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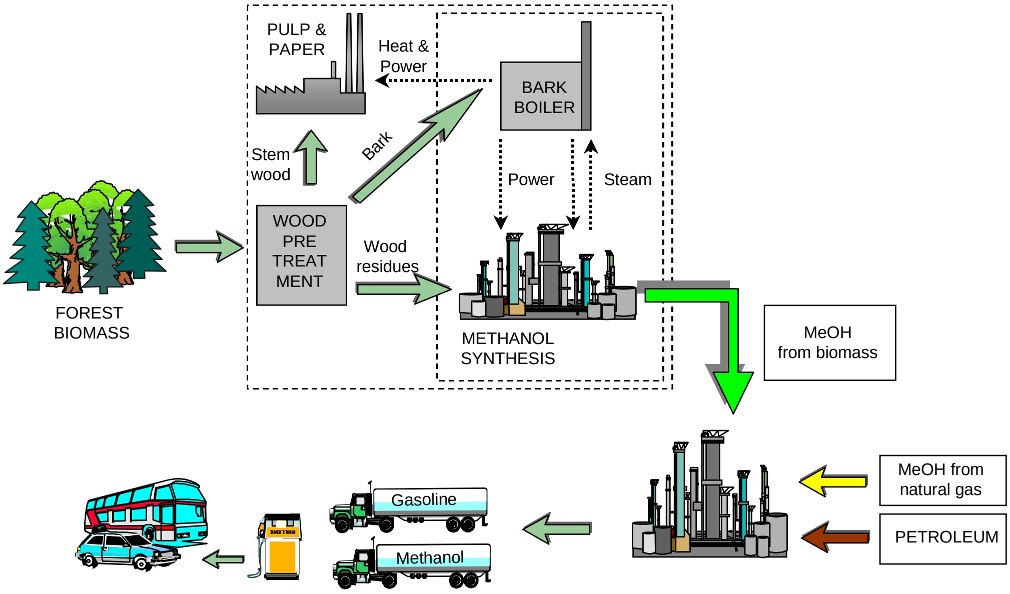
VTT TIEDOTTEITA

Mikael Ohlström, Tuula Mäkinen, Juhani Laurikko & Riitta Pipatti

New concepts for biofuels in transportation

Biomass-based methanol production and reduced emissions in advanced vehicles



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Abstract

In this study, new concepts for methanol and hydrogen production from wood-based biomass were evaluated and the climate benefits that could be achieved from the use of these fuels in advanced vehicles were estimated.

In the process concepts chosen for the techno-economic assessment, methanol or hydrogen production is integrated to CHP production of an existing pulp mill. The production of methanol from biomass requires a fairly advanced gasification and gas cleaning process in order to meet the requirements of the synthesis process. The hydrogen production process is somewhat simpler. However, the evaluation of the hydrogen production processes was, due to priorities set in the project, based on a more shallow evaluation.

Two methanol production concepts were selected for evaluation: methanol production integrated to an existing pulp mill in Finland and in the Far East. Performance and costs of corresponding hydrogen production were also estimated roughly for the Finnish case. The fast growth of wood would allow higher capacities for fuel production in the Far East than in Europe. The capacities were selected based on the availability of the raw material at a moderate price. In the Finnish case (fuel input 100 MW) the raw material was forest residues (pine) and in the Far East case (500 MW) short rotation coppices (eucalyptus). The methanol production would be 83 400 t/a in the Finnish case and 439 400 t/a in the Far East case. The production costs in the Finnish case were estimated at around 16 EUR/GJ methanol. In the Far East case the methanol production costs were lower, approximately 10 EUR/GJ methanol. Recently, the world market price of methanol has been about 4.7 EUR/GJ. The scale of the plant has a considerable effect on the fuel production costs. Currently, the largest natural gas based methanol plants have a capacity of > 800 000 t methanol/a.

By combining the fuel, power, and heat production a high total efficiency can be achieved. In this study, it was estimated that by integrating the methanol production to the power plant of the pulp mill, the total efficiency of the methanol plant could be increased to 67–69% (LHV). Reductions of about 20% were identified in the methanol

production costs by utilising the existing equipment of the pulp mill. Further improvements in the total efficiency and consequent production cost reductions could be achieved by process optimisation (optimised gasification temperature, minimised oxygen consumption, high carbon conversion in gasification, small hydrocarbon content in the gasification gas, optimised methanol synthesis). Possibilities of using low-grade waste heat in district heating would increase the total efficiency.

The greenhouse gas emissions from the use of the biomass-based methanol or hydrogen in specified vehicle types were estimated and compared to corresponding emissions from the use of gasoline, diesel, methanol made from natural gas, hydrogen derived from electrolysis of water and those of electric vehicles. The estimated greenhouse gas emissions included emissions from the production, distribution and use of the fuels in vehicles. All the energy demand of the biomethanol and biohydrogen production processes is met with energy produced by biomass. No CO_2 emissions are therefore allocated to the production processes as the biomass is assumed to be of sustainable origin.

The total greenhouse gas emissions from the fuel chain (emissions from fuel production and distribution + emissions from the use in the vehicles) are significantly lower (approximately 80–90%) for the biomass-based methanol and hydrogen fuels than for the other alternatives. Only battery electric vehicles using electricity produced from biomass have emissions that are as low. Extensive use of battery-electric vehicles using biomass electricity would, however, require even larger biomass resources, as the energy efficiency of electricity production is lower than that of methanol production.

The implementation of biomass-based methanol and hydrogen as transportation fuels involves barriers. The biomass resources are limited and the amount of biomass needed for the substitution of the conventional fuels with the biofuels would be large. Estimates on the availability of raw material (forest residues or eucalyptus) for the concepts studied showed that the entire fuel demand of light-duty vehicles would be difficult to meet by the concepts considered, even if the fuels were used in advanced vehicles.

The reduction in greenhouse gas emissions achievable by methanol or hydrogen produced from forest residues in Finland, considering the limited availability of the resources, was estimated for the years 2010–2020. The forest residue resources were estimated to suffice for methanol or hydrogen production that would give reductions of the order of 10–20% when used in LDVs of family car type compared to use of only gasoline. The use of the methanol in fuel cell or hybrid-ICE vehicles was estimated to give almost equal reductions (~15%), whereas the use in ICE-SI vehicles gave smaller reductions (~10%). The use of hydrogen in fuel cell vehicles gave a few percentage units higher emission reductions than methanol. In a vehicle fleet with a large share of urban commuter type cars using biomethanol or biohydrogen the total emissions would be much smaller.

Methanol from biomass could also be used for MTBE production. In Finland, the whole LDV vehicle fleet could be supplied with MTBE using methanol made from forest residues. The emission reduction achieved would, however, be much less, only one tenth of what could be achieved by using methanol in fuel cell or hybrid vehicles.

The cost of wood-based methanol and hydrogen production is, depending on the concept chosen (fuel input 100–500 MW_{th}), of the order of 2 to 4 times higher than that of gasoline or methanol made from crude oil and natural gas. Subsidies or tax incentives would be needed to introduce the wood-based fuels to the market.

Fuel cell vehicles will likely be introduced to the market within a few years. The market share of the vehicles will be minor for many years, partly because of the time lags in the renewal of the vehicle fleet. The availability of sustainable hydrogen and hydrogen carrier fuels is scarce, and could in the long run become the main obstacle for the success of the fuel cell vehicles. Sustainable hydrogen production technology based on chemical or biological processes or electrolysis utilising renewable energy, or production of hydrogen from fossil fuels combined with CO_2 recovery and disposal, are not expected to be commercial technology until the mid of the century, if even then. Biomass-based methanol, or hydrogen, could enhance the introduction of the fuel cell vehicles to the market before other sustainable concepts for, e.g., hydrogen production are developed. The foreseen growth in the transportation volume and decreasing oil resources could also increase the attractiveness of biomass-based methanol, or hydrogen, as transportation fuels in the future. Environmental benefits are seen especially in urban transportation, where the use of these fuels in fuel cell vehicles could also improve the local air quality substantially.

Preface

Transportation is a major and fast growing contributor to greenhouse gas emissions globally. There are many future technological options to reduce these emissions. In this project, “New concepts for biofuels in transportation: biomass-based methanol production and reduced emissions in advanced vehicles”, new technologies for biomass-based methanol production were identified and assessed, and the potential for reducing greenhouse gas emissions by using the methanol produced in transportation was evaluated. The production of hydrogen from biomass and its use in fuel cell vehicles was also studied, but more coarsely.

The work was carried out at VTT Energy and funded by the National Technology Agency of Finland (Tekes), the Finnish Ministry of Trade and Industry, Fortum Oil and Gas, Toyota Motor Europe and VTT Energy.

The work of the project was guided by a steering group, which comprised members from all funding organisations and companies. The chairman of the steering group was Mr Jukka-Pekka Nieminen of Fortum Power and Heat. The other members were Mrs Raija Pikku-Pyhältö (1998–1999) and Mrs Sirpa Salo-Asikainen (2000) of Tekes, Mrs Teija Lahti-Nuuttila (1998–1999) and Mr Erkki Eskola (1999–2000) of the Finnish Ministry of Trade and Industry, Mr Markku Laurila of Fortum Oil and Gas, Mr Arata Fukada (1998), Dr Muriel Desaeger, (1999–2000) and Dr Mikako Le Lay (1999–2000) of Toyota Motor Europe, and Prof. Kai Sipilä, Dr Riitta Pipatti and Ms Tuula Mäkinen of VTT Energy.

The report was written by Mikael Ohlström (fuel chain greenhouse gas emissions and scenarios for biomethanol and hydrogen use, Ch. 3 and Ch. 4)), Tuula Mäkinen (methanol/hydrogen production, Ch. 2), Dr Juhani Laurikko (vehicle emissions, Ch. 3.3) and Dr Riitta Pipatti (introduction, Ch. 1, global biomass potentials, Ch. 4.1.2, conclusions, Ch. 5) of VTT Energy. Dr Pekka Simell is acknowledged for his help in preparing the state-of-the-art review of biomass gasification and methanol synthesis. Ms Taru Palosuo is acknowledged for her help in the estimation on the global biomass potentials and emissions from eucalyptus plantations. Linde AG is acknowledged for valuable discussions and information about methanol production technology.

Espoo, October 2000

Authors

Contents

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List of symbols

CFC	chlorofluorocarbon
CHP	combined heat and power production
CH_4	methane (see also GHG)
Cl	chlorine
CO	carbon monoxide
CO_2	carbon dioxide (see also GHG)
CO_2(eq)	carbon dioxide equivalent, the sum of CO_2 + CH_4 + N_2O weighed by global warming potential factors over 100 years
CTI	Climate Technology Initiative
EU	European Union
EUR	Euro (currency) (1 EUR = 5.94573 FIM)
EV	electrical vehicle
Family car	reference car with 5 seats used in calculations (5 seats, 50 kW)
FC	fuel cell
FIM	Finnish mark (currency) (1 FIM = 0.16819 EUR)
GHG	greenhouse gases (here mainly CO_2 + CH_4 + N_2O)
GVW	gross vehicle weight
GWP	global warming potential
HCN	hydrogen cyanide
HDV	heavy-duty vehicle
HFC	hydrofluorocarbon
HFO	heavy fuel oil
HHV	higher heating value (calorific value)
H_2	hydrogen
H_2O	water
H_2S	hydrogen sulphide
ICE	internal combustion engine
ICE-CI	internal combustion engine with compression ignition
ICE-CI/H	hybrid vehicle, internal combustion engine with compression ignition combined to electrical batteries
ICE-HYBRID	hybrid vehicle, internal combustion engine combined to electrical batteries
ICE-SI	internal combustion engine with spark ignition
ICE-SI/H	hybrid vehicle, internal combustion engine with spark ignition combined to electrical batteries
LDV	light-duty vehicle
LHV	lower heating value (net calorific value)
LNG	liquefied natural gas
MeOH	methanol, CH_3OH

MEUR	million Euro (see EUR)
MTBE	methyl tertiary-butyl ether, an additive to gasoline
M85	methanol fuel with 15% gasoline blended in it (85% MeOH + 15% gasoline)
M100	neat methanol fuel (100% MeOH)
NG	natural gas
NH_3	ammonia
N_2O	nitrous oxide (see also GHG)
PFC	perfluorocarbon
POX	partial oxidation (fuel cell type)
PSA	pressure swing adsorption
R	stoichiometric value in methanol synthesis, $(H_2 - CO_2)/(CO + CO_2)$
RFD	reformulated diesel
RFG	reformulated gasoline (95E, 10% MTBE)
SF_6	sulphur hexafluoride
STM	steam reformer (fuel cell type)
ULEV	ultra-low emission vehicle
Urban bus	reference bus for 50 passengers used in calculations (50 passengers, 250 kW)
Urban commuter	reference city-car with 2 seats used in calculations (2 seats, 20 kW)
95E	unleaded gasoline, see RFG

1. Introduction

The atmospheric concentrations of the so-called greenhouse gases have increased significantly since the pre-industrial time. This increase is almost entirely caused by human activities. The increasing greenhouse gas concentrations in the atmosphere are changing the radiative energy balance of the Earth, tending to warm and produce other changes to the climate (IPCC 1996). The environmental impacts of the predicted global warming are associated with great uncertainties. Sea level rise, changes in precipitation, increasing climate variability and extreme weather events are predicted. The realisation of the predicted global warming could put the well being of both humans and the environment at risk.

Significant anthropogenic greenhouse gases are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) and some halogenated substances (e.g. chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs) and sulphur hexafluoride (SF_6)). The most important greenhouse gas is CO_2, which is released to the atmosphere mainly from fossil fuel combustion. In most industrialised countries, the CO_2 emissions cause 80–90% of the anthropogenic greenhouse gas emissions. Most of the anthropogenic CH_4 and N_2O emissions come from sources that are not related to energy production or use (animal husbandry, cultivation of agricultural soils, waste management, etc.). Small-scale combustion of biomass can emit significant amounts of CH_4 due to incomplete combustion. In larger combustion units these emissions are, however, small. The emissions of the halogenated greenhouse gases are related to industrial processes or use of various commodities of industrial origin (e.g., refrigeration, isolation materials).

Climate change is a global environmental threat that no country can control alone. The UN Framework Convention on Climate Change (FCCC) was signed by 165 countries in Rio in 1992. The ultimate objective of the convention is the stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner (UNFCCC 1992).

The concentration levels of the greenhouse gases that would lead to dangerous interference with the climate system are not defined in the convention. The first agreement on binding emission reduction commitments was signed in Kyoto in December 1997. The emission reductions will at first concern only the industrialised countries (so-called Annex I countries of the Convention) as the convention recognises the poor nations’ right to economic development.

According to the Kyoto protocol the Annex I countries are required to reduce their anthropogenic carbon dioxide equivalent emissions of CO_2, CH_4, N_2O, HFCs (hydrofluorocarbons), PFCs (perfluorocarbons) and SF_6 (sulphur hexafluoride) by more than 5 per cent below the 1990 levels in the commitment period 2008 to 2012. The individual Annex I countries are given specified emissions limitation or reduction commitments in the protocol. The emission reduction commitment for the European Union is 8%, for USA 7% and for Japan 6% of the base year (1990) emissions. Russia and Ukraine need to stabilise their emissions to the 1990 level and some countries (e.g., Norway, Australia and Iceland) are allowed to increase their emissions compared to the 1990 level (UNFCCC 1997).

Meeting the emission reduction targets of the Kyoto Protocol will only have a small effect on the increase of greenhouse gas concentrations in the atmosphere. The commitments of the Protocol are, however, demanding and put pressure on developing and improving energy and other systems, and even on the economies of countries. New tighter restraints on the emissions will also most likely be set after the commitment period of the Kyoto Protocol.

Transportation is a major contributor to greenhouse gas emissions globally. According to the national greenhouse gas inventories of the industrialised countries, transportation caused approximately 22% of their anthropogenic greenhouse gas emissions in 1996. Transportation was also the fastest growing source of greenhouse gas emissions and the second largest source of emissions after energy industries in these countries (UNFCCC 1999).

The options to reduce greenhouse gas emissions from transportation include alternative fuels, more efficient energy utilisation in vehicles, and improved traffic arrangements and logistics. There are many alternatives for future transportation fuels and vehicle technologies. Fuel cell vehicles, which can convert chemical energy into electricity without combustion technology, have a great long-term potential to reduce greenhouse gas and also other harmful emissions from transportation. The ultimate fuel for fuel cell vehicles is hydrogen. Hydrogen is a very light and flammable gas, and its large-scale distribution and storage pose still many difficulties. Therefore, liquid “hydrogen carriers”, like methanol or ethanol, are attractive, although seen by many as intermediate fuels for fuel cell vehicles.

In order to achieve significant reductions in the greenhouse gas emissions, hydrogen or the so-called “hydrogen carrier fuels” should be produced utilising renewable energy, or employing production combined with carbon dioxide recovery and storage. In this study methanol, and to some extent also hydrogen, production from wood-based raw material is studied. Methanol can be produced via synthesis gas production and thermal gasification of biomass. The technology is known from coal gasification, and some biomass gasifiers are in operation for fuel gas and power production. Ethanol can also be produced from biomass, and the processes are based on hydrolysis and fermentation of the raw material. The production of ethanol was, however, not studied in this project.

The main objective of the project was to identify and assess new technologies for biomass-based methanol production and to evaluate the environmental benefits of the use of the methanol produced in transportation. New economically viable project concepts for biomass-based methanol production by integrating synthesis gas production technology with combined heat and power production were sought for. The present profitable methanol production technology using mainly natural gas as feedstock requires a high production capacity. Currently, the methanol production capacities of the largest plants are more than 800 000 t/a. Capacities this high would mean long and logistically uneconomic transportation distances for most biomass harvesting chains. The aim was to identify and assess process concepts with decreased methanol production capacity below 100 000 t/a. The identified process alternatives were evaluated and compared by a techno-economic assessment.

Alternative uses of biomass-based methanol as a transportation fuel and associated greenhouse gas emissions were evaluated. The alternatives include the use of methanol as MTBE in fuel blends and as the main fuel for ULEV (Ultra Low Emission Vehicles) like fuel cell vehicles. The attainable reductions in greenhouse gas emissions, compared to conventional fuels and electric vehicle cycles, were estimated for the whole chain from biomass harvesting to methanol use in vehicles. A rough estimate on hydrogen production from biomass and its greenhouse impact was also made.

Simplified carbon cycles for biomass-based (biomethanol) and fossil (gasoline) transportation fuels are shown in Figure 1. As can be seen from the figure, the use of biomass-based fuels also causes CO_2 emissions, but these are taken up again by new growth in the forests, and hence the carbon cycle forms a closed loop with no net flux into the atmosphere. According to the international agreements the CO_2 emissions from biomass combustion are not included in the national total emissions, when the biomass originates from a sustainable source (carbon uptake is larger than the carbon released as CO_2). If the biomass use is not sustainable but causes a decline in the total carbon embodied in standing biomass (e.g. forests) this net release of carbon needs to be accounted for (IPCC 1996 Revised Guidelines 1997).

The biomass resources are used in many competing applications (pulp and paper production, wood products, heat and power production etc.) and the availability of the raw material may be limited for all uses. Some speculative scenarios for the studied biomass-based methanol and hydrogen production concepts and for the use of the fuels in fuel cell vehicles in light-duty vehicles in Finland and globally are presented.

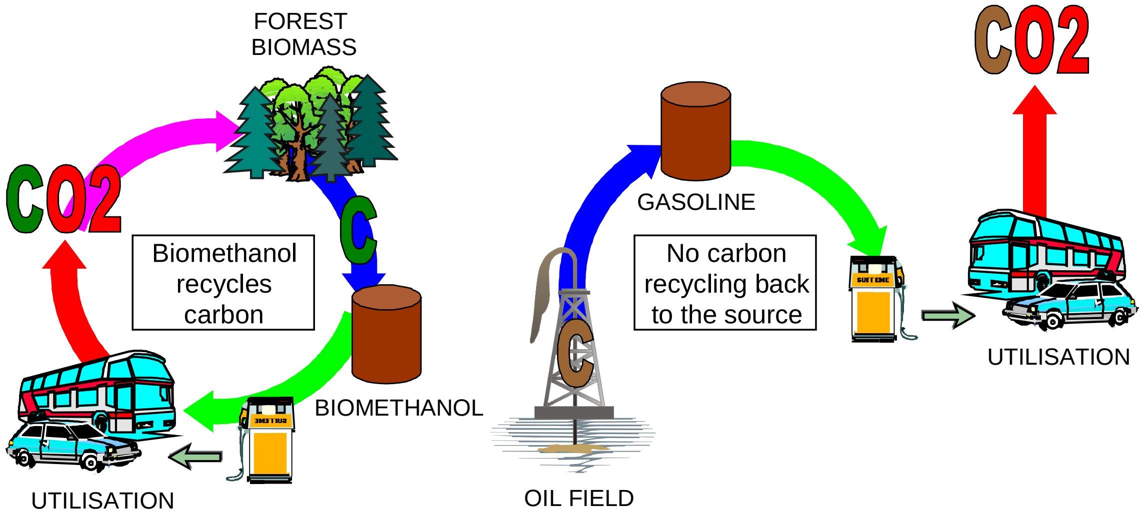


Figure 1. The carbon cycles for a biomass-based (biomethanol) and a fossil (gasoline) transportation fuel.

2. Methanol production from wood

2.1 Methanol production processes

The production of methanol from biomass, or other solid feedstocks like coal, or natural gas involves basically several similar process units. First, raw material containing carbon and hydrogen is converted into synthesis gas, which is a gas mixture containing CO and H_2, and then methanol is produced catalytically from the synthesis gas. The principal method for producing synthesis gas from natural gas is steam reforming, while synthesis gas production from biomass or coal is based on thermal gasification of solid feedstock.

The simplified flow sheets of natural gas-based and wood-based methanol production processes are shown in Figure 2. The wood-based methanol production process includes the following main steps: wood drying, gasification, gas cleaning and conditioning, gas compression, methanol synthesis and distillation. Gasification of biomass is described in more detail in Chapter 2.2 and methanol synthesis in Chapter 2.3. The state-of-the-art of the methanol synthesis processes was reviewed to identify the restrictions placed by methanol synthesis on biomass gasification, gas cleaning and conditioning. Integration of biomass gasification to methanol synthesis is discussed in Chapter 2.4.

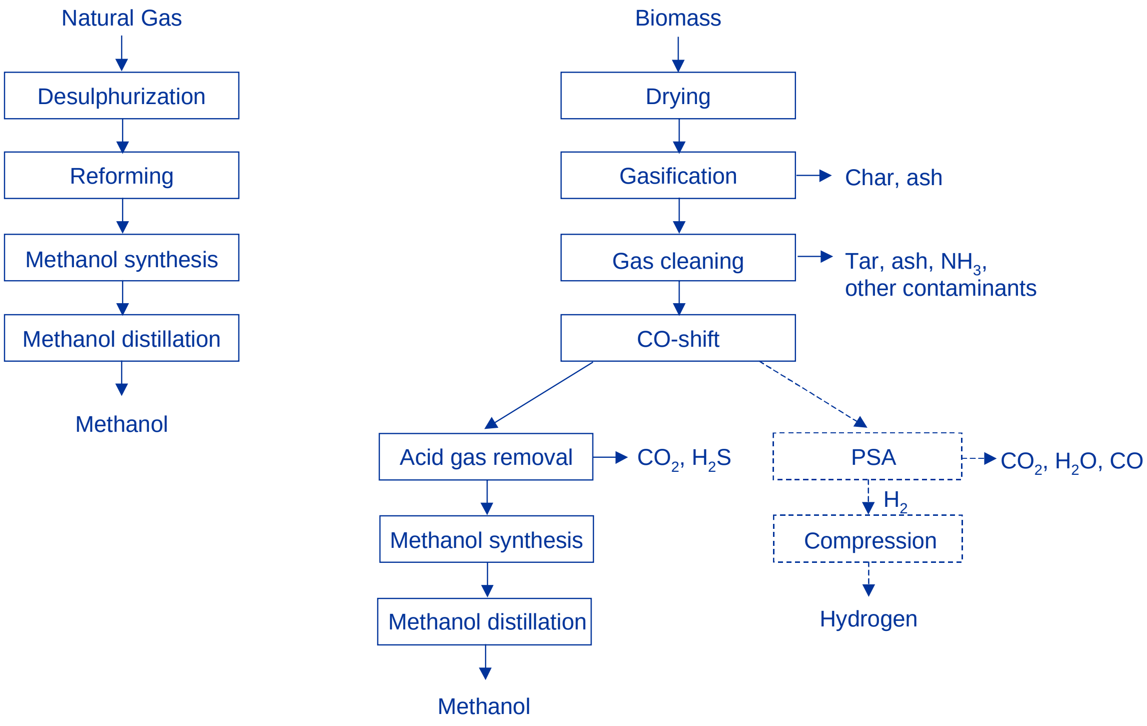


Figure 2. Simplified flow sheets of natural gas-based and wood-based methanol processes.

