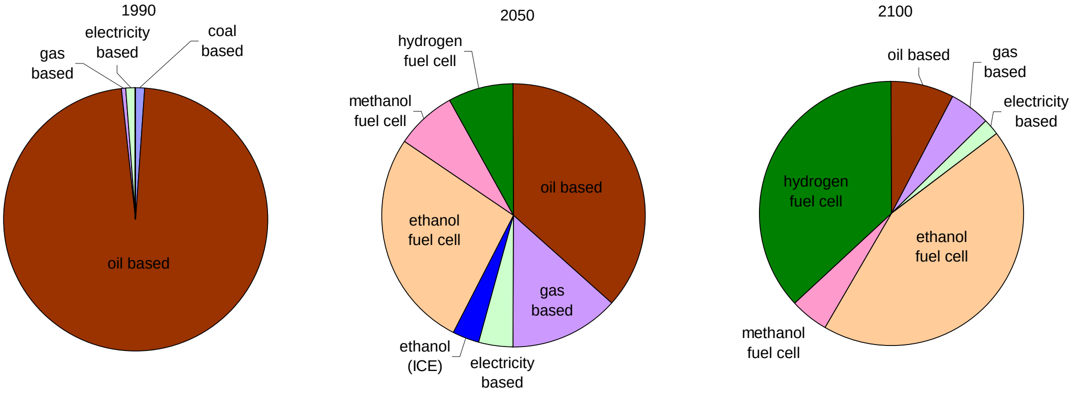

Figure 8: **Shares of transportation technologies in the PF scenario in 1990, 2050, and 2100, in EJ.**

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.