A simplified flow sheet of wood-based hydrogen production process is also shown in Figure 2. The production of wood-based hydrogen is based on a synthesis gas production chain similar to wood-based methanol production. In the CO shift units the conversion of CO into H_2 is maximised. In a modern hydrogen process hydrogen is separated from the converted gas by adsorption on molecular sieves in the PSA (pressure swing adsorption) units.

In 1997, about 86% of methanol was produced from natural gas. About 8.5% of the production was based on heavy oil fractions, 3% on coal, and 0.5% on naphtha. In 1997 the methanol production capacity was about 31 million tonnes/a, of which 86% was utilised. About 33% of the produced methanol was used in the gasoline and fuel sector, while the main share of the methanol was used in the chemical industry to produce other chemical products. (Appl 1997).

2.2 Gasification of biomass

2.2.1 Gasification reactors

In a gasifier, biomass is converted into gases (H_2, CO, CO_2, H_2O, CH_4, light hydrocarbons) and condensable tars at 800–1 200 °C. The gas also contains impurities originating from the fuel, like sulphur, nitrogen and chlorine compounds, and alkali metals. The final product distribution in a gasification gas largely depends on gas-feedstock contact type and process conditions.

Gasification is considered to comprise stages of drying and pyrolysis, as well as gasification and combustion reactions of residual char. The gasification reactions producing carbon monoxide and hydrogen are highly endothermic, and hence, the heat required by the process must be developed by partial combustion of residual char or by introducing heat to the process, employing external heating or a heat carrier. The most conventional method is partial combustion by using either air or oxygen. Gasification can be either an atmospheric or pressurised process.

The main gasifier types that can, in principle, be used in biomass gasification are shown in Figure 3. However, in practice the usability of these processes in synthesis gas applications is limited mainly to updraft and fluidised-bed gasifiers. Examples of gas compositions with different gasification processes are given in Table 1.

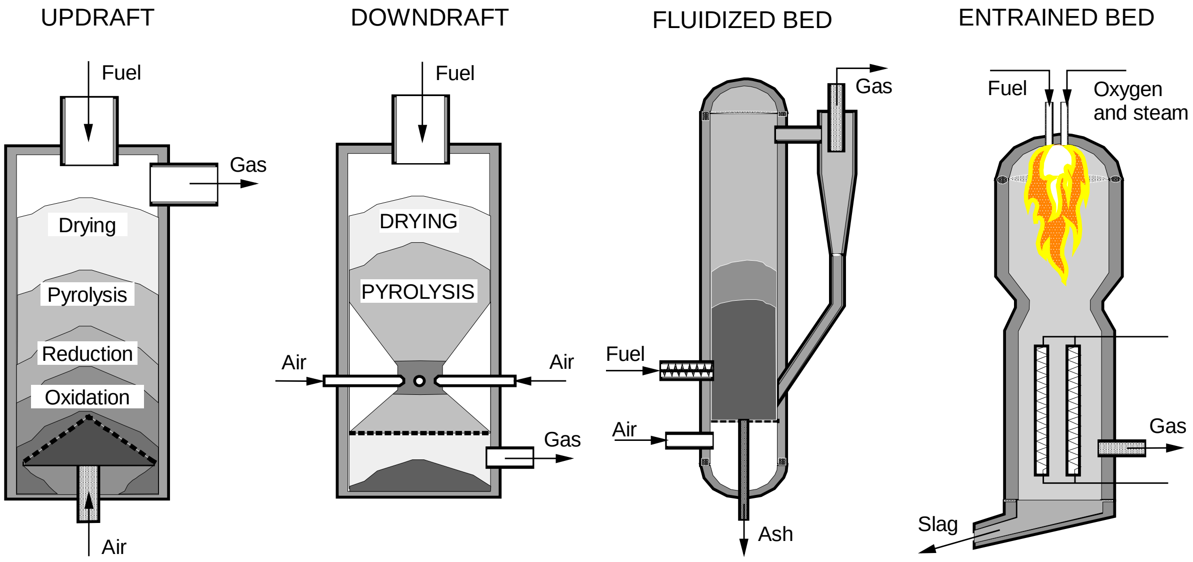


Figure 3. Main gasifier types (Energia... 1999).

Table 1. Composition of gasification gas produced employing various gasification processes and fuels (Reimert 1985, Simell et al. 1996). R is a stoichiometric value (see Chapter 2.3.1).

Process	Fluidised bed (U-GAS)	Fluidised bed (Lurgi CFB)	Fluidised bed (Battelle)	Fluidised bed (VTT PDU tests)	Reformed fluidised-bed gas (VTT PDU tests)
Method	Oxygen	Oxygen	Indirect	Air	Air
Fuel	Coal	Biomass	Biomass	Biomass	Biomass
CO	22.8	33.5	29	12.6	18.1
H_2	42.9	33.4	31.6	9	17.1
CO_2	29.8	26.6	23.1	10.8	7.9
H_2O	-	-	-	19.3	15.5
CH_4	3.7	4.9	13.6	3.4	0.2
Residue	0.8	1.7	2.7	44.7	41.3
R	0.25	0.11	0.16	<0	0.35

Two main types of fixed-bed gasifiers are updraft and downdraft gasifiers. In the updraft gasifier the fuel is fed into the top zone of the reactor, and gasifying air or oxygen into the lower zone. The fuel flows slowly through drying, pyrolysis, gasification and combustion zones in the reactor. Ash is removed from the bottom. As volatiles released in pyrolysis and drying phases are carried along with the exit gas, a high hydrocarbon and tar content and a low temperature of gas, 300–600 °C are characteristic of this gas. As the operation of the updraft gasifier is based on the flow of fuel downwards and on the flow of gases through the fuel layer, only relatively homogeneous fuel of fairly large particle size (some cm) is suitable as fuel.

In a downdraft gasifier the fuel and the gas flow in the same direction, whereat the hydrocarbons and tars released in pyrolysis are carried through the hot combustion and gasification zone and decompose to simpler compounds. For this reason, the tar content of gas from a well-operating downdraft gasifier is lower than that from an updraft gasifier.

Updraft gasification has been applied in several commercial applications. The most long-term experience has been obtained from a Lurgi gasifier developed in Germany. This gasifier has been used for producing synthetic liquid fuels from coal by gasification at the Sasol plants in South Africa. In the 1980s, a Bioneer process was developed in Finland for gasifying biomass and peat. There are commercial applications of atmospheric air gasification based on this process. The Bioneer gasifiers are used for generating combustion gas from peat and biofuels.

Fluidised-bed gasifiers can be divided into bubbling fluidised-bed (BFB) and circulating fluidised-bed (CFB) gasifiers. In the bubbling fluidised-bed gasifier, the particle size of fuel is usually less than 10 mm. The bed formed by fuel particles is fluidised with gas flowing from below, while the product gas exits from the top zone of the reactor. Due to good mixing, good heat and material transfer between gases and fuel particles is characteristic of this method. The temperature distribution of the reactor is fairly stable and the temperature of the exit gas is higher than, e.g., that of the product gas from an updraft gasifier. This enables thermal cracking of tars in the reactor, and as a consequence the tar content of gas is lower than, e.g., in updraft gasification. An abundance of partly reacted solids exits the reactor with the gas. Part of solids are separated and recycled into the gasifier.

In the circulating fluidised-bed gasifier, a higher velocity of fluidising gas is employed than in the bubbling fluidised-bed gasifier. The aim is to increase the output in relation to the cross surface, considerably higher than in the bubbling bed. Consequently, the amount of substances exiting with gases and recycled by the circulating cyclone increases. The flow rate of gases being high, the residence time of gases in the reactor is short. For this reason, circulating bed gasification is suitable for readily gasifying biofuels and, on the other hand, for partial gasification of coal.

Although there is an abundance of commercial experience from fluidised-bed gasification, this gasification process is still a subject of intensive development. Development is being done, i.a., by Institute of Gas Technology (U-Gas), Kellog/Rost/Westinghouse (KRW), Rheinische Braunkohlenwerke (HTW) and Foster Wheeler. A pilot pressurised circulating fluidised-bed gasification plant (18 MW_{th}) has been in operation in Värnamo, Sweden, since 1991. The plant, fuelled with wood chips and wood waste, is a joint R&D project by Sydkraft and Foster Wheeler Energia Oy (former A. Ahlström Oy). An atmospheric CFB gasifier (40–70 MW_{th}) supplied by Foster Wheeler Energia Oy is in operation in Lahden Lämpövoima Oy Kymijärvi Power Plant in Lahti, Finland. The gasifier is fuelled with wood waste, wood chips, and waste-originated fuels. The gasifier is connected to a coal boiler and the gasifier product gas is burned in the coal boiler to substitute fossil coal by renewable fuels. The gasifier has been in operation since 1998. Prior to the Lahti plant, Foster Wheeler Energia Oy has supplied four commercial-scale atmospheric CFB gasifiers to the pulp and paper industry in Finland, Sweden and Portugal with capacities from 17 to 35 MW_{th} in the mid 1980s. These plants utilise bark and waste wood as feedstock (Palonen 1998).

Processes based on indirect gasification are of interest with regard to methanol synthesis, as they offer a possibility to produce non-nitrogenous synthesis gas without any investment in a relatively expensive oxygen plant. In the indirect process, the gasification reactor is heated by hot bed material. The bed material is heated in a separate combustion unit operated in fluidised-bed principle by burning the mixture of residual char and bed material separated from the product gas. An example of this gasifier type is a Battelle gasifier, which has now reached the demonstration stage (42 MW_{th}) in Vermont, the USA (Farris *et al*. 1999).

The entrained flow gasifier has been developed mainly for coal as a feedstock. The entrained flow gasifier operates at high temperature (1 300 °C), which is not necessary for biomass with high reactivity. The feedstock must also be crushed to fine-sized particles, which is energy and cost intensive with biomass.

2.2.2 Gas cleaning

The gasification gas contains impurities, like particulates, tar, and alkali metals, as well as nitrogen and sulphur compounds that can be harmful in end-use applications of the gasification gas or hamper the gas processing for the end-use. The gas cleaning requirements are process-specific. Concentration ranges of the impurities in the gasification gas produced by air-driven fluidised-bed gasification of biomass are shown in Table 2. The concentration ranges are based on VTT's experience on biomass gasification.

Table 2. Concentration ranges of the impurities in the gasification gas produced by air-driven fluidised bed gasification of biomass. The data is based on VTT's experience.

Component	Concentration range
Tars (benzene, naphthalene, PAH)	500–5 000 ppmv
Nitrogen compounds (NH_3, HCN)	300 – 10 000 ppmv
Sulphur compounds (H_2S, COS)	50–500 ppmv
Chlorine compounds (HCl)	1–200 ppmv
Alkali metals (Na, K)	0.1–10 ppmv
Heavy metals (Cd, Zn, Pb, Cu, Co, V)	0.1–3 ppmv
Particulates, dust (C, Si, Fe, Na, K, Ca, Mg, Al)	1–10 g/m^3(n)

The gas clean-up requirements can be achieved by various methods. The gas cleaning methods can be divided roughly into two methods: cold and hot gas cleaning methods.

Cold cleaning usually involves cooling and wet scrubbing of gas, e.g., with water, solvents or adsorption solutions. Solids, condensing tars and compounds soluble in the scrubbing solution are removed from the gas. Sulphur compounds are usually removed with the aid of special scrubbing processes. The scrubbing methods are of commercial technology applied in the chemical industry, e.g. Selexol and Rectisol processes, and enable the production of gas that meets very stringent purity requirements.

Hot gas cleaning usually means the filtration of gas at 300–600 °C to remove solids and alkali metals. Other hot cleaning processes are desulphurisation with sorbents and decomposition of tars and ammonia thermally or with a catalytic process. These methods are either commercial (hot filtration) or under development (catalytic methods).

Reforming of gas with a nickel cell catalyst at about 900 °C is one of the most developed catalytic methods today. With this method (Simell *et al.* 1996), developed in collaboration by VTT and BASF AG, a nearly complete conversion of hydrocarbons into gases (CO, H_2) and about 80% ammonia conversion have been achieved in pilot-scale test equipment. The main components of gasification gas also react under the conditions applied and their contents at the outlet of the reactor have been close to the thermodynamic equilibrium contents of gas. The nickel cell also seems to endure the hydrogen sulphide content of gas (50–100 ppm) without deactivation under the conditions applied, and the cell has been found to endure real gasification conditions in an experiment of 500 operation hours. However, considerable longer-term testing (thousands of hours) is required to verify the usability of the technology.

2.3 Methanol synthesis

2.3.1 Reactions

Methanol formation in the synthesis gas can be formulated as the following reactions of hydrogen with carbon oxides (Appl 1997):

$$CO + 2H_2 \leftrightarrow CH_3OH \qquad \Delta H^0_{298} = -90.8 \text{ kJ/mol} \qquad (1)$$

$$CO_2 + 3H_2 \leftrightarrow CH_3OH \qquad \Delta H^0_{298} = -49.6 \text{ kJ/mol} \qquad (2)$$

These two reactions are linked by the reverse shift conversion reaction:

$$CO_2 + H_2 \leftrightarrow CO + H_2O \qquad \Delta H^0_{298} = 41.2 \text{ kJ/mol} \qquad (3)$$

Both reactions 1 and 2 are exothermic and result in a decrease in volume. Methanol formation is thus favoured by increasing pressure and decreasing temperature, the maximum achievable conversion being limited by the chemical equilibrium.

According to the stoichiometry as given in equations 1–3, the ideal ratio for the synthesis gas should be (Appl 1997):

$$R = (H_2 - CO_2) / (CO + CO_2) = 2 \tag{4}$$

where H_2, CO and CO_2 represent the respective concentrations in the synthesis gas.

2.3.2 Reactors

A specific feature of methanol synthesis is that only a small proportion of synthesis gas is converted into methanol per pass in the reactor. To achieve as high a total conversion of basic materials as possible, synthesis gas is recycled into the reactor. The reaction products, methanol and water, are separated from the outlet gas of the reactor, and fresh gas is then added to it. The gas is then recompressed to the synthesis pressure and led into the reactor. The temperature of the reactor is carefully controlled to maintain the best conditions for the chemical equilibrium. In current processes (low-pressure methanol synthesis) the operating temperature is typically 200–300 °C and the pressure 45–100 bar depending on the catalyst. The principle of the basic methanol synthesis process is shown in Figure 4.

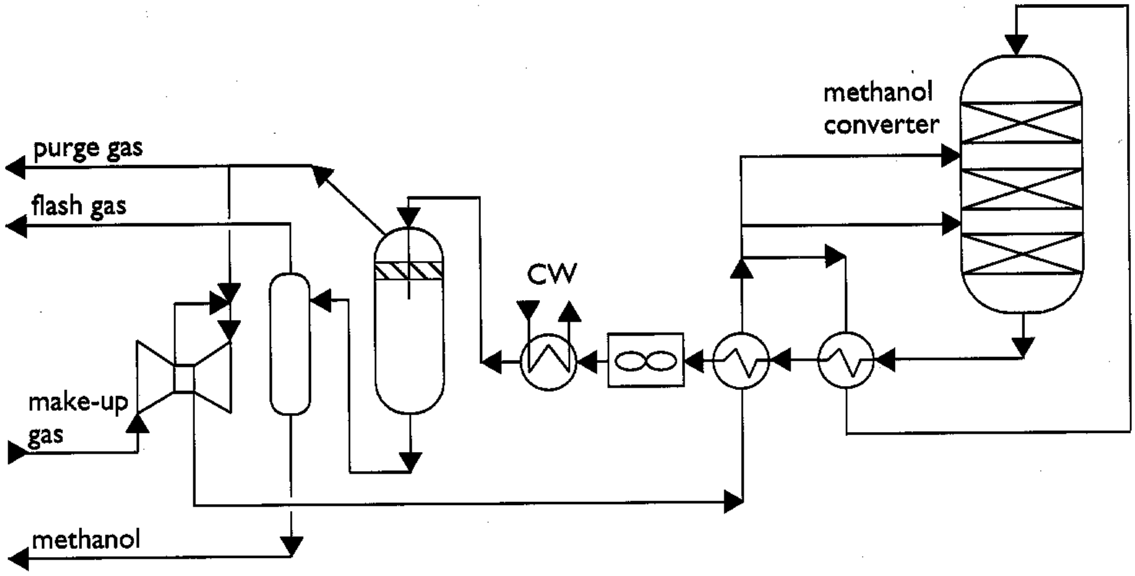


Figure 4. Methanol synthesis, principle of the basic process (Appl 1997).

There are several suppliers of the methanol synthesis reactors, for example, ICI, Lurgi, Linde, and Mitsubishi Gas Chemical. Different methanol processes deviate from each other primarily in the construction of the reactor. There are differences in the management of the removal of heat formed in exothermic reactions in the reactors. On this basis, the reactors can be divided into two main types: quench-cooled and indirectly cooled reactors. In a quench-cooled reactor, the reactor is prevented from overheating by leading cooled gas into the catalyst bed. The structure of indirect reactors is similar to that of a tube heat exchanger, in which the catalyst can be placed either on the side of the tube or the mantle. The reaction heat is recovered in the cooling water flowing either on the side of the mantle or the tube. Examples of the both reactor types are shown in Figures 5 and 6. (Appl 1997).

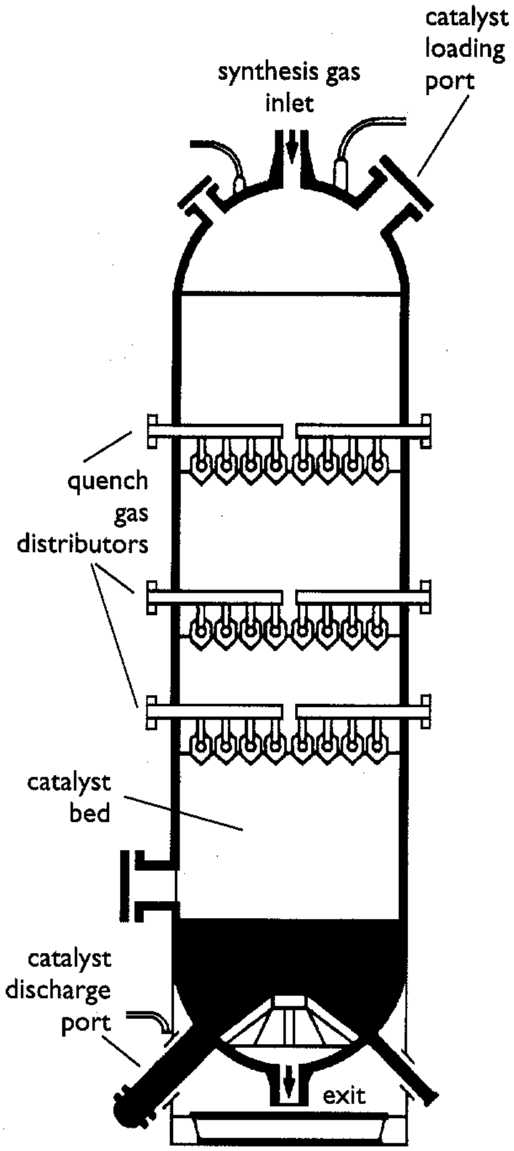
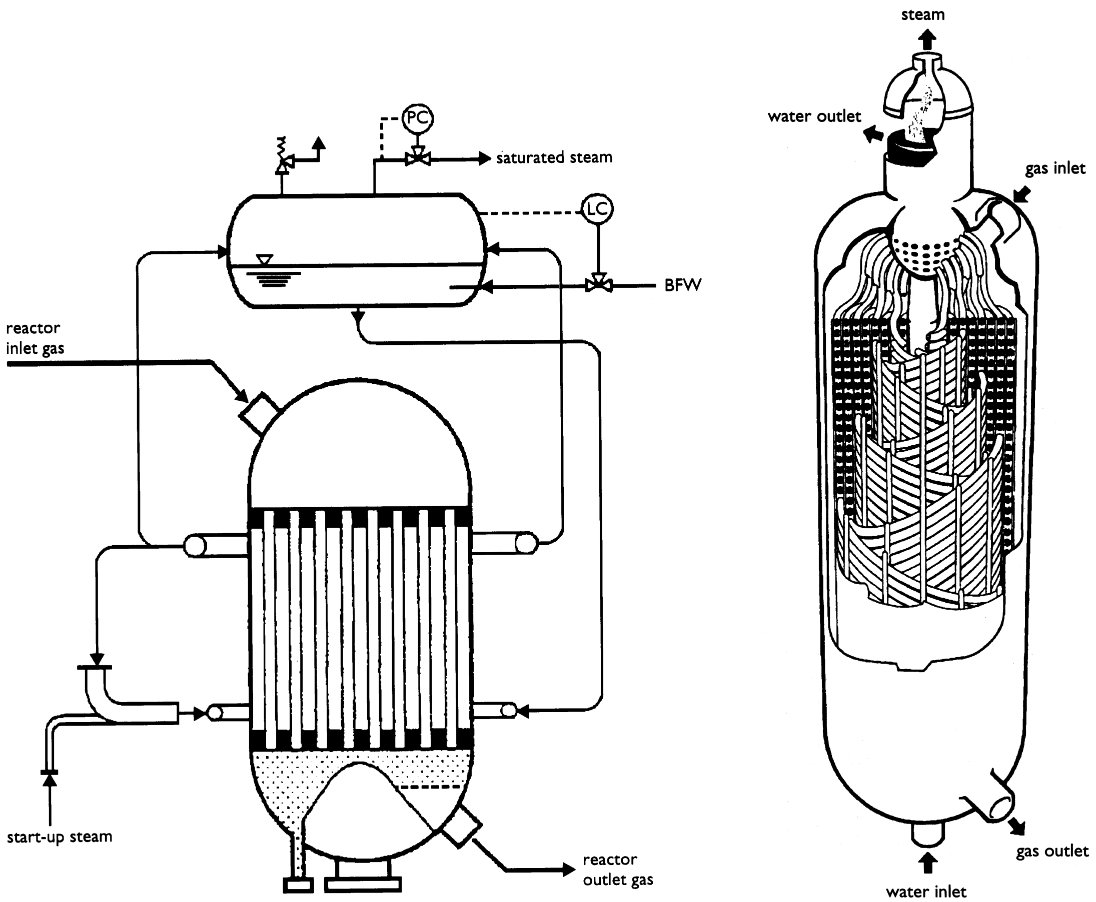


Figure 5. ICI's quench-cooled methanol synthesis converter (Appl 1997).



Lurgi's tubular reactor

Linde isothermal reactor

Figure 6. Indirectly cooled reactors (Appl 1997).

Several research groups have investigated concepts, in which methanol is continuously removed from the reaction zone by a solid or liquid absorption medium (Appl 1997). The aim with these concepts is to avoid the typical disadvantages of the current methanol processes, e.g., the low conversion per pass and the consequent need for high recycle ratios. Among these approaches, the liquid-phase process developed by Air Products and Chemicals seems to be the most promising one. Currently the process is at a demonstration stage (Heydron *et al.* 1998).

In the Air Products process (Appl 1997), fine particles of catalyst are suspended in an inert mineral oil and the synthesis gas passes through the catalyst-oil slurry in fine bubbles. A simplified flow diagram of the process is shown in Figure 7. The process has been reported to have a higher methanol conversion per pass than the current conventional methanol processes, although the actual conversions have not been published. The process is also said to be particularly well suited to substoichiometric synthesis gases, like the synthesis gases produced by gasification. In combination with some gasification processes, it might even be possible to run the process as a once-through process. In these process concepts, the purge gas of the methanol synthesis would be used for energy production, e.g. in a combined cycle.

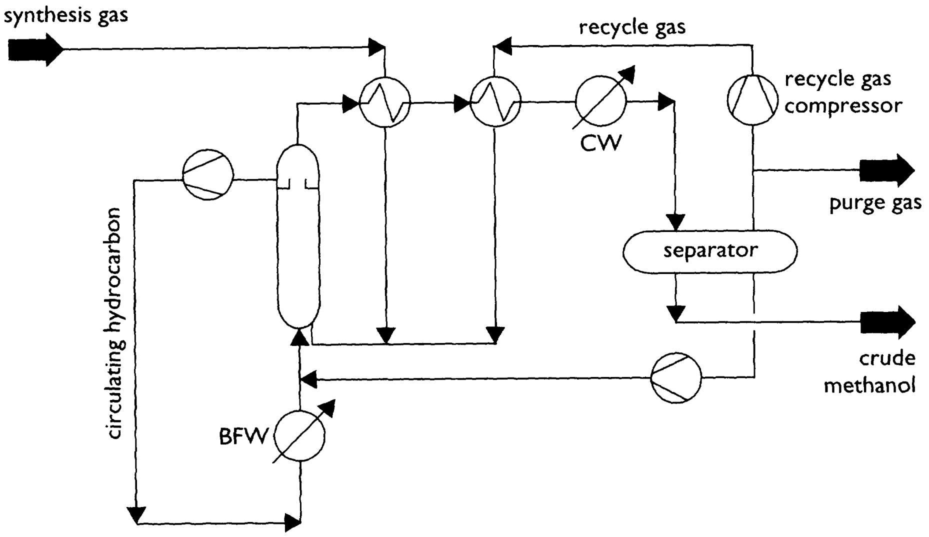


Figure 7. Methanol process of Air Products and Chemicals Inc. (Appl 1997).

The commercial catalysts for methanol synthesis are manufactured, e.g., by ICI Katalco, Süd-Chemie / United Catalysts, Topsøe, BASF, and Mitsubishi Gas Chemical. The catalysts currently used in methanol synthesis reactors are composed of copper oxide and zinc oxide stabilised with alumina, and only proportions of these components vary by the manufacturer (Appl 1997). These copper-based catalysts are particularly sensitive to sulphur and chlorine impurities.

2.4 Integration of gasification to methanol synthesis

The gasification product gas cannot be used as such in methanol synthesis. The gasification gas always contains impurities, like dust, tar, as well as nitrogen and sulphur compounds that must be removed from the gas prior to further treatment. The gas composition must be adjusted to meet the requirements of methanol synthesis chemistry. Requirements concerning the purity and composition of gas are the same for all present methanol processes employing copper-based catalysts. In general, the synthesis gas should meet the requirements listed below (Supp 1990). In addition, the gas should contain neither water nor residues of solvents possibly used for gas scrubbing.

- The stoichiometric ratio R should be 2–2.1.
- At the above stoichiometric rate, the CO content of gas should be as high as possible and the CO_2 content as small as possible, but not less than 2.5 wt%.
- The content of inert gases should be as small as possible (to reduce production costs, the inert gases do not hamper the process).

- The content of sulphur compounds should be less than 0.1 ppm.
- The content of other compounds, Cl, HCN, NH_3 and unsaturated hydrocarbons should not exceed 0.1–3 ppm.

Efficient gas cleaning and conditioning is needed to meet these requirements. Gasification should be either oxygen-driven or indirectly heated in order to avoid the costly ballast of inert gases (nitrogen from air). After gasification, the gas can be reformed with a catalyst to achieve the maximum conversion of hydrocarbons into gases (CO, H_2). After the reformation unit, water scrubbing is needed for removing the remaining condensable tars, solids, and ammonia from the gas. In addition, the composition of gas must be converted by CO conversion (shift) units to adjust the stoichiometric ratio of gas in the range required by methanol synthesis. Sulphur compounds and carbon dioxide must be removed with the aid of special scrubbing processes. An example of a possible process concept for wood-based methanol production is shown in Figure 8.

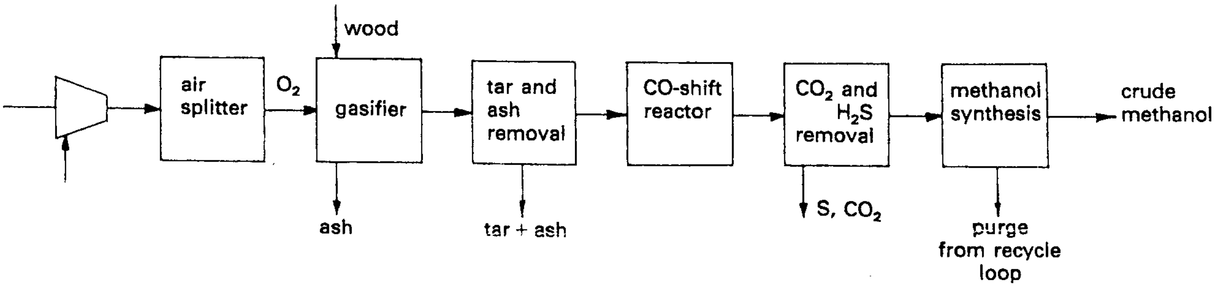


Figure 8. Simplified scheme of a possible process concept for wood-based methanol production (Beenackers & van Swaaij 1984).

2.5 Performance and costs of wood-based methanol processes

Many techno-economic assessments have been carried out and published on methanol production concepts based on biomass gasification. Several development projects have also been carried out in the field, but none of the projects have led up to a commercial-scale production. In principle, all the process units of the wood-based methanol process can be found based on commercial technology. A comparable process was demonstrated in the 1980s in Oulu, Finland, when 80 000 tons/a of ammonia was produced based on pressurised gasification of peat in the Kemira Oyj plants. Sawdust was also used in test runs. The plant was shut down at the beginning of the 1990s due to the declined world market price of ammonia.

The presented mass yields of methanol from wood usually range from about 45 to 55 wt% of dry wood. In a study funded by DOE (1990), the methanol yield of 43.5 wt%

based on dry wood was presented for the conventional process and 50.8 wt% for the future process (employing the pressurised gasification, tar reformer and liquid-phase methanol synthesis). Elam *et al.* (1994) have estimated that employing the best possible technology in the wood-based methanol process the maximum methanol yield would be 55 wt% of dry wood and that the current processes would allow methanol yields around 45 wt% of dry wood. Williams *et al.* (1995) have presented methanol yields of 48–58 wt% of dry wood depending on the gasification technology applied.

Elam *et al.* (1994) have compared the investment and production costs of wood-based methanol and ethanol. In the methanol process concept studied the excess heat of the methanol production was used for district heat production in order to improve the overall efficiency of the wood-based methanol production process. The production of synthesis gas was based on pressurised oxygen-driven gasification. The total efficiency of the methanol process was 82% (LHV basis), and the methanol production efficiency was 55% (LHV basis). The production costs of 14 EUR/GJ were presented for the plant capacity of 250 000 tons dry wood/year (141 MW_{th}, moist wood, LHV basis).

Williams *et al.* (1995) have compared the production costs of wood-based methanol and hydrogen with the production costs of natural gas and coal based methanol and hydrogen. The production costs of 11.2–14.1 USD/GJ and 8.7–11.2 USD/GJ were presented for wood-based methanol and hydrogen production, respectively, depending on the gasification technology applied. The plant capacity was 1 650 tons dry wood/day. The thermal efficiency of processes was 53.9–61.0% for wood-based methanol production and 56.4–64.5% for hydrogen production. Purge gases were assumed to be used for electricity production with efficiencies achievable in a gas turbine/steam turbine combined cycle.

In the study funded by DOE (DOE 1990), the methanol production costs of the conventional technology were compared with the costs of the future technology. The conventional process was based on the atmospheric gasification of the wood and the conventional methanol synthesis, and the future process on the pressurised gasifier followed by the methane reformer and the liquid-phase methanol synthesis. The production costs presented were 18.8 EUR/GJ for the conventional process and 13.5 EUR/GJ for the future one. The capacity of the plant was 603 000 tons dry wood/year.

Faaij *et al.* (2000) have presented preliminary results of their study on the production of methanol and hydrogen from biomass via advanced conversion concepts. The work focuses on identifying conversion concepts that may lead to higher overall efficiencies and lower costs. Improved performance is sought by applying technologies under development, a combined fuel and power production and the economics of the scale. Preliminary results indicate that overall energy efficiencies remain in 50–60% (based on fuel input, HHV basis). The preliminary production costs of 8.5–12 USD/GJ for methanol and 7.5–9 USD/GJ for hydrogen were presented for the plant with the feed capacity of 400 MW_{th} (LHV basis).

2.6 Performance of wood-based methanol process integrated to CHP production

Based on the state-of-the-art review of methanol synthesis and VTT's experience on biomass gasification, the process concept shown in Figure 9 was built for the study. Cost reductions were sought by integrating the methanol production to an existing combined heat and power (CHP) production plant in the forest industry. A similar type of a process concept has been suggested for wood-based ethanol production in Sweden (NUTEK 1995). In the Swedish study the possibilities to decrease the production costs of wood-based ethanol by integrating the ethanol production with other existing industrial plants (a pulp mill, a combined heat and power plant, and a combinate of peat drying and a saw mill) were identified.

The selected methanol process is based on pressurised oxygen-driven gasification followed by the tar reformer and the conventional methanol synthesis. The options of the gasification technology were the oxygen-driven and the indirectly heated gasifier. The oxygen-driven gasification was selected based on the following arguments, similar

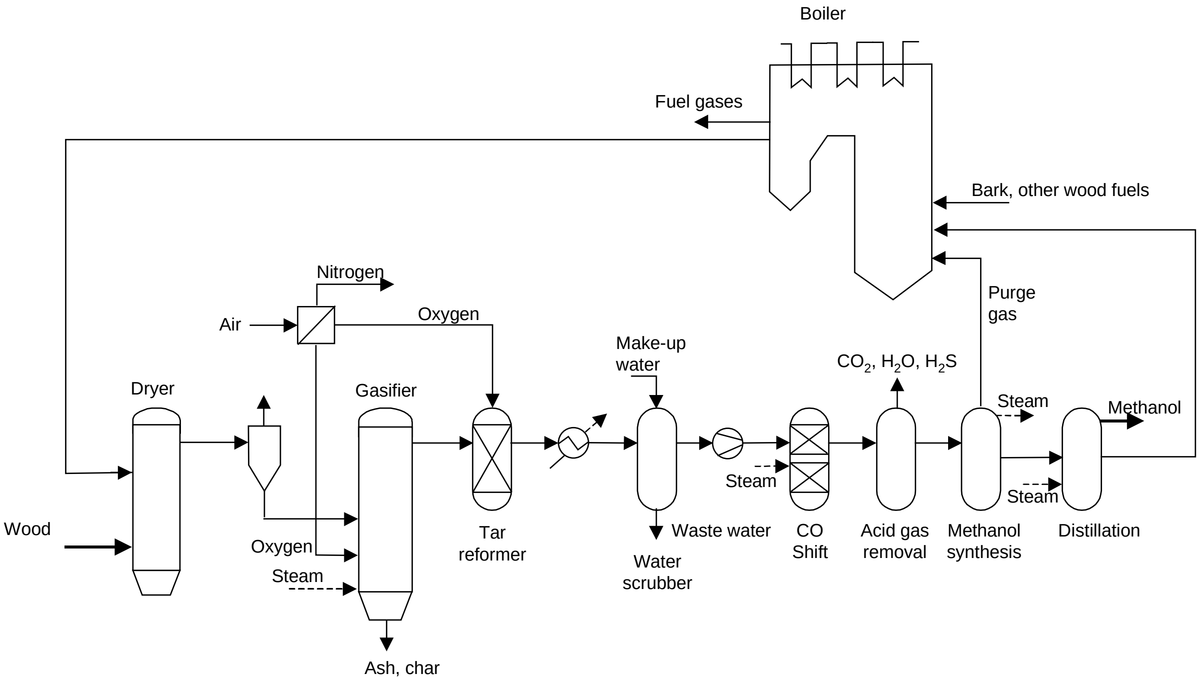


Figure 9. Methanol production combined to CHP production at a pulp and paper mill. Steam production and utilisation is combined to a steam cycle of the pulp mill.

arguments having also been presented by Elam *et al.* (1994). When applying the oxygen-driven gasification the costly investment for the oxygen-production is needed, but on the other hand, with the indirectly-heated gasification higher investment costs are needed for the gasification section, since it is formed of two reactors, namely the gasifier reactor and the combustor. The oxygen-driven gasification is easier to pressurise than the indirectly heated one. The product gas of indirect-heated gasification contains more light hydrocarbons and tar than the product gas of oxygen-driven gasification due to a larger consumption of steam as gasification medium and a lower gasification temperature. The larger amount of tars in the product gas increases the gas cleaning costs. It was also considered that the gas composition more suitable for the methanol synthesis produced by indirectly heated gasification is compensated by the higher total efficiency of the gasification and gas cleaning section typical of oxygen-driven gasification.

The gasification product gas is led to a reformer utilising the nickel cell catalyst to reform the light hydrocarbons and tar to CO and H_2. The reformer is directly heated by oxygen. After the reformation unit the remaining condensable tars, solids, and ammonia are removed from the gas by water scrubbing. Before the water scrubber the gas is cooled down. After water scrubbing the gas is converted in the CO shift units, and acid gases are removed from the gas by a commercial scrubbing process.

In the studied process the methanol production is maximised. The conventional methanol synthesis technology was selected for the process, since the liquid-phase methanol synthesis technology under development was considered to be more suitable for the process concepts based on the once-through methanol synthesis.

The steam cycle of the methanol plant is connected to the steam cycle of the CHP plant of the pulp mill. In the methanol plant, steam is used in the gasification, CO shift conversion, and distillation. Steam is raised in the cooling of gasification gas before the water scrubber and in the waste heat removal of methanol synthesis.

Two methanol production concepts were selected for evaluation: methanol production integrated to an existing pulp mill in Finland and in the Far East. In the Far East case the cost reductions were sought by the economics of the scale and lower price of the raw material. The fast growth of wood would allow higher capacities for methanol production in the Far East than in Europe. No specific country for the Far East case was defined, but Indonesia is a typical example. The plant capacities were set at 100 MW_{th} (moist wood, LHV) as a fuel input to the gasifier in the Finnish case and 500 MW_{th} in the Far East case. The capacities were selected based on the availability of the raw material at a moderate price (2.1 EUR/GJ in Finland and 1.6 EUR/GJ in Far East). In the Finnish case the raw material was forest residues (pine) and in the Far East case short rotation coppices (eucalyptus).

The model of the methanol process was built for mass and energy balance calculations employing Aspen Plus™ programme as a tool. The mass and energy balances of the methanol processes are based on the experience of VTT Energy, the public literature (especially DOE 1990, Katofsky 1993, Elam *et al*. 1994, Williams *et al*. 1995) and on the discussions with equipment suppliers, especially Linde AG.

The estimated performances of the methanol plants are presented in Table 3. The methanol production would be 83 400 t/a in the Finnish case and 439 400 t/a in the Far East case. The mass yield of methanol was estimated at 50% of dry wood and the energy yield at 57.7% of the raw material (lower heating values) for forest residues (pine) as the feedstock and 49% and 60.8%, respectively, for eucalyptus. The total efficiency of the methanol production process was estimated at 66.7% (LHV) for forest residues and 68.7% for eucalyptus, taking into account all the energy needed and all the products (methanol, steam, combustible side-products).

Table 3. Performances of the methanol plants.

Case	Finland	Far East
Wood consumption		
t/a (moisture 50%)	333 800	1 794 000
MW (LHV)	100.0	500.0
Steam consumption, MW	25.5	135.5
Power consumption, MW	11.0	60.0
Methanol production		
t/a	83 440	439 400
MW	57.7	303.9
Steam generation, MW	33.3	177.7
Other side-products, MW	9.9	51.5
Methanol yield, wt-% of dry wood	50.0	49.0
Methanol yield, % (LHV/LHV feedstock)	57.7	60.8
Total efficiency (LHV), %	66.7	68.7

Further improvements in the total efficiency could be achieved by process optimisation (optimised gasification temperature, minimised oxygen consumption, high carbon conversion in gasification, small hydrocarbon content in the gasification gas, optimised methanol synthesis).

Utilising lower-grade waste heat for the production of district heat in the Finnish case or hot water for the forest industry process would increase the overall efficiency of the methanol plant, e.g. Elam *et al*. (1994) presented the total efficiency of 82% for the methanol plant integrated to district heat production. As in Finland the district heat load close to the forest industry is often already covered, the possibility for district heat production was not considered. No detailed integration of methanol production to the water system of the pulp mill was carried out. Typically, the pulp and paper industry has overproduction of lower grade heat.

Both in the Finnish case and in the Far East case the methanol process was combined to a non-integrated kraft pulp mill. The plants have a conventional recovery boiler and a bark/wood boiler for the energy production. The simplified flowsheet of the power plant at a pulp mill is shown in Figure 10. The feedstocks of the pulp production are pine in the Finnish case and eucalyptus in the Far East case. The annual production of chemical pulp is 600 000 adt/a (air-dry tons/year). Currently the largest capacity among the Finnish pulp mills is 620 000 adt/a (Stora-Enso, the Enocell mill).

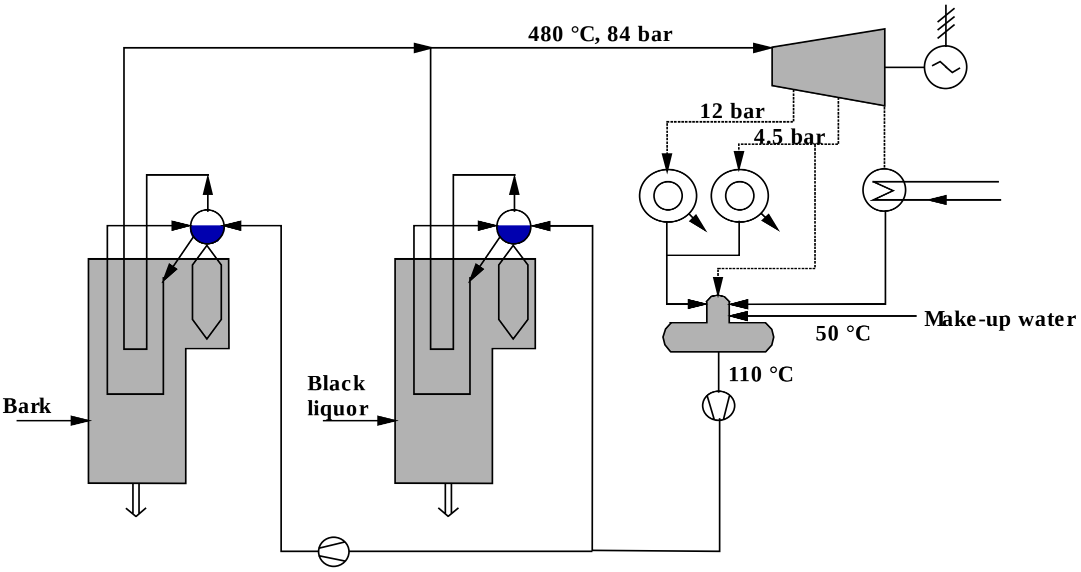


Figure 10. Simplified flowsheet of the power plant at a pulp mill.

The performances of the energy production in the pulp mills were determined using an Aspen Plus^{TM} model based on data provided by Jaakko Pöyry Consulting Oy (Jaakko... 1993) and on the publication by Komulainen *et al.* (1994). The pulp production from eucalyptus is also based on the publication by Gullichsen (1968). The main operating data for the energy production of the pulp mills are presented in Table 4. The main operating data of the integrated methanol and pulp plants are presented in Table 5.

The performance of a comparable hydrogen plant was roughly estimated for the Finnish case. The estimation is based mainly on the publication by Williams *et al.* (1995). The estimated performance of the hydrogen plant and the integrated hydrogen plant and the pulp mill are presented in Tables 6 and 7. The results should be considered as indicative. The hydrogen production was estimated to have a higher fuel yield than the methanol production, 70% and 58% (LHV basis), respectively. Due to the higher power consumption in the hydrogen production, the difference in the total efficiency was smaller, 70% and 67% (LHV basis), respectively.

Table 4. The main operating data of the kraft pulp mills. The production of chemical pulp is 600 000 adt/a in both cases.

Case	Finland	Far East
Raw material	Pine	Eucalyptus
Wood consumption, t ds/a	851 000	769 000
Steam generation, MW	431.7	399.2
Black liquor	370.5	343.1
Bark	61.2	56.1
Steam consumption in pulp mill, MW	224.9	224.9
Generated power, MW	100.3	89.8
Power consumption, MW	39.6	39.6
Power for sale, MW	60.7	50.2

Table 5. The main operating data of the integrated methanol and pulp plants.

Case	Finland	Far East
Raw material in pulp production	Pine	Eucalyptus
Raw material in methanol production	forest residues (pine)	Eucalyptus
Wood consumption in pulp mill, t ds/a	851 000	769 000
Wood consumption in methanol plant, t ds/a	167 000	897 000
Methanol production, t/a	83 400	439 400
Methanol production, MW	57.7	303.9
Pulp production, adt/a	600 000	600 000
Steam generation, MW	473.4	620.8
Black liquor	370.5	343.1
Bark + side-products of methanol production	69.6	100.0
Steam generation in methanol production	33.3	177.7
Steam consumption in pulp mill, MW	224.9	224.9
Steam consumption in methanol plant, MW	25.5	135.5
Generated power, MW	109.7	131.3
Power consumption in pulp mill, MW	39.6	39.6
Power consumption in methanol plant, MW	11.0	60.0
Power for sale, MW	59.1	31.7

Table 6. The indicative performance of the hydrogen plant.

Case	Finland
Wood consumption	
t/a (moisture 50%)	333 800
MW (LHV)	100
Steam consumption, MW	16
Power consumption, MW	18
Hydrogen production	
t/a	16 700
MW	70
Steam generation, MW	21
Other side-products, MW	14
Hydrogen yield, wt% of dry wood	10
Hydrogen yield, % (LHV/LHV feedstock)	70
Total efficiency (LHV), %	70

Table 7. The indicative main operating data of the integrated hydrogen and pulp plant.

Case	Finland
Raw material in pulp production	Pine
Raw material in hydrogen production	Forest residues (pine)
Wood consumption in pulp mill, t ds/a	851 000
Wood consumption in hydrogen plant, t ds/a	167 000
Hydrogen production, t/a	16 700
Hydrogen production, MW	70
Pulp production, adt/a	600 000
Steam generation, MW	459
Black liquor	371
Bark + side-products of hydrogen production	73
Steam generation in hydrogen production	21
Steam consumption in pulp mill, MW	225
Steam consumption in hydrogen plant, MW	16
Generated power, MW	107
Power consumption in pulp mill, MW	40
Power consumption in methanol plant, MW	18
Power for sale, MW	50

2.7 Costs of wood-based methanol process integrated to CHP production

The methanol production costs were estimated for the wood-based methanol process integrated to an existing power plant of a non-integrated pulp mill. No detailed optimisation of integrating the methanol plant to a specified existing pulp mill was carried out. The following main assumptions in the integration and cost estimation were used:

- the following existing equipment of the pulp mill can be utilised in the methanol production: raw material reception, power plant, waste water treatment, utility systems, and treatment of sulphurous gases
- the utilities are bought from the pulp mill
- the combustible side-products of methanol production are sold to the power plant
- the steam produced in the methanol plant is sold to the pulp mill, the price of steam depending on the steam pressure.

In the Finnish case the studied capacity of methanol production fits well in a context of a modern pulp mill, but in the Far East case the higher methanol production capacity would probably yield some investments in increasing capacity. For example, in the Finnish case the integration of methanol production to the pulp mill increases the capacity of the bark boiler only from 61.2 MW to 69.6 MW, while in the Far East case the capacity increases from 56.1 MW to 100 MW. Therefore, the estimated costs of the Far East case should be considered as the minimum.

The production costs comprise fixed and variable production costs and capital charges. Annual capital charges were estimated from the capital investments by the annuity method. The estimated investment costs are based on public information, mainly on the publications by Elam *et al*. (1994) and Williams *et al*. (1995). The investment costs of different origin were unified and adjusted to the price level of spring 1999 using Chemical Engineer Index. By-product credits were taken into account by subtracting the income received by selling the by-products from the annual production costs. The price of the feedstock was used as the value of combustible by-products. The main parameters of the cost estimation are presented in Table 8. The cost estimation is based on the plant capacities and performances presented in Chapter 2.6.

Table 8. Main parameters in the cost estimation.

Time of the investment	Spring 1999
Place of the investment	A pulp mill, Finland/Far East
Annual operating time	8 000 h/a
Plant life	20 a
Interest rate	10%
Feedstock price, forest residues/Finland	7.6 EUR/MWh
Feedstock price, eucalyptus/Far East	5.9 EUR/MWh
Electricity price	25.2 EUR/MWh
Steam price	11.8–16.8 EUR/MWh (depending on the pressure level)

The estimated investment costs of the methanol production plants are presented in Table 9. The fixed capital investment was estimated at 87 MEUR for the methanol plant in Finland and 238 MEUR for the plant in the Far East. The total capital requirement was estimated to be 112 MEUR and 305 MEUR, respectively. The cost reductions achieved by utilising the existing equipment of the pulp mill were estimated to be about 20%. It should borne in mind that the accuracy of this kind of cost estimate is ±30%.

Table 9. Investment costs of the wood-based methanol plant.

Investment cost, million Euro	Finland	Far East
Fixed capital investment	79.4	216.6
Contingencies	7.9	21.7
Fixed capital investment	87.3	238.2
Start-up	8.7	23.8
Working capital	4.4	11.9
Interest during construction	11.3	31.0
Total capital requirement	111.7	305.0
Capital to be depreciated	107.4	293.0

The production costs in the Finnish case were estimated at around 16 EUR/GJ methanol, i.e. more than threefold compared to the current prices of methanol. In the Far East case the methanol production costs were lower, approximately 10 EUR/GJ methanol, which is about twice the current prices of methanol. Since the produced methanol was considered to be used in Europe the costs of sea transportation (20 USD/m^3, IEA/AFIS 1998) were added to the production costs in the Far East case. The combined production and transportation costs are then about 11 EUR/GJ. The methanol production costs are presented in Figure 11 and in further detail in Table 10.

The production costs of comparable hydrogen production for the Finnish case were estimated roughly. The fixed capital investment was estimated at 68 MEUR and the total capital requirement at 87 MEUR, i.e. about 20% less than the comparable costs of methanol production due to the simpler process. The production costs were estimated at 12.5 EUR/GJ, i.e. about 20% less than the comparable costs of methanol production.

Employing the district heat production for utilising the low-grade waste heat and optimising the integration of the methanol plant to the pulp mill would increase the total efficiency. Further improvements in the total efficiency of the methanol plant and consequent reductions in the production costs could be achieved by process optimisation (optimised gasification temperature, minimised oxygen consumption, high carbon conversion in gasification, small hydrocarbon content in the gasification gas, optimised methanol synthesis).

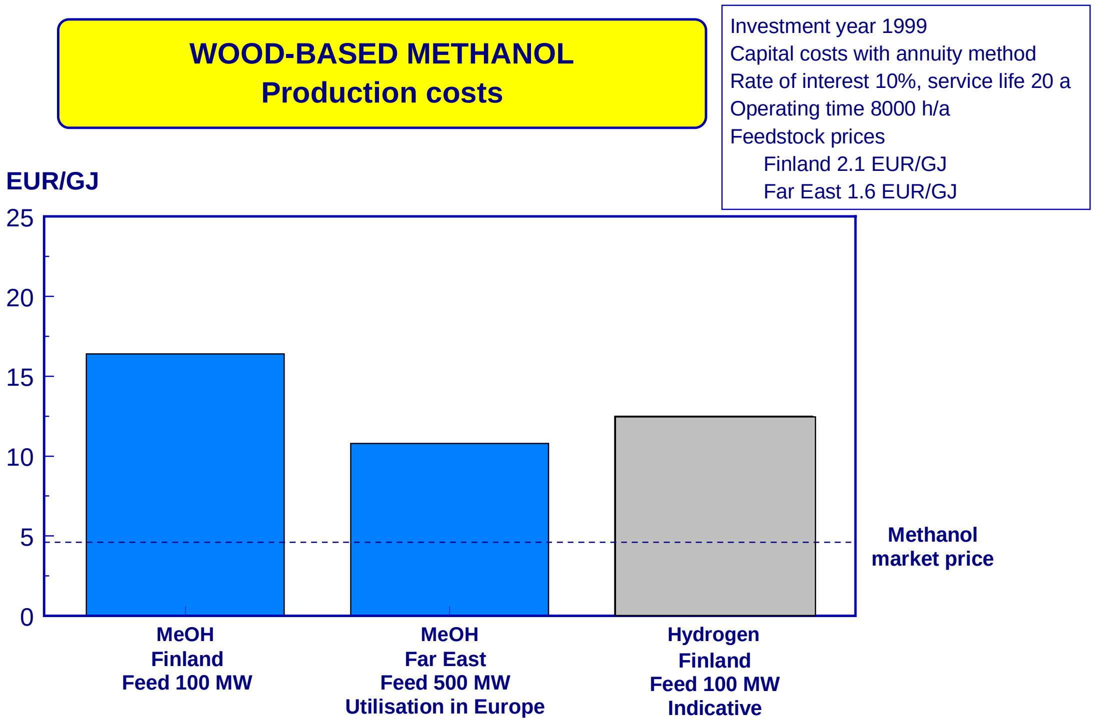


Figure 11. Methanol production costs.

Table 10. Production costs of the wood-based methanol.

Costs, EUR/GJ	Finland	Far East
Fixed operating cost		
Operating labour	0.5	0.2
Maintenance labour	0.5	0.3
Overheads	0.3	0.1
Maintenance materials	1.6	0.8
Taxes, insurance	1.1	0.6
Others	0.5	0.3
Total	4.5	2.3
Variable operating cost		
Feedstock	3.6	2.7
Electricity	1.3	1.4
Chemicals	0.3	0.3
Steam	1.6	1.6
Water, waste water	0.0	0.0
Total	6.9	6.0
By-product credit	2.8	2.8
Capital charges	7.9	4.1
Production cost	16.4	9.6
Sea transportation		1.2
Production and transportation costs	16.4	10.8

3. Greenhouse gas emissions for selected fuel production and use chains

Many alternative fuels and vehicle technologies are in use today, and in the future more choices will be available as new technologies evolve. In this study the greenhouse gas emissions of biomass-based methanol use as a transportation fuel were compared with those of a selected set of other automotive fuels and engine technologies. For all cases the greenhouse gas emissions for full fuel cycles are presented. The following cases of use were considered:

1. a) Reformulated gasoline (RFG) in light duty vehicles (95E, 2% oxygen, 10% MTBE (methanol from natural gas))
   b) Diesel in light-duty vehicles
2. Reformulated gasoline in light-duty vehicles, same as the reference case above, but methanol for MTBE production is produced from biomass
3. Methanol (both from biomass and natural gas) in fuel cell vehicles
4. Gasoline and methanol (both from biomass and natural gas) in ICE-hybrid vehicles
5. Electrical vehicles with
   a) electricity produced from biomass
   b) electricity from average production (Europe).

The greenhouse gas emissions for hydrogen production from biomass and its use in fuel cell vehicles were also estimated, but the emission estimates are based on rougher and more uncertain data.

The fuel chain greenhouse gas emissions for methanol production from wood-based biomass are presented for the cases described in the previous chapter (Finland (pine) and the Far East (eucalyptus)). In the Finnish case the production and end use is assumed to take place in Finland. In the Far East case the methanol production is assumed to take place in the Far East and the use of the fuel take place in Europe (the methanol is assumed to be shipped to Europe). The existing methanol production from natural gas and the gasoline and diesel production from crude oil are considered as reference cases.

Greenhouse gas emissions from the production of the fuels (methanol from natural gas and biomass, gasoline and diesel from crude oil, hydrogen from biomass) are presented in Chapter 3.1. The emissions of local fuel distribution are presented in Chapter 3.2 and emissions from fuel use in different kinds of vehicles in Chapter 3.3. Finally, in Chapter 3.4, the total fuel chain greenhouse gas emissions of the different cases are put together and compared.

In the calculations the biomass is assumed to originate from a sustainable source and therefore the associated CO_2 emissions are not taken into account. The availability of sustainably grown biomass is addressed in Chapter 4.

3.1 Emissions from fuel production

3.1.1 Methanol production from natural gas

Two alternative production chains of fossil methanol fuel (i.e., methanol derived from natural gas) are presented below in a simplistic schematic diagram (Figure 12).

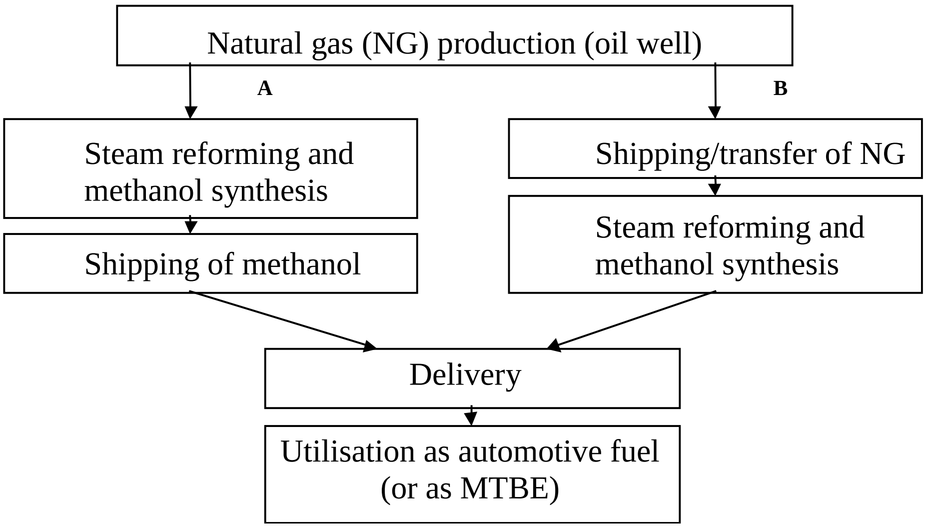


Figure 12. Two alternative production chains of fossil methanol fuel (derived from natural gas).

Natural gas is often a by-product of crude oil drilling, and the emission factors for crude oil production are used here also for natural gas production. IEA/AFIS (1996) reports emission factors of 0.85 kg CO_2/GJ and 0.79 g CH_4/GJ for North Sea production. Calculated as CO_2 equivalents (global warming potential (GWP) factors for CO_2 is 1 and for CH_4 21 for the time period of 100 years) this gives 0.87 kg CO_2(eq)/GJ.

Methanol is usually produced from natural gas by steam reforming. The synthesis processes can take place either in connection with natural gas production (at the production field) or near the end-use destination (long-distance transport as natural gas). The shipping of LNG (liquefied natural gas) is more costly than that of methanol, and hence, the production of methanol often takes place at the production field. Transferring the natural gas along pipelines also enables the methanol production near the end-use destination (alternative B, Figure 12).

During the steam reforming and methanol synthesis processes some leakage of methane can occur, but there is no data on them available. These emissions are, however, expected to be small. Carbon dioxide emissions caused by the energy use of the conversion of natural gas to synthesis gas and methanol are of the order of 8 kg CO_2/GJ CH_3OH (Ecotraffic 1992).

In methanol shipping (alternative A, Figure 12) the transported methanol itself could be used as transportation fuel. The option to use methanol in shipping is, however, not considered in this report.

Natural gas (alternative B, Figure 12) is transferred either in pipelines or shipped in liquefied form (LNG). Methane leakages during pipeline transfer are country- and case-specific, depending on the condition and maintenance of pipelines. In Finland, the GHG emissions of pipeline transfer are estimated at approximately 0.1 kg CO_2(eq)/GJ of natural gas transferred (Energy-Ekono 1997). Natural gas burned as fuel in shipping of LNG produces 2.75 kg CO_2/kg CH_4, about 58.5 kg CO_2/GJ of natural gas (IEA/AFIS 1996).

The summary of the greenhouse gas (GHG) emissions for the different natural gas-to-methanol production chains, assuming a conversion efficiency of 82% for the synthesis process, is presented in Table 11.

Table 11. Greenhouse gas emissions of the alternative production chains of fossil methanol derived from natural gas. (Initial data: IEA/AFIS 1996).

Process alternative A		Process alternative B1		Process alternative B2	
kg CO_2(eq)/GJ MeOH					
natural gas production	1.1	natural gas production	1.1	natural gas production	1.1
steam reforming and methanol synthesis *	8	shipping of natural gas as LNG *	1.1	pipeline transfer of natural gas **	0.1
shipping of methanol	1.0	steam reforming and methanol synthesis *	8	steam reforming and methanol synthesis *	8
TOTAL	10.1		10.2		9.2

* kg CO_2/GJ ** in Finland (Energy-Ekono, 1997)

Energy-Ekono (1997) has estimated the greenhouse gas emissions for methanol production in a case, where the fossil methanol would be produced in Finland using natural gas from Russia. These estimates are roughly eight times higher than those given in Table 11 (alternative B2: natural gas production and pipeline transfer of natural gas). The difference can probably be explained by the fact, that the Russian natural gas net is not in as good a condition as the Finnish net and the leakages are much larger. The corresponding fuel chain greenhouse gas emissions are presented in Table 12. In estimating the total fuel chain greenhouse gas emissions in this study, the values of alternative B2 in Table 11 are used.

Table 12. Greenhouse gas emissions for the production fossil methanol assuming production in Finland from natural gas from Russia (Initial data: Energy-Ekono 1997; IEA/AFIS 1996).

Process step	kg CO_2(eq)/GJfuel
Natural gas production, refining and transportation in Russia	8.1
Steam reforming and methanol synthesis in Finland *	8
Methanol from NG production chain, total	16.1

* kg CO_2/GJ

3.1.2 Methanol production from wood-based biomass

3.1.2.1 The production chains

Besides from natural gas, methanol can be produced from almost any other carbon-containing raw material, like biomass. High production costs have been the main limiting factor in introducing methanol production from biomass. According to international agreements, the carbon dioxide emissions from biomass burning are considered as zero, when the biomass is grown in a sustainable manner (i.e. annual use is less than annual growth) (IPCC 1996 Revised Guidelines 1997). Hence, the CO_2 emissions from combustion of methanol made from biomass need neither be taken into account. The emissions from fossil fuel use in the biomethanol production chain (harvesting, transportation of raw material etc.) must, however, be considered. The estimation of these emissions is described below for the Finnish and the Far East cases.

1) The Finnish case

The process concept (the Finnish case) considered here is as follows: the methanol production plant (including biomass gasification, gas cleaning and methanol synthesis processes) is combined to an energy production system at an existing kraft pulp mill, which consists of recovery boiler, bark boiler, steam cycle, and steam turbine. The kraft pulp mill provides an excess supply of energy. All the electricity and steam required in the methanol process come from the energy production at the pulp mill. In addition, all combustible by-products from methanol production are carried to the bark boiler, reducing the amount of supplementary fuel (forest residue) possibly needed for the increased demand of electricity and steam production caused by the methanol production. The steam produced in the methanol production plant is also introduced to the steam cycle of the pulp mill.

In the Finnish case, the raw material is assumed to be forest residues and no supplementary fossil fuels are needed for the methanol production. The combustible by-products and steam from the methanol production process cover the additional demand of energy (electricity + steam). The net power production of the integrated plant is, however, 2–3 per cent less than that of the non-integrated power plant.

All the CO_2 emissions of the integrated plant originate from biomass (sustainable origin, need not to be considered) and the emissions of the other greenhouse gases, CH_4 and N_2O, are estimated to be negligible. For the production process (gasification and methanol synthesis) no greenhouse gas emissions are therefore taken into account in the calculations.

A rough schematic production chain of methanol derived from forest residues (chips) is shown in Figure 13.

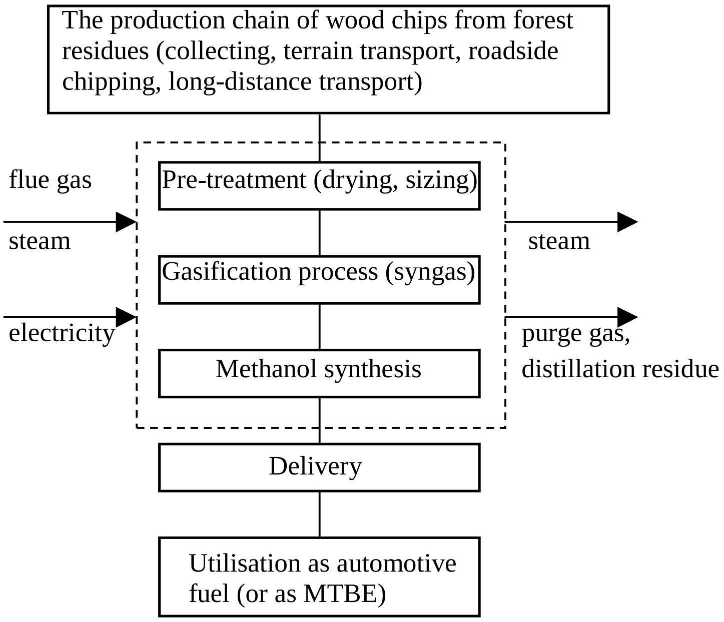


Figure 13. The production chain of methanol fuel derived from wood-based biomass. The arrows describe flows from and to the bark boiler.

2) The Far East case

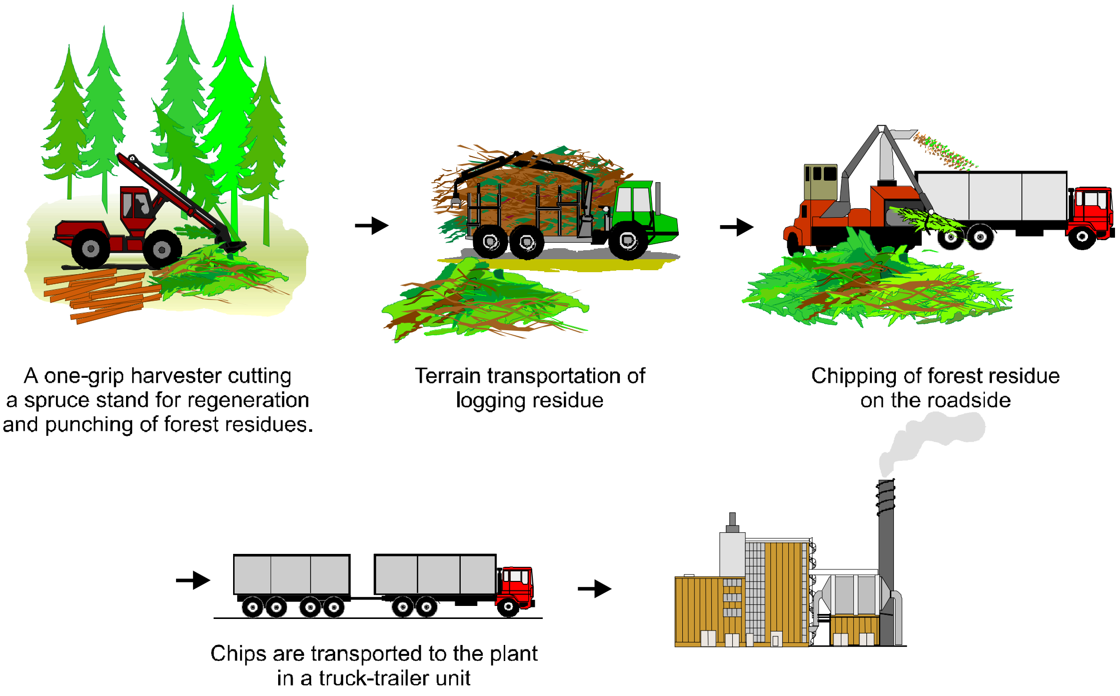
In the Far East case the short rotation coppices (eucalyptus) are used for methanol production. The fast growth of wood would allow for higher capacities (and thus, lower production costs) for methanol production in the Far East than in Europe. The wood consumption of the methanol production process also exceeds that needed for the non-integrated pulp mill, due to the large production capacity. In the Far East the methanol production plant is five times bigger than in the Finnish case (see Tables 2–4). Otherwise the production concept (integrated to kraft pulp mill) is similar to the Finnish case, and zero greenhouse gas emissions from the production are assumed. The total net energy (power + steam) produced is, as in the Finnish case, larger than that for the non-integrated plant. The net electricity production decreases, however, much more, approximately by 30–40 per cent.

The methanol produced in the Far East is transported to and used in Europe. Long-range sea transportation also produces GHG emissions, which must be added to the fuel chain emissions.

3.1.2.2 Emissions from the fuel supply chains

1) The Finnish case

The production of wood chips from forest residues comprises a number of steps (Figure 14). After the trees have been cut and delimbed, the remaining logging residue must be collected and chipped. In addition, some forest transport is needed in order to haul forest residues to a roadside for chipping. The wood chips are then transported further to the end-use location. The forest tractors and chippers that produce the wood chips are fuelled with petroleum fuels (diesel oil) and hence produce carbon dioxide and other greenhouse gas emissions.



A one-grip harvester cutting
a spruce stand for regeneration
and punching of forest residues.

Terrain transportation of
logging residue

Chipping of forest residue
on the roadside

Chips are transported to the plant
in a truck-trailer unit

Figure 14. Harvesting chain of logging residue based on roadside chipping (Alakangas et al. 1999).

Because stemwood is produced anyway, only greenhouse gas emissions from forest residue collecting, forest transport and chipping are considered. Pingoud *et al.* (1999) give an energy consumption value of 1.08 dm^3 diesel/m^3 chips produced. Use of this value would give CO_2 emissions of 3 160 t for the wood chip production in the Finnish case [334 000 t (800 GWh/a, see chapter 2) wood chips for methanol production, average moisture of 50% and average density of 300 kg/m^3 employed in the calculation].

Long-distance transportation of wood chips from a roadside chipping site to a methanol production plant is assumed to be based on diesel fuel use. Using the value of 51 dm^3 diesel/100 km (Pingoud *et al.* 1999), the CO_2 emissions due to transport of wood chips amount to 1 340 g CO_2/km. The total transportation mileage assuming a transportation distance of 40 km (one way) and an average value of 100 m^3/truck would be

$$2 \times 40 \text{ km/truck} \times 11\,139 \text{ trucks/a} = 891\,120 \text{ km/a}.$$

The return trip of the empty truck is also considered. Thus, the CO_2 emissions due to transports of wood chips would amount to 1 194 t CO_2/a. The maximum transportation distance (less than 100 km) is determined by economical feasibility. In the case of one-way distance of 100 km, the corresponding CO_2 emissions would be 2 985 t CO_2/a.

The total CO_2 emissions from the production and transports of wood chips (distance 40 km) would then be 4 353 t CO_2/a (or max. 6 145 t CO_2/a for distance 100 km). The specific CO_2 emissions calculated from these total emissions are presented in Table 13.

Table 13. The specific CO_2 emissions from the production and transports of wood chips in this study (calculated from the initial data by Pingoud et al. 1999).

	kg CO_2/GJ fuel energy (wood chips)
Production	1.1
Transportation	0.4
Total	1.5

The specific CO_2 emissions from a Swedish study (Vattenfall 1996) are presented in Table 14. This study took the whole supply chain of wood chips into account (i.e. also cutting and delimbing, which are not accounted for in Table 13, as the stemwood would be produced anyway for pulp production).

In addition to CO_2, methane (CH_4) and nitrous oxide (N_2O) emissions are produced. The emissions from the logging machinery are not considered. For transportation, the CH_4 and N_2O emissions can be calculated using the emission factors (0.06 g CH_4/km and 0.03 g N_2O/km) given by IPCC (1997). The GHG emissions expressed in CO_2

equivalents would be 10.6 g CO_2 (eq)/km. The significance of the CH_4 and N_2O emissions is small.

Table 14. The specific CO_2 emissions of the whole supply chain of wood chip production from forest residues and transportation (Vattenfall 1996).

	kg CO_2/GJ fuel energy (wood chips)
Production	2.1
Transportation	0.5
Total	2.6

Wihersaari (2000) has estimated, in a recent subproject of the Finnish Wood Energy Technology Programme of Tekes, the total fuel chain greenhouse gas emissions for the harvesting chain of logging residue and its transportation to a site at the distance of 40 km. The total energy consumption was estimated as 2–2.5 dm^3 diesel/MWh wood fuel energy (1.6–2.0 kg CO_2(eq)/GJ wood chips). In the calculation of the fuel chain greenhouse gas emissions in this study (see chapter 3.4) the mean value of this range, 1.8 kg CO_2(eq)/GJ wood chips, is used for wood chips production and transportation.

2) The Far East case

In the case of fast growing coppices (eucalyptus) the fuel supply chain is different from the Finnish forest residue collecting and chipping chain. Eucalyptus is cultivated as a dense field and harvested as whole. The growth is much faster than the forest growth in Finland, e.g., in Brazil typically six to seven years, when eucalyptus is cultivated for use in cellulose production (Hakkila *et al*. 1992). This means that fertilisers are used to enhance the growth, which leads to emissions of nitrous oxide (N_2O). The greenhouse gas emissions due to fertiliser production also need to be considered.

The emissions caused by the fertilisation of the eucalyptus cultivation are estimated as follows: Approximately 600 kg NPK fertiliser (15% nitrogen) per ha is assumed to be applied during a rotation period of 7 years[1]. Mean growth is estimated as 35 $m^3ha^{-1}a^{-1}$ and the density of eucalyptus to be 500 kgm^{-3}. The N_2O emissions are calculated using IPCC default emission factor: 1.25% of the nitrogen content of the fertiliser emitted as N_2O. Greenhouse gas emission from fertiliser production, transportation and spreading are estimated to be 550 kg CO_2(eq)/t fertiliser. The total emissions from fertiliser use would then be approximately 0.007 kg CO_2(eq)/kg wood (0.9 kg CO_2(eq)/GJ).

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[1] Seppo Vuokko, Stora Enso, personal communication, 19 May 2000.

The emissions from eucalyptus harvesting and transport to the production site are calculated as in the Finnish case, but the emissions caused by fertilisation are also added when summarising the fuel chain GHG emissions. The greenhouse gas emissions estimates for eucalyptus cultivation and harvesting are rather rough because of minor data available.

3.1.2.3 Emissions from the methanol production integrated to the pulp mill

As mentioned before, the bark boiler does not require any supplementary fuel in this specific case, because the combustible by-products and steam from the methanol production process cover the additional demand of electricity and steam. This means that no additional GHG emissions are produced in the bark boiler. In addition, because the methanol production chain runs with synthesis gas from biomass (wood chips) gasification, no net CO_2 emissions are produced from the production process either (sustainable silviculture assumed).

The small amount of CH_4 formed in gasification is reformed in the tar reformer, and hence the negligible CH_4 emissions to the atmosphere are not considered in the calculations.

The amount of surplus power from kraft pulp plant is reduced, when the methanol production plant is integrated to the existing bark boiler, slightly in the Finnish case and 30–40% in the Far East case (see Tables 4 and 5). This affects the total system costs but, however, not directly the net GHG emission balances.

Because the methanol produced in the Far East is assumed to be used in Europe, the GHG emissions from long-range sea transportation are also considered. The specific GHG emissions from sea transportation are presented in Table 15.

Table 15. The specific GHG emissions (kg CO_2(eq)/GJ heavy fuel oil (hfo)) from sea transportation (IPCC 1997).

Ocean-going ships (diesel engines, heavy fuel oil)

Emission component	CO_2	CH_4	N_2O	NO_x	**CO_2(eq)**
Global warming potential	1	21	310	1%	**GWP_{100}**
Emission factor (kg/GJ)	77.6	0.007	0.002	2.1	**85**

Ecotraffic (1992) reports an energy consumption of 0.012 GJ hfo/GJ MeOH for long-range sea transportation of methanol. Hence, the total GHG emissions of shipping are 1.0 kg CO_2(eq)/GJ MeOH shipped. This value is used for sea transportation when summarising the total fuel chain GHG emissions in the Far East case (see chapter 3.4).

3.1.3 Gasoline and diesel production from crude oil

Gasoline and diesel production is also considered here in order to compare the fuel chain emissions between biomass-based methanol and gasoline. The greenhouse gas emissions for gasoline production from crude oil (North Sea production) are presented in Table 16.

Table 16. GHG emissions for gasoline refined from crude oil (IEA/AFIS 1996).

Fuel chain step	Specific emission [kg CO_2(eq)/GJ]
Crude oil production *	0.87
Transportation **	0.15–2.45
Refining	2–3.7
Total fuel chain (prod., transp. and ref.)	3.0–7.0

* North Sea production
** min: North Sea – Rotterdam – North Sea; max: Persian Gulf – Rotterdam – Persian Gulf

Allocation of the aggregate emissions from crude oil production and refining to individual products cannot be made accurately as several of the processes are common to several products, the yields of which vary from case to case. However, in Table 17, ranges for CO_2 emissions allocated to gasoline and diesel for different steps in the production chain are given based on the reference (IEA/AFIS 1999).

Life cycle CO_2 emissions from reformulated gasoline refined from crude oil and used in passenger cars in Finland, given by Fortum Oil & Gas (former Neste), are presented in Table 18. It can be seen that the end-use produces almost ten times more CO_2 emissions per litre gasoline than the whole fuel production chain. The corresponding life cycle CO_2 emissions from city-diesel are presented in Table 19.

The IEA/AFIS (1996) values in Table 16 were used in the calculation of the total fuel chain greenhouse gas emissions in this study (see chapter 3.4).

Table 17. CO_2 emissions of gasoline and diesel refined from crude oil (IEA/AFIS 1999).

A. Feedstock production	CO_2, min kg/GJ	CO_2, max kg/GJ	B. Feedstock transportation	CO_2, min kg/GJ	CO_2, max kg/GJ
Gasoline	1.8	3.4	Gasoline	0.6	0.6
Diesel	1.7	3.4	Diesel	0.6	0.6
C. Fuel production	CO_2, min kg/GJ	CO_2, max kg/GJ	D. Total Fuel production chain	CO_2, min kg/GJ	CO_2, max kg/GJ
Gasoline	6.1	12	Gasoline	8.5	16
Diesel	3.0	7.0	Diesel	5.3	11

Table 18. CO_2 emissions of reformulated gasoline refined from crude oil (Fortum Oil & Gas 1999).

Life cycle emissions of gasoline (Neste) Heat value 32,1 MJ/l Density 745 kg/m^3				
	Emission per gasoline volume g CO_2/l	Emission per gasoline mass g CO_2/kg	Heat value of gasoline MJ/kg	Emission per energy content of gasoline kg CO_2/GJ
Crude oil production, transportation, refining and delivery	260	349	43.1	8.1
Use in passenger car	2 350	3 154	43.1	73.2
TOTAL	2 610	3 503		81.3

Table 19. CO_2 emissions of city-diesel refined from crude oil (Fortum Oil & Gas 1999).

Life cycle emissions of diesel fuel (Neste) Heat value 35.9 MJ/l Density 835 kg/m^3				
	Emission per diesel volume g CO_2/l	Emission per diesel mass g CO_2/kg	Heat value of diesel MJ/kg	Emission per energy content of diesel kg CO_2/GJ
Crude oil production, transportation, refining and delivery	190	228	43.0	5.3
Use in passenger car/van/HDV	2 650	3 174	43.0	73.8
TOTAL	2 840	3 401		79.1

3.1.4 Hydrogen production from biomass

The greenhouse gas emissions for hydrogen production from biomass and its use in fuel cell vehicles are also estimated, but the emission estimates are based on rougher data. The hydrogen production is integrated to the kraft pulp mill in the same way as the methanol production described earlier. Only the Finnish case is studied, i.e. the gasification facility of 100 MW wood chips (334 000 t/a). The hydrogen yield is somewhat greater than in the case of methanol. Again, no net CO_2 emissions are produced and the emissions of CH_4 and N_2O are negligible. Also hydrogen production from electrolysis of water is considered roughly for reference.

The energy efficiencies used are estimated based on IEA/AFIS (1999) for electrolysis and process calculations in Ch. 2.5 for steam reforming/gasification of biomass. For electrolysis, average emissions for biomass-based electricity (4 g CO_2(eq)/MJ) and average power mix of Finland (250 g CO_2/kWh) are used in the calculations. For steam reforming, the emissions of raw material production (biomass and natural gas) calculated in the other cases are used.

For sea transportation of hydrogen, IEA/AFIS (1996) gives an energy consumption value of (0.06 GJ/GJ) that is used in calculation (see Ch. 3.4).

3.2 Local distribution

Liquid methanol can be distributed for consumption like gasoline. If the tank trucks use petroleum fuels (i.e. diesel), the greenhouse gas emissions can be calculated by using emission factors given in literature. If the biomass-based methanol fuel were also used in tank trucks, the methanol fuel distribution would not cause any additional net carbon dioxide emissions. This alternative is, however, not considered here.

Hydrogen distribution requires special transportation equipment. A new infrastructure for the hydrogen distribution network would be expensive. For greenhouse gas emission calculations of hydrogen sea transportation and local distribution the energy consumption values (0.06 GJ hfo/GJ hydrogen shipped and 0.11 GJ diesel/GJ hydrogen distributed, respectively) from the reference IEA/AFIS (1996) are used.

The greenhouse gas emissions from gasoline, methanol and hydrogen transportation in trucks must be calculated so that the differences in distribution mileage are also taken into account. The distribution mileage is greater for methanol than for gasoline due to its lower density and heat value (i.e. the same energy content of methanol needs more transportation volume than gasoline). The energy consumption values of fuel distribution used here include these differences.

The specific energy consumption figures of local fuel distribution for different fuels are presented in Table 19. Fugitive energy losses are also included in most cases. When overseas transportation is needed (e.g. for hydrogen distribution), the specific energy consumption of sea tankers must be added (e.g. 0.06 GJ hfo/GJ for hydrogen and 0.012 GJ hfo/GJ for methanol, Ecotraffic 1992) to the figures in Table 19.

In the calculation of the total fuel chain greenhouse gas emissions (see chapter 3.4) the values of Ecotraffic (1992) in Table 20 were used for fuel distribution.

Table 20. Specific energy consumption of local fuel distribution for different automotive fuels.

Fuel distribution	Energy consumption GJ/GJ	GJ/GJ	GJ/GJ
Reference:	ETSU UK, 1995	Ecotraffic Sweden, 1992	DeLuchi USA, 1991
Gasoline	0.002	0.010	0.0083
Diesel		0.010	0.0091
Natural gas	0.03	0.09	0.086
Methanol	0.010	0.010	
Hydrogen		0.11	

The minimum and maximum specific carbon dioxide emissions (IEA/AFIS 1999) of local fuel distribution are presented in Table 21.

Table 21. The minimum and maximum specific CO_2 emissions of local fuel distribution for different automotive fuels (IEA/AFIS 1999).

Fuel distribution	CO_2, min kg/GJ_{fuel}	CO_2, max kg/GJ_{fuel}
Reference:	IEA, AFIS, 1999	
Gasoline	0.2	0.7
Diesel	0.2	0.7
Natural gas	1.4	11.2
Methanol	0.4	2.7
Hydrogen	1.5	5.4

The local distribution is in most cases done by diesel fuelled road tankers. The GHG emissions of diesel fuelled HDV are calculated in Table 22.

Table 22. The GHG emissions of diesel fuelled HDV (Wihersaari 2000).

CO_2 1	CH_4 21	N_2O 310	NO_x 1%	**CO_2 (eq) GWP100**	
2 660	0.3	0.1	40	**2 821**	g/l diesel
GHG emission (HDV)		2.8	kg CO_2 (eq)/l diesel		
Density, diesel fuel		0.835	kg/l		
LHV, diesel fuel		43	MJ/kg		
LHV, diesel fuel		35.9	MJ/l diesel		
GHG emission		**78.6**	**kg CO_2(eq)/GJ diesel**		

For comparison, corresponding emissions calculated with IPCC default values (IPCC 1997) would amount to 75.1 kg CO_2(eq)/GJ.

3.3 Use in vehicles

Emissions originating from the vehicle stage were determined using vehicle parameters and assumed total powertrain efficiencies to determine the gross energy use and actual fuel usage. This stage incorporated emissions only from the direct use of fuel, i.e. not from refuelling at the filling stations.

The carbon dioxide emissions from fuel cell vehicles fuelled with biomass-derived neat methanol (M100) are not taken into account. Biomass-derived M85 fuel (fuel blend containing 85% methanol and 15% gasoline) used in hybrid vehicles (combination of internal combustion engine (ICE) and electric motor/generator) produces fossil carbon dioxide emissions in proportion to the mass of gasoline in the fuel. The CO_2 emissions from biomass-derived methanol are not added to the estimated GHG emissions.

3.3.1 Vehicles

Emissions of GHGs from the vehicle use were determined for three different cases: family cars, urban commuters and urban buses. The primary case was a family car, with five seats and approximated net weight (excluding powertrain and fuel) of 800 kg. The target output of the powertrain was set at 50 kW, delivering the maximum speed of approximately 150 km/h. The target range was established at 600 km (200 km for pure battery EV) yielding in different sizes for fuel tank depending on the fuel's energy density. The total gross vehicle weight was in the range of 1 260–1 315 kg depending on the powertrain type and on the amount of fuel on-board that was sufficient to reach the targeted range. The other car under consideration was a small urban commuter with two seats and only 200 km range (100 km for pure battery EV) and power output of 20 kW. Table 23 lists the basic vehicle parameters.

The third case, urban bus, was considered to have a capacity for 50 persons, net weight of 7 000 kg and target range 400 km. The powertrain output was assumed to be 250 kW. With a sufficient amount of fuel onboard, the gross vehicle mass was around 13 500 kg.

Table 23. Basic vehicle parameters.

Case	Net weight (kg)	Gross weight (kg)	Power output (kW)	Max. speed (km/h)	Target range (km) [EV]
Family car	800	~ 1 300*	50	150	600 [200]
Urban commuter	400	~ 725*	20	100	200 [100]
Urban bus	7 000	~ 13 600*	250	80	n/a

* average, actual value depending on configuration

3.3.2 Powertrains

Four types of powertrains were considered for both vehicles. The basic one was a spark-ignition internal combustion engine (ICE), either spark-ignited (otto, SI) or compression-ignited (diesel, CI). A more advanced case was a hybrid-drive with an ICE and some type of electric storage buffer for regenerated energy (ICE-SI/H or ICE-CI/H). The third option was a fuel cell drive (FC) either with direct hydrogen on-board or with a fuel processor (reformer) for hydrogen production. Two types of reformers were compared, steam reformer (STM) and partial oxidation type (POX). STM was considered suitable for using methanol as feedstock, and POX reformer was considered for gasoline (RFG). The fourth powertrain option was a battery powered pure electrical vehicle (EV). Table 24 lists assumed efficiencies for the different powertrain options. These assumptions are quite general, and were made using recently published data in Docter & Lamm (1999), Karlhammer *et al.* (1998), Ogden *et al.* (1999), Stodolsky *et al.* (1999), and Thomas (1999).

Table 24. Assumed efficiencies for the different powertrain options.

Powertrain type	Pure EV	ICE -SI	ICE -CI	ICE-SI/H	ICE-CI/H	FC+ reformer	FC-Direct H_2
Net engine efficiency, %	95	34 35[1]	40	34 35[1]	40	60	60
Part load / full load ratio, %	95	70	80	80	80	95	95
Fuel reformer efficiency, %	n/a	n/a	n/a	n/a	n/a	51 STM 57 POX	n/a
Mechanical drivetrain eff., %	80	80	80	80	80	80	80
Hybrid drivetrain gains, %	125	100	100	120	120	120	120 ***100*[2]**
Powertrain total efficiency, %	**90**	**19**	**26**	**25** **26**[1]	**31**	**31 STM** **28 POX**	**54** **45**[2]

[1] methanol allows higher compression ratio => increased net efficiency

[2] direct FC-EV drive, no regenerative braking

3.3.3 Fuels

Theoretically, neat methanol can be used as fuel for ICE, but for safety reasons it is usually blended with gasoline. It ensures cold start and gives the necessary luminosity for the flame. A typical composition for vehicle distribution is M85, i.e. 15% gasoline in methanol. Gasoline in current reformulated quality that includes 10% of MTBE, was considered as the base case. For fuel cell vehicles, the fuel choices were neat methanol (M100) or RFG, although in reality a single-component hydrocarbon fuel rather than a blend would be the ideal feedstock for the reformer.

3.3.4 Energy consumption

The energy consumption for all vehicles was computed using the ICE vehicle with RFG (or diesel for the urban bus case) as the reference case. The family car with a regular ICE powertrain yielded a gross vehicle weight (GVW) of 1 281 kg, and for a mixed type of driving, fuel consumption (RFG) was approximated to be 7 dm^3/100 km. With the estimated powertrain total efficiency of 19%, the net energy required to move this type of vehicle was 0.414 MJ/km (or 0.00032 MJ/km*kg). For the urban commuter the base case was a similar ICE powertrain, but because of a lower GVW (712 kg) and slow-speed driving, fuel (RFG) consumption was set at 3.5 dm^3/100 km. This gave 0.222 MJ/km (or 0.00031 MJ/km*kg) for basic energy use.

The urban bus case was calibrated for 55 dm^3/100 km consumption, giving 5.22 MJ/km or 0.00039 MJ/km*kg, for the energy requirement, as the respective GVW was 13 335 kg.

The net energy requirement for the other cases was then computed using these figures as the basis considering different GVWs. From these values the final gross energy use was then determined using the estimated total efficiency figures for each of the powertrain cases. The calculated fuel use and gross energy values for the different vehicle and powertrain types are presented in Tables 25 and 26.

Table 25. Actual fuel use (dm^3/100 km) for different vehicle and powertrain types.

Fuel consumption [dm^3/100 km]	ICE-SI / ICE-CI		ICE-hybrid		Fuel cell vehicle (regeneration)					
	(medium size class)				Steam reformer		POX		Hydrogen	
	RFG/M85 or RFD/M100		RFG/M85 or RFD/M100		M100		RFG		H_2	
	Fam. car	Urban comm.	Fam. car	Urban comm.	Fam. car	Urban comm.	Fam. car	Urban comm.	Fam. car	Urban comm.
Gasoline (RFG)	7.0	3.5	5.4	2.7			5.0	3.4		
M85	12.4	6.3	9.2	4.8						
Citydiesel (RFD in LDVs)	4.4	2.4	3.8	2.1						
M100 in diesel LDVs	10.6	5.8	9.0	5.1						
M100 in fuel cell					9.4	5.1				
Hydrogen									7.6	4.2

Note: the fuel use [dm3/100 km] refers to the case fuel; i.e. RFG, RFD, M100, H_2

Table 26. Gross energy values (MJ/km) for different vehicle and powertrain types.

Gross energy use MJ/km	ICE-SI / ICE-CI (medium size class)		ICE-hybrid		Fuel cell vehicle (regeneration)					
					Steam reformer		POX		Hydrogen	
	RFG/M85 or RFD/M100		RFG/M85 or RFD/M100		M100		RFG		H_2	
	Fam. car	Urban comm.	Fam. car	Urban comm.	Fam. car	Urban comm.	Fam. car	Urban comm.	Fam. car	Urban comm.
Gasoline (RFG)	2.18	1.09	1.68	0.85			1.60	1.09		
M85	2.22	1.12	1.65	0.85						
Citydiesel (RFD in LDVs)	1.60	0.89	1.37	0.77						
M100 in diesel LDVs	1.63	0.90	1.39	0.78						
M100 in fuel cell					1.44	0.78				
Hydrogen									0.81	0.44
Electrical vehicle (EV)	0.51 (for family car)					0.41 (for urban commuter)				

3.3.5 Emissions

The GHG emissions derived from vehicle use considered here were CO_2, CH_4 and N_2O. Direct CO_2 from fuel combustion was calculated from the carbon content of the fuel. Specific emissions for CH_4 and N_2O were determined first for the reference case (ICE-SI, RFG), and then a relative figure was established for the various optional powertrain and fuel combinations.

Apart from these GHGs, an estimate for specific NO_x emission was also established. Table 27 outlines the assumed specific emission rates for the base case (ICE-SI, RFG).

Table 27. Assumed specific emission rates for the base case (ICE-SI, RFG).

Fuel use [dm^3/100 km]		7.0	Estimated
Gross energy use [MJ/km]		2.18	Calculated
direct CO_2 [g/km]	3.13 kg/kg_{fuel}	163	Calculated
	GWP values		
N_2O [g/km]	310	0.03	Est., CORINAIR (2005)
CH_4 [g/km]	21	0.02	10% of EU4 HC (2005)
NO_x [g/km]	n/a	0.08	EU4 standard (2005)

Table 28 summarises the relative emissions estimated for different powertrain options.

Table 28. The relative emissions estimated for different powertrain options.

powertrain	ICE-SI	ICE-SI	ICE-SI/H	ICE-SI/H	FC
fuel	RFG	M85	RFG	M85	
N2O [g/MJgross]	100 %	100 %	100 %	100 %	n/a
	N2O is only catalyst dependent				
CH4 [g/MJgross]	100 %	50 %	50 %	50 %	n/a
		MeOH less volatile	less transients on hybrid drive, better control of emissions	less transients on hybrid drive, better control of emissions	
NOx [g/km]	100 %	100 %	50 %	50 %	n/a
			less transients on hybrid drive, better control of emissions	less transients on hybrid drive, better control of emissions	

3.4 Fuel chain GHG emissions for the selected cases

The total fuel chain emissions from fuel production to end use in vehicles are summarised for the different fuels in the following sub-chapters. In addition to CO_2, the CH_4 and N_2O emissions are considered. The emissions from manufacturing the vehicles, power plants, etc. are not considered. In the sub-chapters the fuel chain emissions are presented separately for fuel production (including distribution) and end use in vehicles.

The GHG emissions for the different fuel production chains (including transportation and distribution of the fuel) are summarised in Table 29. The GHG emissions (kg CO_2(eq)/GJ) of the fuel production chains have been converted to g/km emissions with gross energy use values (MJ/km) of specific vehicle types and summarised with end use GHG emissions.

Table 29. The summarised GHG emissions (kg CO_2(eq)/GJ fuel) from fuel production chains (including delivery, see chapters 3.1–3.2 for details).

RFG from crude		MeOH from natural gas		M100 from biomass		Electricity production			Hydrogen (no sea transport.)	
Conv.	Biomass-MeOH in MTBE	M100	M85	Finland	Far East	Finland, average	EU, average (estimate)	From biomass	Electrolysis, average power	Steam ref., biomass
6.8	6.7	10	11.2	3.8	5.8	83	111	7	120.6	11.6

3.4.1 CASE 1: Reference cases (gasoline and diesel in LDVs)

Reformulated gasoline (RFG) in light-duty vehicles (95E, 10% MTBE (methanol from natural gas))

The total fuel chain GHG emissions of reformulated gasoline (RFG) production, delivery and end use in ICE-SI family car (medium size class) and in the urban commuter (city-car) are presented in Table 30.

The GHG emission of gasoline fuel production chain is about 15 g CO_2(eq)/km when used in the present-type ICE-SI car. The fuel use in vehicles produces 173 g CO_2(eq)/km with a gasoline consumption of 7 l/100 km or 33.6 mpg, and the total GHG emissions are then 188 g CO_2(eq)/km. The use of gasoline in vehicles produces over 90% of the total well-to-wheel GHG emissions.

Table 30. The summary of fuel chain GHG emissions (g/km) of LDVs using reformulated gasoline (RFG) produced from crude oil.

ICE-SI, RFG GHG TOTAL (g CO_2(eq)/km))		
A.	RFG fuel production chain	g CO_2(eq)/km
A1.	Family car (5 seats, 50 kW)	15
A2.	Urban commuter (2 seats, 20 kW)	7
B.	End use in vehicles (net CO_2(eq))	g CO_2(eq)/km
B1.	Family car (5 seats, 50 kW)	173
B2.	Urban commuter(2 seats, 20 kW)	86
FUEL CHAIN GHG, TOTAL		**g CO_2(eq)/km**
1.	**Family car (5 seats, 50 kW)**	**188**
2.	**Urban commuter (2 seats, 20 kW)**	**94**

If RFG is used in ICE-SI urban commuters (2 seats, 20 kW, see Ch. 3.3), the total GHG emissions are reduced to 94 g CO_2(eq)/km. The emissions from the use of RFG in ICE-hybrid or fuel cell vehicles were also calculated for reference for the following cases (see Table 50).

Diesel use in light-duty vehicles

The total fuel chain GHG emissions for reformulated diesel (RFD, citydiesel) production, delivery and use in the ICE-CI family car (medium size class) and in the urban commuter (city-car) are presented in Table 31a. A hybrid car using diesel fuel is also considered (Table 31b).

The GHG emissions of diesel fuel production chain are about 10 g CO_2(eq)/km when used in the present-day type ICE-CI car. The end use produces 119 g CO_2(eq)/km with a diesel consumption of 5.0 l/100 km, and the total GHG emissions are then 130 g CO_2(eq)/km. When RFD is used in the ICE-CI urban commuter (2 seats, 20 kW, see Ch. 3.3), the total GHG emissions are reduced to 72 g CO_2(eq)/km.

When diesel is used in ICE-CI/H hybrid cars, the GHG emissions are slightly reduced: 111 and 63 g CO_2(eq)/km for the family car and the urban commuter, respectively. This is due to the reduced gross energy use – and hence, diesel consumption – because of the electric storage buffer for regenerated energy (i.e. from braking).

Table 31a. The summary of fuel chain GHG emissions (g/km) of ICE-CI LDVs using reformulated diesel (RFD) produced from crude oil.

a.	ICE-CI, citydiesel RFD	
	GHG TOTAL (g CO_2(eq)/km))	
A.	RFD fuel production chain	g CO_2(eq)/km
A1.	Family car (5 seats, 50 kW)	10
A2.	Urban commuter(2 seats, 20 kW)	6
B.	End use in vehicles (net CO_2(eq))	g CO_2(eq)/km
B1.	Family car (5 seats, 50 kW)	119
B2.	Urban commuter (2 seats, 20 kW)	66
	FUEL CHAIN GHG, TOTAL	**g CO_2(eq)/km**
1.	**Family car (5 seats, 50 kW)**	**130**
2.	**Urban commuter (2 seats, 20 kW)**	**72**

Table 31b. The summary of fuel chain GHG emissions (g/km) of hybrid LDVs using reformulated diesel (RFD) produced from crude oil.

b.	hybrid, citydiesel (RFD)	
	GHG TOTAL (g CO_2(eq)/km))	
A.	RFD fuel production chain	g CO_2(eq)/km
A1.	Family car (5 seats, 50 kW)	9
A2.	Urban commuter (2 seats, 20 kW)	5
B.	End use in vehicles (net CO_2(eq))	g CO_2(eq)/km
B1.	Family car (5 seats, 50 kW)	102
B2.	Urban commuter (2 seats, 20 kW)	58
	FUEL CHAIN GHG, TOTAL	**g CO_2(eq)/km**
1.	**Family car (5 seats, 50 kW)**	**111**
2.	**Urban commuter (2 seats, 20 kW)**	**63**

3.4.2 CASE 2: MTBE from wood-derived MeOH (gasoline in LDVs)

If the MTBE additive for reformulated gasoline is produced from wood-based methanol rather than from natural gas based methanol, the net carbon dioxide emissions are reduced. This reduction is rather small because there is only 10% MTBE in RFG and moreover, only 20% of the carbon content in MTBE comes from methanol. Because of limited biomass resources (see Ch. 4), the MTBE production from biomass-based methanol could still be justified.

The full fuel chain GHG emissions of RFG containing biomass-based MTBE production, delivery and end use in the ICE-SI family car (medium size class) and in the urban commuter (city-car) are presented in Table 33. The emissions from RFG (MTBE from biomethanol) use in ICE-hybrid and fuel cell vehicles were also calculated for reference (see Table 50).

It can be seen from Tables 30 and 32 that the fuel chain GHG emissions of RFG with MTBE from biomass-based methanol are reduced by less than 2% (185 vs. 188 g CO_2(eq)/km) compared to conventional RFG with MTBE from natural gas based methanol. In urban commuters this reduction is even smaller (about 1%, 94 vs. 93 g CO_2(eq)/km) due to lower fuel consumption.

Table 32. The summary of fuel chain GHG emissions (g/km) of ICE-SI Family cars using reformulated gasoline (RFG), which include MTBE from biomass-based methanol.

ICE-SI, RFG (medium size class)		
GHG TOTAL (g CO_2(eq)/km))		
A.	RFG fuel production chain	g CO_2(eq)/km
A1.	Family car (5 seats, 50 kW)	14
A2.	Urban commuter (2 seats, 20 kW)	7
B.	End use in vehicles (net CO_2(eq))	g CO_2(eq)/km
B1.	Family car (5 seats, 50 kW)	171
B2.	Urban commuter (2 seats, 20 kW)	85
FUEL CHAIN GHG, TOTAL		**g CO_2(eq)/km**
1.	**Family car (5 seats, 50 kW)**	**185**
2.	**Urban commuter (2 seats, 20 kW)**	**93**

3.4.3 CASE 3: MeOH (both from biomass and natural gas) in fuel cell vehicles

3.4.3.1 Biomass

1) The Finnish case

The total fuel chain greenhouse gas emissions of light-duty fuel cell vehicles using neat methanol (M100) produced from biomass (pine chips) are listed in Table 33. Carbon dioxide emissions from fuel cells are not considered, when the methanol fuel is made from biomass. The total GHG emissions are then composed only of emissions from the methanol production and distribution.

When biomass-based M100 is used in a fuel cell vehicle of family car size class, the total GHG emissions are 6 g CO_2(eq)/km (with M100 consumption of 4.5 l/100 km or 51.8 mpg), whereas the use in an urban commuter fuel cell vehicle (2 seats, 20 kW, see Ch. 3.3) produces total GHG emissions of 3 g CO_2(eq)/km. These fuel chain GHG emissions are only 3 and 2%, respectively, of the fuel chain emissions of reference case (RFG in ICE-SI Family car, Ch. 3.4.1).

Table 33. Fuel chain GHG emissions of fuel cell vehicles using neat methanol (M100) produced from biomass (Finland).

Fuel cell, M100 (Steam reformer)		
GHG TOTAL (g CO_2(eq)/km))		
A.	Methanol fuel production chain	g CO_2(eq)/km
A1.	Family car (5 seats, 50 kW)	6
A2.	Urban commuter (2 seats, 20 kW)	3
B.	End use in vehicles (net CO_2(eq))	g CO_2(eq)/km
B1.	Family car (5 seats, 50 kW)	0
B2.	Urban commuter (2 seats, 20 kW)	0
FUEL CHAIN GHG, TOTAL		**g CO_2(eq)/km**
1.	**Family car (5 seats, 50 kW)**	**6**
2.	**Urban commuter (2 seats, 20 kW)**	**3**

2) The Far East case

For eucalyptus harvesting and transportation, the same energy losses and emissions as in the Finnish case (pine) are assumed. In addition, the emissions of sea transport of methanol from the Far East to Europe are considered. Fertiliser use in the plantations also causes GHG emissions (mostly N_2O, see Ch. 3.2.1).

In Table 34, the total GHG emissions of M100 produced in the Far East and shipped to Europe, and used in fuel cell vehicles of family car and urban commuter size classes are presented.

Tables 32 and 34 show that the total fuel chain GHG emissions are increased by 1–2 g/km due to eucalyptus fertilising and sea transportation of methanol. Even so, the fuel chain GHG emissions are still only 4 and 2% for the family car and the urban commuter, respectively, of the fuel chain emissions of the reference case (RFG in ICE-SI family car, Ch. 3.4.1). This indicates that it would be totally reasonable to produce biomass-based methanol in areas of fast growing biomass and use it elsewhere. However, the cost of long-range sea transportation would be a problem, at least until the production costs of biomass-based methanol can be reduced to the cost level of RFG production.

Table 34. Fuel chain GHG emissions of fuel cell vehicles using neat methanol (M100) produced from eucalyptus in the Far East and transported to Europe for end use.

Fuel cell, M100 (Steam reformer)		
GHG TOTAL (g CO_2(eq)/km))		
A.	Methanol fuel production chain	g CO_2(eq)/km
A1.	Family car (5 seats, 50 kW)	8
A2.	Urban commuter (2 seats, 20 kW)	4
B.	End use in vehicles (net CO_2(eq))	g CO_2(eq)/km
B1.	Family car (5 seats, 50 kW)	0
B2.	Urban commuter (2 seats, 20 kW)	0
FUEL CHAIN GHG, TOTAL		**g CO_2(eq)/km**
1.	**Family car (5 seats, 50 kW)**	**8**
2.	**Urban commuter (2 seats, 20 kW)**	**4**

3.4.3.2 Natural gas

The total fuel chain greenhouse gas emissions of light-duty fuel cell vehicles using neat methanol (M100) produced from natural gas are listed in Table 35. As the methanol is now produced from a fossil raw material, also the CO_2 emissions from use in fuel cells are considered and the total emissions are therefore much larger than in the case of biomethanol.

The GHG emissions from natural gas based M100 fuel production and distribution are about 14 g CO_2(eq)/km when using the fuel in fuel cell vehicles of family car size class. The end use produces 102 g CO_2(eq)/km (with M100 consumption of 4.5 l/100 km or 51.8 mpg), and the total GHG emissions are then 117 g CO_2(eq)/km. If the natural gas based M100 is used in fuel cell vehicles of urban commuter size class (2 seats, 20 kW, see Ch. 3.3), the total GHG emissions are reduced to 63 g CO_2(eq)/km.

Table 35. Fuel chain GHG emissions of fuel cell vehicles using neat methanol (M100) produced from natural gas.

Fuel cell, M100 (Steam reformer)		
GHG TOTAL (g CO_2(eq)/km))		
A.	Methanol fuel production chain	g CO_2(eq)/km
A1.	Family car (5 seats, 50 kW)	14
A2.	Urban commuter (2 seats, 20 kW)	8
B.	End use in vehicles (net CO_2(eq))	g CO_2(eq)/km
B1.	Family car (5 seats, 50 kW)	102
B2.	Urban commuter (2 seats, 20 kW)	55
FUEL CHAIN GHG, TOTAL		**g CO_2(eq)/km**
1.	**Family car (5 seats, 50 kW)**	**117**
2.	**Urban commuter (2 seats, 20 kW)**	**63**

These total fuel chain GHG emissions are 62 and 34%, respectively, of the fuel chain emissions of the reference case (RFG in ICE-SI family car, Ch. 3.4.1). In these cases, the end use produces 87% of the total fuel chain GHG emissions compared to over 90% in the reference case.

3.4.4 CASE 4: Methanol use in ICE-hybrid vehicles

3.4.4.1 Biomass

1) The Finnish case

The total fuel chain greenhouse gas emissions of ICE-hybrid vehicles using M85, i.e. methanol (85%) blended with gasoline (15%), produced from forest residues in Finland are listed in Table 36.

The GHG emissions of the biomass-based M85 fuel production chain are about 7 g CO_2(eq)/km if used in a hybrid vehicle of family car size class. The end use produces 41 g CO_2(eq)/km (with M85 consumption of 5.2 l/100 km or 44.9 mpg), and the total GHG emissions are 49 g CO_2(eq)/km. If the biomass-based M85 is used in a hybrid vehicle of urban commuter size class (2 seats, 20 kW, see Ch. 3.3), the total GHG emissions are reduced to 25 g CO_2(eq)/km. These fuel chain GHG emissions are 26 and 13%, respectively, of the fuel chain emissions of reference case (RFG in ICE-SI Family car, Ch. 3.4.1).

For diesel ICE-hybrid vehicles using neat methanol (M100) produced from forest residues in Finland, the total fuel chain greenhouse gas emissions are 8 and 5 g/km for family cars and urban commuters, respectively. These fuel chain GHG emissions are only 4 and 2%, respectively, of the fuel chain emissions of the reference case (RFG in ICE-SI family car, Ch. 3.4.1) and about 7–8% of the fuel chain emissions of ICE-hybrid vehicles using conventional city-diesel fuel.

Table 36. Fuel chain GHG emissions of ICE-hybrid vehicles using methanol (M85) produced from biomass (Finland).

Hybrid, M85		
GHG TOTAL (g CO_2(eq)/km))		
A.	Methanol fuel production chain	g CO_2(eq)/km
A1.	Family car (5 seats, 50 kW)	7
A2.	Urban commuter (2 seats, 20 kW)	4
B.	End use in vehicles (net CO_2(eq))	g CO_2(eq)/km
B1.	Family car (5 seats, 50 kW)	41
B2.	Urban commuter (2 seats, 20 kW)	21
FUEL CHAIN GHG, TOTAL		**g CO_2(eq)/km**
1.	**Family car (5 seats, 50 kW)**	**49**
2.	**Urban commuter (2 seats, 20 kW)**	**25**

2) The Far East case

In Table 37, the total GHG emissions of M85 (methanol produced in and shipped from the Far East to Europe) used in hybrid vehicles of family car and urban commuter size classes are presented.

Tables 36 and 37show that the total fuel chain GHG emissions for ICE-hybrid vehicles using M85 are increased by 1–2 g/km due to the eucalyptus fertilising and sea transportation of methanol compared to the Finnish case. The fuel chain GHG emissions are 27 and 14%, for the family car and the urban commuter, respectively, of the fuel chain emissions of reference case (RFG in ICE-SI family car, Ch. 3.4.1).

For diesel ICE-hybrid vehicles using neat methanol (M100) produced from biomass (eucalyptus) in the Far East, the total fuel chain greenhouse gas emissions are 11 and 6 g/km for the family car and the urban commuter, respectively. These fuel chain GHG emissions are only 6 and 3%, respectively, of the fuel chain emissions of the reference case (RFG in ICE-SI Family car, Ch. 3.4.1) and about 10% of the fuel chain emissions of ICE-hybrid vehicles using conventional city-diesel fuel.

Table 37. Fuel chain GHG emissions of ICE-hybrid vehicles using methanol (M85) produced from biomass (the Far East).

Hybrid, M85		
GHG TOTAL (g CO_2(eq)/km))		
A.	methanol fuel production chain	g CO_2(eq)/km
A1.	Family car (5 seats, 50 kW)	10
A2.	Urban commuter (2 seats, 20 kW)	5
B.	End use in vehicles (net CO_2(eq))	g CO_2(eq)/km
B1.	Family car (5 seats, 50 kW)	41
B2.	Urban commuter (2 seats, 20 kW)	21
FUEL CHAIN GHG, TOTAL		**g CO_2(eq)/km**
1.	**Family car (5 seats, 50 kW)**	**51**
2.	**Urban commuter (2 seats, 20 kW)**	**26**

3.4.4.2 Natural gas

The total fuel chain greenhouse gas emissions of ICE-hybrid vehicles using methanol (M85) produced from natural gas are listed in Table 38.

Table 38. Fuel chain GHG emissions of ICE-hybrid vehicles using methanol (M85) produced from natural gas.

Hybrid, M85		
GHG TOTAL (g CO_2(eq)/km))		
A.	Methanol fuel production chain	g CO_2(eq)/km
A1.	Family car (5 seats, 50 kW)	18
A2.	Urban commuter (2 seats, 20 kW)	9
B.	End use in vehicles (net CO_2(eq))	g CO_2(eq)/km
B1.	Family car (5 seats, 50 kW)	126
B2.	Urban commuter (2 seats, 20 kW)	65
FUEL CHAIN GHG, TOTAL		**g CO_2(eq)/km**
1.	**Family car (5 seats, 50 kW)**	**145**
2.	**Urban commuter (2 seats, 20 kW)**	**75**

The GHG emission of the natural gas based M85 fuel production chain is about 18 g CO_2(eq)/km when used in a hybrid vehicle of family car size class. The end use produces 126 g CO_2(eq)/km (with M85 consumption of 5.2 l/100 km or 44.9 mpg), and the total GHG emissions are 145 g CO_2(eq)/km. If natural gas based M85 is used in the hybrid vehicle of urban commuter size class (2 seats, 20 kW, see Ch. 3.3), the total GHG emissions are reduced to 75 g CO_2(eq)/km. These fuel chain GHG emissions are 77 and 40%, respectively, of the fuel chain emissions of the reference case (RFG in ICE-SI Family car, Ch. 3.4.1).

For diesel ICE-hybrid vehicles using neat methanol (M100) produced from natural gas, the total fuel chain greenhouse gas emissions are 115 and 65 g/km for the family car and the urban commuter, respectively. These fuel chain GHG emissions are 61 and 34%, respectively, of the fuel chain emissions of the reference case (RFG in ICE-SI Family car, Ch. 3.4.1) and about 103–104% of the fuel chain emissions of ICE-hybrid vehicles using conventional city-diesel fuel.

3.4.5 CASE 5: Methanol use in ICE vehicles (reference case)

3.4.5.1 Biomass

1) The Finnish case

The total fuel chain greenhouse gas emissions of ICE-SI vehicles using methanol (M85) produced from forest residues in Finland are listed in Table 39.

Table 39. Fuel chain GHG emissions of ICE-SI vehicles using methanol (M85) produced from biomass (Finland).

ICE-SI, M85 (medium size class)		
GHG TOTAL (g CO_2(eq)/km))		
A.	Methanol fuel production chain	g CO_2(eq)/km
A1.	Family car (5 seats, 50 kW)	10
A2.	Urban commuter (2 seats, 20 kW)	5
B.	End use in vehicles (net CO_2(eq))	g CO_2(eq)/km
B1.	Family car (5 seats, 50 kW)	55
B2.	Urban commuter (2 seats, 20 kW)	28
FUEL CHAIN GHG, TOTAL		**g CO_2(eq)/km**
1.	**Family car (5 seats, 50 kW)**	**65**
2.	**Urban commuter (2 seats, 20 kW)**	**33**

The GHG emissions of the biomass-based M85 fuel production are about 10 g CO_2(eq)/km when used in ICE-SI vehicle of family car size class. The end use produces 55 g CO_2(eq)/km (with M85 consumption of 7.1 l/100 km or 33.3 mpg), and the total GHG emissions are 65 g CO_2(eq)/km. If biomass-based M85 is used in the ICE-SI vehicle of urban commuter size class (2 seats, 20 kW, see Ch. 3.3), the total GHG emissions are reduced to 33 g CO_2(eq)/km. These fuel chain GHG emissions are 35 and 18 per cent, respectively, of the fuel chain emissions of reference case (RFG in ICE-SI Family car, Ch. 3.4.1).

For ICE-CI (diesel) vehicles using neat methanol (M100) produced from biomass the total fuel chain greenhouse gas emissions are listed in Table 40.

Table 40. Fuel chain GHG emissions of ICE-CI (diesel) vehicles using neat methanol (M100) produced from biomass (Finland).

ICE-CI, M100 in diesel vehicles		
GHG TOTAL (g CO_2(eq)/km))		
A.	Methanol fuel production chain	g CO_2(eq)/km
A1.	Family car (5 seats, 50 kW)	6
A2.	Urban commuter (2 seats, 20 kW)	3
B.	End use in vehicles (net CO_2(eq))	g CO_2(eq)/km
B1.	Family car (5 seats, 50 kW)	4
B2.	Urban commuter (2 seats, 20 kW)	2
FUEL CHAIN GHG, TOTAL		**g CO_2(eq)/km**
1.	**Family car (5 seats, 50 kW)**	**10**
2.	**Urban commuter (2 seats, 20 kW)**	**5**

The GHG emissions of biomass-based M100 fuel production are about 6 g CO_2(eq)/km when used in the ICE-CI (diesel) vehicle of family car size class. The end use produces 4 g CO_2(eq)/km (with M100 consumption of 5.1 l/100 km), and the total GHG emissions are 10 g CO_2(eq)/km. If the biomass-based M100 is used in the ICE-CI vehicle of urban commuter size class (2 seats, 20 kW, see Ch. 3.3), the total GHG emissions are reduced to 5 g CO_2(eq)/km. These fuel chain GHG emissions are only 5 and 3%, respectively, of the fuel chain emissions of reference case (RFG in ICE-SI Family car, Ch. 3.4.1) and about 7% of the fuel chain emissions of ICE-CI vehicles using conventional city-diesel fuel.

2) The Far East case

The full fuel chain greenhouse gas emissions of ICE-SI vehicles using methanol (M85) produced from biomass (eucalyptus) in the Far East are listed in Table 41.

It can be seen from Tables 39 and 41 that the total fuel chain GHG emissions for ICE-SI vehicles using M85 are increased by 2–4 g/km due to the eucalyptus fertilising and sea transportation of methanol compared to the Finnish case. The fuel chain GHG emissions are 37 and 18%, for the family car and the urban commuter, respectively, of the fuel chain emissions of the reference case (RFG in ICE-SI family car, Ch. 3.4.1).

For the ICE-CI (diesel) vehicles using neat methanol (M100) produced from biomass (eucalyptus) in the Far East the total fuel chain greenhouse gas emissions are given in Table 42.

Table 41. Fuel chain GHG emissions of ICE-SI vehicles using methanol (M85) produced from biomass (the Far East).

ICE-SI, M85 (medium size class)		
GHG TOTAL (g CO_2(eq)/km))		
A.	Methanol fuel production chain	g CO_2(eq)/km
A1.	Family car (5 seats, 50 kW)	13
A2.	Urban commuter (2 seats, 20 kW)	7
B.	End use in vehicles (net CO_2(eq))	g CO_2(eq)/km
B1.	Family car (5 seats, 50 kW)	55
B2.	Urban commuter (2 seats, 20 kW)	28
FUEL CHAIN GHG, TOTAL		**g CO_2(eq)/km**
1.	**Family car (5 seats, 50 kW)**	**69**
2.	**Urban commuter (2 seats, 20 kW)**	**35**

Table 42. Fuel chain GHG emissions of ICE-CI (diesel) vehicles using neat methanol (M100) produced from biomass (the Far East).

ICE-CI, M100 in diesel vehicles		
GHG TOTAL (g CO_2(eq)/km))		
A.	Methanol fuel production chain	g CO_2(eq)/km
A1.	Family car (5 seats, 50 kW)	9
A2.	Urban commuter (2 seats, 20 kW)	5
B.	End use in vehicles (net CO_2(eq))	g CO_2(eq)/km
B1.	Family car (5 seats, 50 kW)	4
B2.	Urban commuter (2 seats, 20 kW)	2
FUEL CHAIN GHG, TOTAL		**g CO_2(eq)/km**
1.	**Family car (5 seats, 50 kW)**	**13**
2.	**Urban commuter (2 seats, 20 kW)**	**7**

It can be seen from Tables 40 and 42, that the total fuel chain GHG emissions for diesel vehicles using M100 are increased by 2–3 g/km due to eucalyptus fertilising and sea transportation of methanol compared to the Finnish case. The fuel chain GHG emissions are 7 and 4% for the family car and the urban commuter, respectively, of the fuel chain emissions of the reference case (RFG in ICE-SI Family car, Ch. 3.4.1), and about 10% of the fuel chain emissions of the ICE-CI Family car using conventional city-diesel fuel.

3.4.5.2 Natural gas

The total fuel chain greenhouse gas emissions of ICE vehicles using methanol (M85) produced from natural gas are listed in Table 43.

Table 43. Fuel chain GHG emissions of ICE vehicles using methanol (M85) produced from natural gas.

ICE-SI, M85 (medium size class)		
GHG TOTAL (g CO_2(eq)/km))		
A.	Methanol fuel production chain	g CO_2(eq)/km
A1.	Family car (5 seats, 50 kW)	25
A2.	Urban commuter (2 seats, 20 kW)	13
B.	End use in vehicles (net CO_2(eq))	g CO_2(eq)/km
B1.	Family car (5 seats, 50 kW)	170
B2.	Urban commuter (2 seats, 20 kW)	86
FUEL CHAIN GHG, TOTAL		**g CO_2(eq)/km**
1.	**Family car (5 seats, 50 kW)**	**195**
2.	**Urban commuter (2 seats, 20 kW)**	**98**

The GHG emissions of natural gas based M85 fuel production amount to about 25 g CO_2(eq)/km when used in an ICE-SI vehicle of family car size class. The end use produces 170 g CO_2(eq)/km (with M85 consumption of 7.1 l/100 km or 33.3 mpg), and the total GHG emissions are 195 g CO_2(eq)/km. If natural gas based M85 is used in the ICE-SI vehicle of urban commuter size class (2 seats, 20 kW, see Ch. 3.3), the total GHG emissions are reduced to 98 g CO_2(eq)/km. These fuel chain GHG emissions are 104 and 52%, respectively, of the fuel chain emissions of reference case (RFG in ICE-SI Family car, Ch. 3.4.1), i.e., the total fuel chain emissions are increased by 4% compared to the RFG use.

For ICE-CI (diesel) vehicles using neat methanol (M100) produced from natural gas in the Far East the total estimated fuel chain greenhouse gas emissions are in Table 44.

Table 44. Fuel chain GHG emissions of ICE-CI (diesel) vehicles using neat methanol (M100) produced from natural gas.

ICE-CI, M100 in diesel vehicles		
GHG TOTAL (g CO_2(eq)/km))		
A.	Methanol fuel production chain	g CO_2(eq)/km
A1.	Family car (5 seats, 50 kW)	16
A2.	Urban commuter (2 seats, 20 kW)	9
B.	End use in vehicles (net CO2(eq))	g CO_2(eq)/km
B1.	Family car (5 seats, 50 kW)	119
B2.	Urban commuter (2 seats, 20 kW)	66
FUEL CHAIN GHG, TOTAL		**g CO_2(eq)/km**
1.	**Family car (5 seats, 50 kW)**	**135**
2.	**Urban commuter (2 seats, 20 kW)**	**75**

The GHG emissions of natural gas based M100 fuel production are about 16 g CO_2(eq)/km when used in the ICE-CI (diesel) vehicle of family car size class. The end use produces 119 g CO_2(eq)/km (with M100 consumption of 5.1 l/100 km), and the total GHG emissions are 135 g CO_2(eq)/km. If natural gas based M100 is used in the ICE-CI vehicle of urban commuter size class (2 seats, 20 kW, see Ch. 3.3), the total GHG emissions are reduced to 75 g CO_2(eq)/km. These fuel chain GHG emissions are 72 and 40%, respectively, of the fuel chain emissions of the reference case (RFG in ICE-SI Family car, Ch. 3.4.1) and about 104% of the fuel chain emissions of ICE-CI vehicles using conventional city-diesel fuel. The total fuel chain emissions are increased by 4% compared to the city-diesel use.

3.4.6 CASE 6: Electrical vehicles (electricity produced from biomass vs. average production)

The fuel chain carbon dioxide emissions of electrical vehicles (EV) using average electricity produced in Finland (case A) and average electricity produced in Europe (EU, rough estimate, case B) are presented in Table 45. In addition to CO_2, methane and

Table 45. Fuel chain CO_2 emissions of electrical vehicles (EV) using average electricity produced in Finland (case A) and average electricity produced in Europe (EU, rough estimate) (case B).

NiMH battery EV (e.comm)			
CO_2 TOTAL (g CO_2km))			
A.	Electric power production		
A1.	Finland's average power mix		
A1a.	Family car (5 seats, 50 kW)	58	g CO_2(eq)/km
A1b.	Urban commuter (2 seats, 20 kW)	38	g CO_2(eq)/km
A2.	Europe's average power mix		
A2a.	Family car (5 seats, 50 kW)	77	g CO_2/km
A2b.	Urban commuter (2 seats, 20 kW)	51	g CO_2/km
B.	End use in vehicles		
B1.	Family car (5 seats, 50 kW)	0	g CO2(eq)/km
B2.	Urban commuter (2 seats, 20 kW)	0	g CO_2(eq)/km
FUEL CHAIN CO_2, TOTAL (g CO_2/km)			
A.	**FINLAND**		
1.	**Family car (5 seats, 50 kW)**	**58**	**g CO_2(eq)/km**
2.	**Urban commuter (2 seats, 20 kW)**	**38**	**g CO_2(eq)/km**
B.	**EUROPE**		
1.	**Family car (5 seats, 50 kW)**	**77**	**g CO2/km**
2.	**Urban commuter (2 seats, 20 kW)**	**51**	**g CO2/km**

nitrous oxide emissions from electricity production should be calculated to the total GHG emissions. For Europe, emission data for the other gases for average electricity production were not available. As CO_2 causes most the emissions from energy production, this does not affect the estimates much. For production and transportation of primary fuels for average electricity production in Finland and in Europe, a rough average estimate of 4 kg CO_2(eq)/GJ fuel and an efficiency of 30% (3.3 GJ fuel/GJ electricity) were used. The emissions from electricity production in power plants in Finland are about 250 g CO_2(eq)/kWh (69 kg CO_2(eq)/GJ), which includes emissions of N_2O and CH_4.

When electricity is produced from biomass, no net carbon dioxide emissions are emitted. Only the greenhouse gas emissions from biomass fuel production, and other greenhouse gases (CH_4 and N_2O) from electricity production need to be considered. In this case, the other greenhouse gases than CO_2 from electricity production were not evaluated. However, the amount of non-CO_2 GHGs is rather small. In Table 46, the fuel chain GHG emissions of electrical vehicles using electricity produced from biomass in Finland are presented.

Table 46. Fuel chain CO_2 emissions of electrical vehicles (EV) using electricity produced from biomass in Finland.

NiMH battery EV (e.comm)			
CO_2 TOTAL (g CO_2/km)			
A.	Electric power production		
A1a.	Family car (5 seats, 50 kW)	5	g CO_2/km
A1b.	Urban commuter (2 seats, 20 kW)	3	g CO_2/km
B.	End use in vehicles		
B1.	Family car (5 seats, 50 kW)	0	g CO_2(eq)/km
B2.	Urban commuter (2 seats, 20 kW)	0	g CO_2(eq)/km
FUEL CHAIN CO_2, TOTAL (g CO_2/km)			
1.	**Family car (5 seats, 50 kW)**	**5**	**g CO_2/km**
2.	**Urban commuter (2 seats, 20 kW)**	**3**	**g CO_2/km**

The CO_2 emissions of average electricity production in Finland are about 58g CO_2/km for an electrical vehicle of family car size class (see Table 45). The end use does not produce any GHG emissions, so the total CO_2 emissions are 58 g CO_2/km. For average electricity production in EU the emissions would be somewhat greater (77 g CO_2/km, see Table 45). If an electrical vehicle of urban commuter size class (2 seats, 20 kW, see Ch. 3.3) is considered, the total CO_2 emissions are reduced to 38 and 51 g CO_2/km for Finland and EU, respectively. These CO_2 emissions are 20–31 and 27–41% for Finland and EU, respectively, of the fuel chain emissions of the reference case (RFG in ICE-SI Family car, Ch. 3.4.1).

If the electricity were produced using only biomass, the fuel chain GHG emissions would be reduced to 3–5 g/km (see Table 46). This is only 2–3% of the fuel chain emissions of the reference case (RFG in ICE-SI Family car, Ch. 3.4.1).

3.4.7 CASE 7: Hydrogen use in fuel cell vehicles

The use of hydrogen produced from biomass was also studied, but the results are not as thorough as for the other cases due to uncertain/lacking data (e.g., local delivery of hydrogen), and priorities set in the project.

In Table 47, the estimated CO_2 emissions of different hydrogen production chains are listed. The end use in fuel cell vehicle does not produce any GHG emissions.

Table 47. Fuel chain CO_2 emissions of fuel cell vehicles using hydrogen.

Fuel cell, H_2		
A.	Hydrogen production & distribution	
A1.	Hydrogen production with average power mix	g CO_2/km
	Family car (5 seats, 50 kW)	97
	Urban commuter (2 seats, 20 kW)	53
A2.	hydrogen production with biomass-based electricity	
	Family car (5 seats, 50 kW)	16
	Urban commuter (2 seats, 20 kW)	9
A3.	H_2 prod. from natural gas	g CO_2/km
	Family car (5 seats, 50 kW)	21
	Urban commuter (2 seats, 20 kW)	12
A4.	H_2 prod. from biomass	g CO_2/km
	Family car (5 seats, 50 kW)	9
	Urban commuter (2 seats, 20 kW)	5
B.	End use in vehicles	g CO_2(eq)/km
B1.	Family car (5 seats, 50 kW)	0
B2.	Urban commuter (2 seats, 20 kW)	0
FUEL CHAIN, TOTAL (g CO_2/km)		
A1.	Hydrogen production with average power mix	g CO_2/km
	Family car (5 seats, 50 kW)	97
	Urban commuter (2 seats, 20 kW)	53
A2.	Hydrogen production with biomass-based electricity	
	Family car (5 seats, 50 kW)	16
	Urban commuter (2 seats, 20 kW)	9
A3.	H_2 prod. from natural gas	g CO_2/km
	Family car (5 seats, 50 kW)	21
	Urban commuter (2 seats, 20 kW)	12
A4.	H_2 prod. from biomass	g CO_2/km
	Family car (5 seats, 50 kW)	9
	Urban commuter (2 seats, 20 kW)	5

When the hydrogen is produced from biomass by steam reformation (see Ch. 2.5), the fuel chain GHG emissions are 9 and 5 g/km for the family car and the urban commuter, respectively. These emissions are 3–5% of the fuel chain emissions of the reference case (RFG in ICE-SI Family car, Ch. 3.4.1).

If the hydrogen were produced by electrolysis with average electricity in Finland, the fuel chain CO_2 emissions would be 97 and 53 g/km for the family car and the urban commuter, respectively. These emissions are 28–52% of the fuel chain emissions of reference case (RFG in ICE-SI Family car, Ch. 3.4.1).

3.4.8 Urban buses

Also city-buses were considered in this study. The summary of GHG emissions is presented in Tables 48 and 49 and graphically in Figure 15.

GHG emissions estimates for the city-buses were not carried out for as many powertrain and fuel options as for the light-duty vehicles. The biomass-based methanol and hydrogen are the best fuels for urban buses from the GHG emissions point of view. These fuels produce only 4–8% of the GHG emissions of the reference case (urban diesel bus with reformulated diesel fuel).

Table 48. Summary table of fuel chain GHG emissions for different bus cases studied (g CO_2(eq)/km).

CO_2 (eq) emissions (g/km)	ICE-CI, urban bus, RFD/ M100	ICE-hybrid, urban bus, RFD/ M100	Fuel cell, steam reformer, urban bus, M100	Fuel cell, POX, urban bus, RFG	Fuel cell, hydrogen, urban bus, H_2
Gasoline (RFG)				1 559	
RFG; MTBE from biomass				1 537	
Diesel (RFD)	1 593	1 350			
Natural gas -based M100	1 622	1 363	1 420		
Biomass-M100, Finland	90	75	67		
Hydrogen, electrolysis, average power prod.					1 224
Hydrogen, steam ref., biomass					113

Table 49. Summary table of fuel chain GHG emissions for different bus cases studied (indexes, diesel in "conventional" ICE-CI urban bus = 100).

CO2 (eq) emissions (indexes)	ICE-CI, urban bus, RFD/ M100	ICE-hybrid, urban bus, RFD/ M100	Fuel cell, steam re-former, urban bus, M100	Fuel cell, POX, urban bus, RFG	Fuel cell, hydrogen, urban bus, H_2
Gasoline (RFG)				98	
RFG; MTBE from biomass				97	
Diesel (RFD)	100	85			
Natural gas -based M100	102	86	89		
Biomass-M100, Finland	6	5	4		
Hydrogen, electrolysis, average power prod.					77
Hydrogen, steam ref., biomass					7

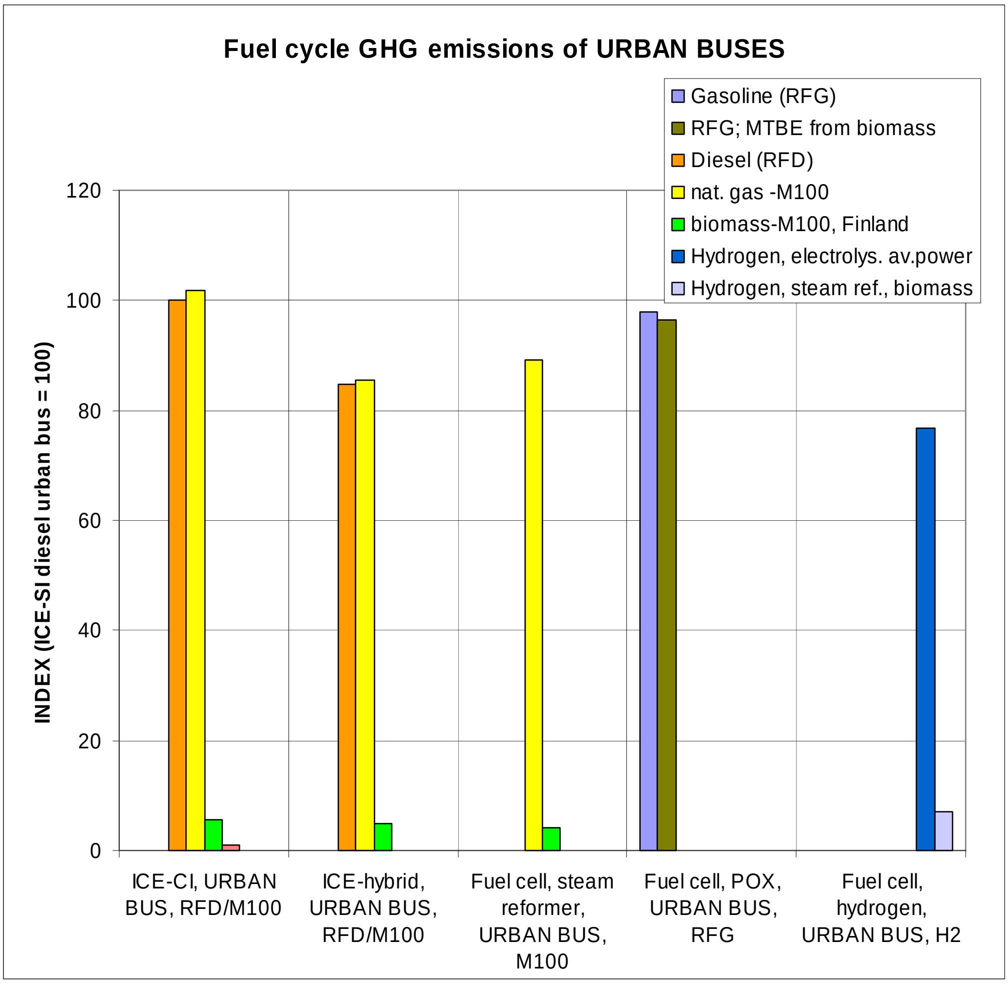

Figure 15. Fuel chain GHG emissions of urban buses (indices, urban diesel bus = 100).

3.4.9 Summary of fuel chain GHG emissions

The summary of the estimated fuel chain greenhouse gas (GHG) emissions for LDVs in the different cases studied is presented in Table 50.

In Table 51, the GHG emissions are presented as indexes in proportion to reformulated gasoline (RFG) use in conventional spark-ignited internal combustion engines (ICE-SI) of family car (medium) size class (= 100). From these results it can be seen that the use of methanol produced from natural gas in ICE-SI Family cars would increase the total fuel chain GHG emissions by approximately 4% compared to present reformulated gasoline use. In the ICE-hybrid vehicles, the use of natural gas based methanol would reduce the GHG emissions by about 23% and 60% for the family cars and urban commuters, respectively. In the fuel cell vehicles the reduction would be 38% and 66% for the family cars and urban commuters, respectively.

However, a much greater GHG reduction potential could be achieved, when the methanol is made from biomass. In the Finnish case, the use of the biomethanol fuel would reduce the total fuel chain GHG emissions by 65% and 82% for the conventional ICE-SI family cars and urban commuters, respectively. Even greater emission reductions could be achieved by using the biomass-based methanol in the ICE-hybrid vehicles (74–87%) and especially, in the fuel cell vehicles, which produce only a couple per cents of the GHG emissions from gasoline use in ICE-SI Family cars.

In the case of methanol production from eucalyptus in the Far East, the emission reduction potentials are slightly (0.5–2%) decreased compared to the Finnish case. This is due to the GHG emissions of fertilisation (short rotation coppices) and long-range sea transportation of methanol from the Far East to Europe.

Electrical vehicles using the electricity from average production mix in Finland have also a significant CO_2 emission reduction potential (of the same order as biomass-based methanol in ICE-hybrid vehicles). The achievable reduction in GHG emissions for the electrical vehicles is very dependent on the way the electricity is produced, e.g., in Europe (EU) the average emissions from electricity production are approximately 50% higher than in Finland. If the electricity needed to power EVs could be produced completely from biomass, the total GHG emissions would drop near to zero (only non-CO_2 emissions from combustion and the emissions from the biomass fuel production chain, i.e., diesel use in HDVs, would then need to be considered).

Hydrogen use in the fuel cell vehicles would have nearly as a high GHG reduction potential as biomass-based methanol in fuel cell vehicles, if the hydrogen could be produced from biomass. A new infrastructure would be needed for the distribution of gaseous hydrogen (expensive). Distribution of liquid methanol is more easy, and smaller changes would be required in the present gasoline distribution infrastructure (e.g. new tanks or old ones coated to resist increased corrosion).

In diesel light-duty vehicles, the use of biomass-based methanol (M100) could have as a high reduction potential as in fuel cell vehicles, over 95% when compared to reformulated gasoline using ICE-CI vehicles. When compared to the present diesel cars, the GHG emission reduction potential of biomass-based M100 is fairly high (over 90%).

The emissions from urban commuters are considerably lower, in many cases 40–50%, than those from family cars. This is due to the lower fuel consumption of the urban commuters compared to the family cars. Increased use of such dedicated vehicles in urban conditions could therefore lead to significant reductions in greenhouse gas emissions from transportation, for all fuels considered.

The results of Table 51 for Family cars are presented graphically in Figure 16 and for urban commuters in Figure 17. In Figure 18, the total fuel chain GHG emissions from Table 50 are presented separately for fuel production (including distribution) and end use in vehicles. For the fossil fuels, 80–90% of the fuel chain GHG emissions come from the end use.

Table 50. Summary table of fuel chain GHG emissions for the different cases studied (g CO_2(eq)/km).

CO2 (eq) emissions (g/km)	ICE-SI		ICE-CI (diesel)		ICE-SI/H (hybrid)		ICE-CI/H (hybrid)		Fuel cell vehicle (with regeneration)						Elect. vehicle (EV)	
									Steam reformer		POX		Hydrogen			
	RFG/M85		RFD/M100		RFG/M85		RFD/M100		M100		RFG		H2		electricity from grid	
	FAM. CAR	URBAN COMM.	FAM. CAR	URBAN COMM.	FAM. CAR	URBAN COMM.	FAM. CAR	URBAN COMM.	FAM. CAR	URBAN COMM.	FAM. CAR	URBAN COMM.	FAM. CAR	URBAN COMM.	FAMILY CAR	URBAN COMM.
Gasoline (RFG, 10% MTBE)	**188**	94			145	74					129	88				
RFG; MTBE from biomass	185	93			143	73					127	87				
Citydiesel (RFD)			130	72			111	63								
MeOH from natural gas	195	98	135	75	145	75	115	65	117	63						
MeOH from biomass, Finland	65	33	10	5	49	25	8	5	6	3						
MeOH from biomass, Far East	69	35	13	7	51	26	11	6	8	4						
Electricity, Finland aver. *															58	38
Electricity, Europe (EU) *															77	51
Electricity, biomass															5	3
Hydrogen, electrolys. av.power *													97	53		
Hydrogen, steam ref., biomass													9	5		

* non-CO2 GHGs not included

Table 51. Summary table of fuel chain GHG emissions for the different cases studied (indexes, RFG in ICE-SI Family car = 100).

CO2 (eq) emissions (indexes)	ICE-SI		ICE-CI (diesel)		ICE-SI/H (hybrid)		ICE-CI/H (hybrid)		Fuel cell vehicle (with regeneration)						Elect. vehicle (EV)	
									Steam reformer		POX		Hydrogen			
	RFG/M85		RFD/M100		RFG/M85		RFD/M100		M100		RFG		H2		electricity from grid	
	FAM. CAR	URBAN COMM.	FAM. CAR	URBAN COMM.	FAM. CAR	URBAN COMM.	FAM. CAR	URBAN COMM.	FAM. CAR	URBAN COMM.	FAM. CAR	URBAN COMM.	FAM. CAR	URBAN COMM.	FAMILY CAR	URBAN COMM.
Gasoline (RFG, 10% MTBE)	**100**	50			77	39					69	47				
RFG; MTBE from biomass	99	49			76	39					68	46				
Citydiesel (RFD in LDVs)			69	38			59	33								
MeOH from natural gas	104	52	72	40	77	40	61	34	62	34						
MeOH from biomass, Finland	35	18	5	3	26	13	4	2	3	2						
MeOH from biomass, Far East	37	18	7	4	27	14	6	3	4	2						
Electricity, Finland aver. *															31	20
Electricity, Europe (EU) *															41	27
Electricity, biomass															3	2
Hydrogen, electrolys. av.power *													52	28		
Hydrogen, steam ref., biomass													5	3		

* non-CO2 GHGs not included

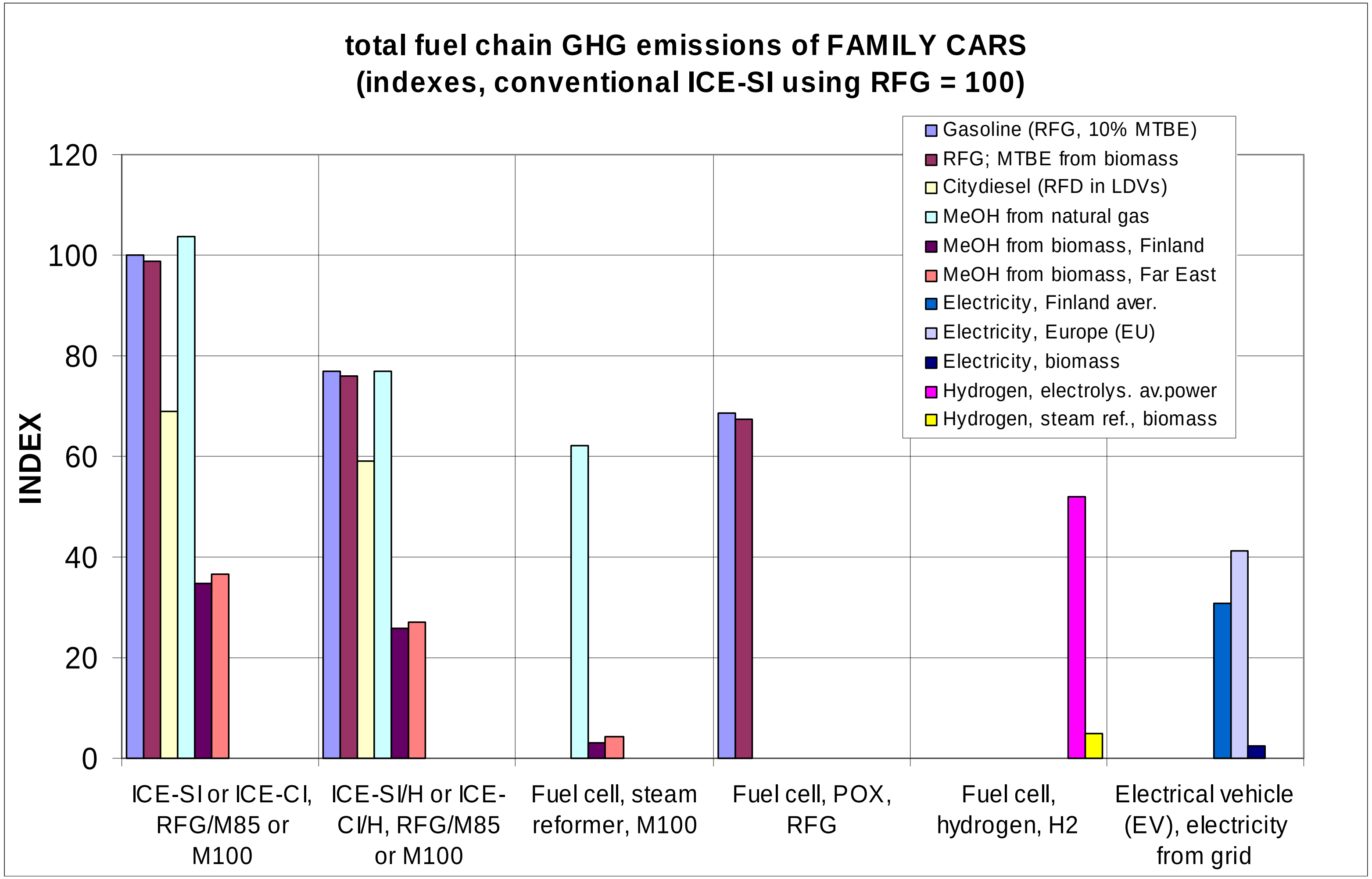

Figure 16. Full fuel chain GHG emissions of different vehicles and fuels for the family car size class (indexes, RFG in ICE-SI Family car = 100). In cases of average electricity (in Europe) and hydrogen use, only CO_2 emissions are considered.

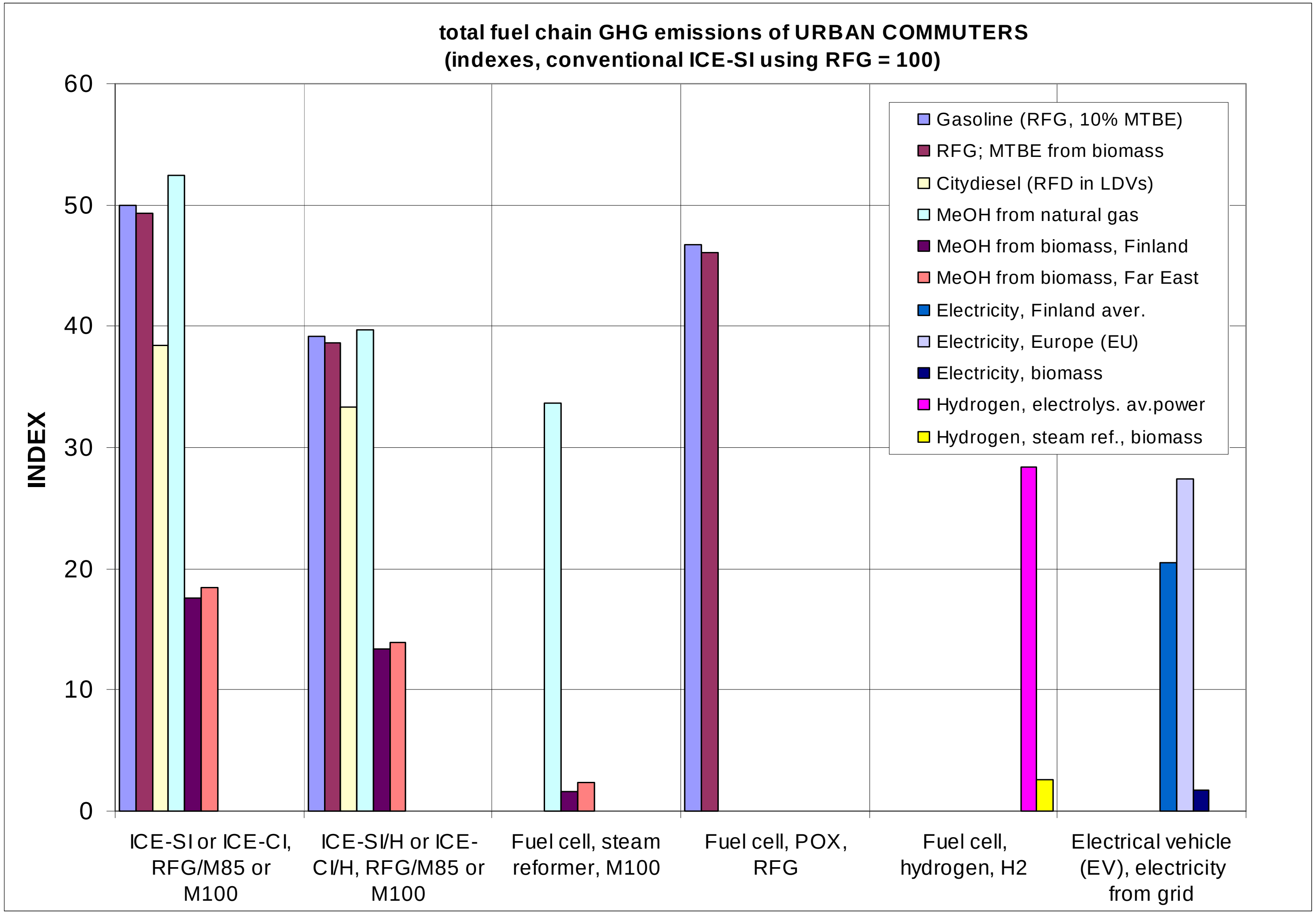

Figure 17. Full fuel chain GHG emissions of different vehicles and fuels for the urban commuter size class (indexes, RFG in CE-SI family car = 100). In cases of average electricity (in Europe) and hydrogen use, only CO_2 emissions are considered.

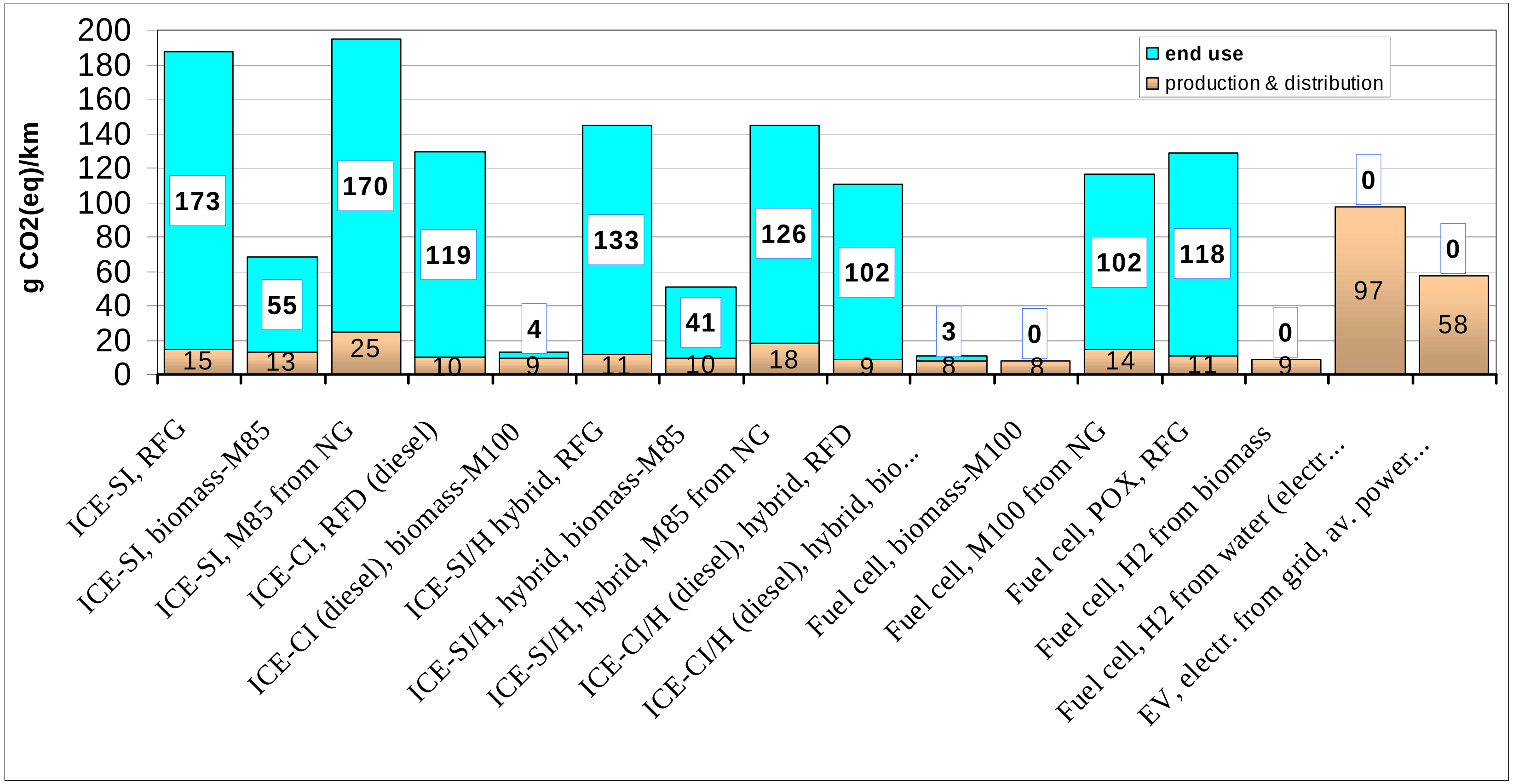

Figure 18. Full fuel chain GHG emissions of different vehicles and fuels for the family car size class divided to production & distribution and end use in the vehicle. In cases of hydrogen use, only CO_2 emissions are considered.

4. Scenarios for the use of biomethanol and hydrogen in vehicles

In the following sub-chapters estimates of the potential to produce biomass-based methanol and hydrogen using the concepts studied are given for Finland and globally. Only the use of the fuels in light-duty vehicles is considered.

For Finland, the potential was calculated from estimates of the availability of forest residue resources. Estimates of how much raw material (wood chips) would be needed to supply the whole fleet with biomass-based methanol or hydrogen are also given. The greenhouse gas emission reduction potentials are given for two cases: 1) The LDV vehicle fleet that would comprise totally family cars (the 2010 case) and 2) the LDV vehicle fleet that would comprise 75% of family cars and 25% would be urban commuters (the 2020 case). The reduction in potential greenhouse gas emissions is given for the two cases for some selected powertrains (fuel cell, hybrid and ICE-SI vehicles). The emission reduction achievable by replacing the fossil MTBE with biomass-based MTBE is also presented.

The global estimates are more uncertain. An estimate of how much biomass resources would be required if all the estimated energy used by LDVs in 2010 would be met by either biomass-based methanol or hydrogen is given. Estimates of how large land areas would be needed if all the biomass needed for the methanol or hydrogen production would come from new eucalyptus plantations are presented. Rough estimates of the achievable reductions in greenhouse gas emissions are also given.

The estimates are theoretical calculations on what could be achieved by the alternative options, if the fuels and powertrain and vehicle types would be used. Large changes in fuels and vehicle types are not expected by 2010, because of the time lag in vehicle fleet renewal. In chapter 4.2 estimates of the production costs of the biomass-based fuels are given and the impact of the costs discussed.

4.1 Biomethanol use vs. biomass potentials

4.1.1 Finland

M100/M85

In 1998 the total motor gasoline consumption in Finland was 80 PJ/a and the number of light-duty vehicles was almost 2 million. About 90% of the vehicles were gasoline (ICE-SI) vehicles, so there were about 1.8 million ICE-SI vehicles. The consumption with 15 000 km/vehicle per year would yield 2.95 MJ/km. It is estimated that there will be about 2.5 million light-duty vehicles in Finland in 2010. 90% are assumed to be gasoline vehicles and 10% diesel vehicles, if no alternative fuels are introduced before that. The total motor gasoline consumption would increase only to 82 PJ/a due to estimated increased fuel efficiency (2.18 MJ/km, ICE-SI Family car with RFG (see Ch. 3.3)).

If all 2.5 million vehicles would be fuel cell vehicles of family car size class (theoretical calculation), the total fuel consumption would be 54 PJ/a (1.44 MJ/km, see Ch. 3.3). With biomass-based methanol this would mean 94 PJ/a of wood chips energy (methanol yield 57.7% (LHV), see Table 3). The methanol production would require 11 Mt wood chips, which is about 29 Mm^3 (solid meters) wood chips per year. The technically available forest residue potential is, however, estimated to be only 8.6 Mm^3/a (to date, Hakkila *et al*. 1998). The total amount of forest residues in Finland is estimated to be about 30 Mm^3/a (solid meters, Hakkila *et al*. 1998). All forest residues cannot, however, be collected because it would harm the nutrient balance in forests, and even more simply, because of the economics (a maximum of 150 km transportation distance is economically feasible).

Energy use of wood chips made from forest residues in Finland was 0.5 Mm^3/a in 1998 (less than 0.1 Mtoe). In the Finnish “Action plan for renewable energy sources”, the target is to increase this use to 5 Mm^3/a (0.9 Mtoe/a) in 2010 (Ministry of Trade and Industry 1999). The technically available forest residue potential in 2010 and beyond is estimated to be 10 Mm^3/a. This means, that approximately 5 Mm^3/a (16 PJ/a) forest residues could be available for methanol production and vehicle use. This is only one sixth of the theoretical amount that a 100% fuel cell vehicle fleet would need. The conclusion is that in 2010 maximally 17% of the total vehicle fleet (0.425 million out of 2.5 million) could be fuel cell vehicles using biomass-based methanol that is produced in Finland. To produce this methanol (9 PJ/a), six (5.5) methanol plants (100 MW each) would be needed. In Finland, there are about 20 kraft pulp mills, and so it would be possible to add a methanol production plant to six of them at appropriate distances from each other (optimising fuel supply potential and costs).

The total primary energy consumption by transport in Finland was 175 PJ in 1998, which means that about 5% (9 PJ/a) of energy needed in transportation could be produced from biomass-based methanol by using it in fuel cell vehicles of family car size class.

In Table 52, the GHG emission reductions from the use of this amount of biomass-based methanol (9 PJ/a, 5.5 MeOH plants, 100 MW each) in different cases and vehicle type fleets are presented. If all the methanol would be used for fuel cell vehicles of family car size class, the total GHG emission reduction would be 1.2 Mt CO_2(eq)/a. If all these fuel cell vehicles would be urban commuters (city-cars with 2 seats, see Ch. 3.3), the total GHG emission reduction is 2.2 Mt CO_2(eq)/a (theoretical maximum).

Table 52. Theoretical fuel chain GHG emission reductions for different vehicle fleets (whole fleet is the same vehicle type) using biomass-based methanol (M100 or M85).

by 2010	2.5	Mill. LDVs (ALL FAMILY CARS)		
by 2020	2.5	Mill. LDVs (not increasing over 2.5 million)		
from which				
	75%	Family cars		
	25%	Urban commuters		
Theoretical	**100%**	Urban commuters		
by 2010:	**fuel cell**	**hybrid**	**ICE-SI**	
1 MeOH plant:				
MeOH (M85/M100)	3.1	3.7	2.8	% of total number of vehicles
MeOH (M85/M100) (9 PJ/a, 5.5 plants)	17.0	20.5	15.2	% of total number of vehicles
CO_2(eq) reduction potential, biomass-MeOH	16.5	15.2	9.9	% of GHGs from ICE-SI using RFG in 2010
Reduction potential, MeOH from biomass	**1.2**	**1.1**	**0.7**	**Mt CO_2(eq)/a**
by 2020:	**fuel cell**	**hybrid**	**ICE-SI**	
1 MeOH plant:				
MeOH (M85/M100)	3.6	4.4	3.3	% of total number of vehicles
MeOH (M85/M100) (9 PJ/a, 5.5 plants)	19.8	24.3	18.2	% of total number of vehicles
CO_2(eq) reduction potential, biomass-MeOH	19.3	18.6	12.5	% of GHGs from ICE-SI using RFG in 2010
Reduction potential, MeOH from biomass	**1.4**	**1.3**	**0.9**	**Mt CO_2(eq)/a**
Theoretical (all urban commuters):	**fuel cell**	**hybrid**	**ICE-SI**	
1 MeOH plant:	5.7	7.2	5.5	% of total number of vehicles
9 PJ MeOH/a, 5.5 plants	31.3	39.7	30.1	% of total number of vehicles
CO_2(eq) reduction potential, biomass-MeOH	30.8	34.4	24.8	% of GHGs from ICE-SI using RFG in 2010
Reduction potential, MeOH from biomass	**2.2**	**2.4**	**1.7**	**Mt CO_2(eq)/a**

The theoretical maximum GHG emission reduction potential would be somewhat higher (2.4 Mt CO_2(eq)/a compared to 2.2 Mt CO_2(eq)/a for Urban fuel cell commuters) if the methanol (9 PJ/a) were used for M85 in hybrid vehicles of urban commuter size class (see Table 52). This is due to the limited forest residue potential. The methanol-gasoline blends would suffice for a higher number of vehicles than M100 (in fuel cells). However, the situation in 2010 (all hybrid vehicles of family car size class) would lead to a slightly smaller reduction potential of 1.1 Mt CO_2(eq)/a (compared to 1.2 Mt CO_2(eq)/a for fuel cell vehicles).

If the forest residue potential was unlimited, biomethanol use in fuel cell vehicles could reduce Finnish GHG emissions by 6.8 Mt CO_2(eq)/a out of a total of 7.0 Mt CO_2(eq)/a (RFG in ICE-SI) in 2010 (97% for family cars, see Table 51). This would increase the number of methanol plants needed to 33.

MTBE

Another option would be to use the forest residues available to make all the methanol needed for MTBE (10% MTBE in RFG) production from biomass and use it in conventional ICE-SI Family car. Only one methanol plant would then be needed (see Table 53), and the GHG emission reduction potential would be only 0.1 Mt CO_2(eq)/a compared to conventional RFG (natural gas based methanol in MTBE) use in 2010. This reduction is only approximately one tenth of what could be achieved by methanol use in fuel cell or hybrid RFG vehicles (family cars).

Table 53. The methanol production of one plant for MTBE use. The MTBE suffices for the gasoline consumption of 1.2–3 times the whole fleet (2.5 million).

MTBE production, 1 MeOH plant				
	if all vehicles would be of this type (theoretical maximum)			
	fuel cell RFG	**hybrid RFG**	**ICE-SI RFG**	
MeOH production	83 440	83 440	83 440	t MeOH/a
MTBE production	231 778	231 778	231 778	t MTBE
RFG production.	2 317 778	2 317 778	2 317 778	t RFG/a
Energy available	99 896	99 896	99 896	TJ/a
Family car	1.60	1.68	2.18	MJ/km
Urban commuter	1.09	0.85	1.09	MJ/km
Family car	62 378	59 566	45 926	Mkm/a
Urban commuter	91 377	117 062	91 851	Mkm/a
Average driving distance/vehicle	15 000	15 000	15 000	km/vehicle, a
Family car	4 158 564	3 971 040	3 061 705	vehicles
Urban commuter	6 091 771	7 804 153	6 123 409	vehicles
Family car	**166**	**159**	**122**	% of total number of vehicles
Urban commuter	**244**	**312**	**245**	% of total number of vehicles

Hydrogen

If the 2.5 million cars in Finland (in 2010) would be fuel cell vehicles of family car size class (again, theoretical calculation), the total fuel consumption would be 54 PJ/a (1.44 MJ/km, see Ch. 3.3) as mentioned before. With biomass-based hydrogen this would mean 78 PJ/a of wood chip energy (hydrogen yield 70% (LHV), see Table 6) and further, 9 Mt wood chips, which is about 24 Mm^3 (solid meters) wood chips per year.

Again, the technically available forest residue amount is less and would suffice only for maximally one fifth of the amount that the theoretical 100% fuel cell vehicle fleet would need. The conclusion is that in 2010 maximally 20% of the total vehicle fleet (0.5 million out of 2.5 million) could be fuel cell vehicles using biomass-based hydrogen that is produced in Finland. To produce this hydrogen (10.8 PJ/a), six (5.4) hydrogen plants (100 MW each) would be needed. In Finland, as discussed earlier, there are about 20 kraft pulp mills and so it would be possible to add hydrogen production plants to six of them with appropriate distances from each other (optimising fuel supply potential and costs).

The total primary energy consumption by transport in Finland was 175 PJ in 1998, i.e. about 6% (10.8 PJ/a) of energy needed in transportation could be produced from biomass-based hydrogen by using it in fuel cell vehicles of family car size class.

In Table 54, the GHG emission reductions from the use of this amount of biomass-based hydrogen (10.8 PJ/a) in different cases and vehicle type fleets are presented. If all 10.8 PJ MeOH/a would be used for fuel cell vehicles of Family car size class the total GHG emission reduction would be 1.4 Mt CO_2(eq)/a. If all fuel cell vehicles would be Urban commuters (city-car of 2 seats, see Ch. 3.3), the total GHG emission reduction is 2.6 Mt CO_2(eq)/a (theoretical maximum).

Unlimited forest residue potential would give a GHG emission reduction of 6.6 Mt CO_2(eq)/a out of a total of 7.0 Mt CO_2(eq)/a (RFG in ICE-SI) in 2010 (94% for Family cars, see Table 51). This would increase the number of hydrogen plants needed to 27.

The examinations above show that the potential for methanol or hydrogen production from forest residues is limited in the near future in Finland. The sustainable stem wood production in Finland is used mainly by the pulp and paper industry including energy production. The expected growth of the pulp and paper industry, and new harvesting techniques for forest residues, may increase the technical and economic availability of the forest residues. There are, however, also other competing uses for this raw material. Energy production (electricity and heat) from this biomass resource is currently seen as more promising and economic than methanol or hydrogen production.

Table 54. Theoretical fuel chain GHG emission reductions for fuel cell vehicle fleet (whole fleet is the same vehicle type) using hydrogen.

By 2010	2.5	Mill. LDVs (FAMILY CARS)
By 2020	2.5	Mill. LDVs
from which		
75%	2	Mill. family cars
25%	0.5	Mill. urban commuters
Theoretical	2.5	Mill. urban commuters
By 2010:	**Fuel cell**	
1 hydrogen plant	3.7	% of total number of vehicles
11 PJ hydrogen/a, 5.5 plants	20.4	% of total number of vehicles
CO_2(eq) reduction potential, biomass-H_2	19.3	% of GHGs from ICE-SI using RFG in 2010
Reduction potential, H_2 from biomass	**1.4**	**Mt CO_2(eq)/a**
By 2020:	**Fuel cell**	
1 hydrogen plant	4.3	% of total number of vehicles
11 PJ hydrogen/a, 5.5 plants	23.8	% of total number of vehicles
CO_2(eq) reduction potential, biomass-H_2	23.2	% of GHGs from ICE-SI using RFG in 2010
Reduction potential, H_2 from biomass	**1.6**	**Mt CO_2(eq)/a**
Theoretical (all urban commuters):	**Fuel cell**	
1 hydrogen plant	6.8	% of total number of vehicles
11 PJ hydrogen/a, 5.5 plants	37.6	% of total number of vehicles
CO_2(eq) reduction potential, biomass-H_2	36.5	% of GHGs from ICE-SI using RFG in 2010
Reduction potential, H_2 from biomass	**2.6**	**Mt CO_2(eq)/a**

Therefore, due to the limited forest residue potential, the best option to reduce GHG emissions by biomass-based transportation fuels seems to be hydrogen or methanol use in urban fuel cell commuters (2 seats, 20 kW). This would also lead up to better air quality in urban areas.

4.1.2 Global

Globally the transportation sector (international bunkers excluded) consumed slightly over 69 EJ, or more than 20% of the primary energy in 1997. The growth in the energy consumption in the transportation sector has been fast, and this growth is expected to continue. Road transportation is a major energy consumer in transportation sector, it is estimated to account for more than 70% of transport energy use, light-duty vehicles alone comprise about 50%. Assuming a growth of about 15% in energy consumption of road transportation by 2010, the total energy use would be around 58 EJ for road transportation and around 40 EJ for light-duty vehicles.

The global potential of biomass availability for methanol or hydrogen production is more difficult to estimate. The Finnish forest resources, annual growth of forest and fellings, and forest residue availability, are well-known, whereas global similar estimates are much more uncertain.

International statistics on forest resources are collected and published by the Food and Agricultural Organisation of the United Nations FAO (Finnish Statistical Yearbook on Forestry 1999). The last global assessment of forest resources was published in 1995 (1990 resources). Some preliminary information is available on 1998 resources in industrialised countries (only boreal and temperate forests). In 1990, about one fourth of the global land area was estimated to be forest land. The volume of growing stock was estimated to be about 380 000 Mm^3 (incl. bark). The largest forest resources are in Latin America and the Caribbean (appr. 110 000 Mm^3) and Russia (appr. 80 000 Mm^3). The forest resources in North America, Asia and Africa are also significant (more than 50 000 Mm^3/area), while in Europe forest resources are less than 20 000 Mm^3 and in Oceania only about half of this.

The global figures on annual growth of the forests and fellings are not known. IPCC (2000a) has estimated that the net terrestrial uptake of carbon has been approximately 700 mill. t CO_2(eq) during the 1980s and more than 2 500 mill. t CO_2(eq) in the 1990s. The estimates are, however, very uncertain.

The above estimates on global forest resources and the annual growth of terrestrial uptake indicate that the biomass resources available could cover a large part of the global energy demand. IPCC (2000b) gives an estimate of 2 700 EJ for annual bioenergy potential, of which however only 270 EJ could currently be available on a sustainable basis. This figure is almost the same (266.9 EJ) as given by Johansson *et al.* (1993) as the estimated potential supply of biomass energy by biomass plantations. The value was calculated using an average annual yield of 15 dry t/ha, a value typical of high-yield plantations.

To support the future growth in bioenergy use, additional land for biomass plantations would be needed. However, the need for new agricultural land limits the extent, to which this option can be utilised. Leach and Johnson (1999) have made estimates on bioenergy potentials based on FAO estimates of potentially cultivable land. Land requirement for food crop production is subtracted, assuming that the need in 2025 will be 1.5 times the 1990 figure. One-tenth of remaining land was then assumed to be dedicated to energy crops with an average annual yield of 10 dry t/ha. The estimated potential for Africa is 79 mill. ha and for Latin America 89 mill. ha.

A rough estimate on the land-area needed to supply the total global light-duty vehicle fleet with methanol or hydrogen used in fuel cell vehicles in 2010 is given (theoretical calculation). Taking into account the better efficiencies of the fuel cell vehicles the fuel demand would be approximately 25 EJ methanol (FC STM) and 17 EJ hydrogen (direct FC-EV drive, no regenerative braking). Assuming the Far East concept would mean that approximately 2 500 Mill. t ds/a eucalyptus would be needed for the methanol production. About 2 800 plants would need to be built which would mean a production capacity of chemical pulp that is almost 10 times the current production. The corresponding demand for land area for the plantations would be about 250 mill. ha assuming an annual yield of 10 dry t/ha. This area would be equal to about 7 times Finland’s or Japan’s land area.

The amount of biomass needed would be less if hydrogen was produced, approximately 1 700 mill. t ds/a, corresponding to a land area of about 170 mill. ha (approximately five times the area of Finland or Japan).

The associated greenhouse gas emission reduction would be in the same order for both methanol and hydrogen, approximately 3 000 Mill. t CO_2(eq)/a (current total anthropogenic emission is about 23 000 mill. t CO_2(eq)/a).

The above calculations are theoretical, but they show that the entire fuel demand of light-duty vehicles would be difficult to meet by producing methanol or hydrogen from biomass, even if they were used in advanced vehicles. Large land areas would be needed for the production of the raw material, and there are many competing uses for it. The possibilities to integrate methanol and hydrogen production to pulp production are also limited.

In more restricted use, e.g. in urban transportation, the fuels could have potential, especially as their use in clean vehicles like the fuel cell vehicles, would have also other environmental benefits (improved air quality).

4.2 Production costs and implementation

The costs of methanol production from biomass and natural gas are compared in Table 55. Tax-free consumer prices for gasoline and diesel and an estimated value of average electricity production cost are also presented to see the order of magnitude. However, direct cost comparison cannot be made between present vehicle fuels and methanol, because the tax-free consumer prices include, e.g., distribution costs and profits for interested parties and thus are not pure production costs.

Table 55. Summary of estimated fuel production costs (present).

	EUR/GJ	FIM/MWh
Gasoline (RFG, 10% MTBE) *	9.8	210
Citydiesel (RFD) *	5.7	123
MeOH from natural gas**	4.7	ca. 100
MeOH from biomass, Finland	16.4	351
MeOH from biomass, Far East	9.6	205
Electricity, Finland average ***	7.0	150
Hydrogen, steam ref., biomass	12.3	263

* tax-free consumer price, calculated from 6.75 FIM/l for gasoline and 4.90 FIM/l for diesel (actual production costs are much lower, as these include also distribution costs and profits).

** current world market price of methanol

*** rough estimate, actual production cost is unknown (tax-free consumer prices are 0.3 – 0.4 FIM/kWh.

From Table 55, it is seen that methanol production in the Far East is clearly cheaper than in Finland due to the larger size class of production facility (5-fold, see Ch. 2). The production cost is still about two times more expensive than that of the present methanol from natural gas production. In the Finnish case, the difference is about 3.5-fold. The production costs of hydrogen from wood chips in Finland are in between the methanol production costs in the Far East and Finland. This means, that it is cheaper to produce hydrogen than methanol.

The production costs of the different vehicle types, and the fuel distribution and refuelling costs were not considered in the study.

With the production costs presented in Table 55, the rough GHG emission reduction costs were calculated (only for production costs, fuel distribution and vehicle costs were not considered, see Table 56). In the case of gasoline (RFG) it was assumed that the production cost would be 80% of the tax-free consumer price (47 FIM/GJ). The costs of reduction were obtained by comparing production costs of other fuels to this value and dividing the difference with the potential of emission reduction (from Table 51).

For biomass-based M100 produced in Finland the emission reduction is 82 kg CO_2(eq)/GJ when used in a fuel cell vehicle of family car size class. The production of this M100 fuel is about 51 FIM/GJ more expensive than RFG production (98–47 FIM/GJ). Hence, the emission reduction cost (fuel production costs only taken into account) is about 620 FIM/t CO_2(eq) (104 EUR/t CO_2(eq)), which is quite expensive. Additional costs from changes in fuel distribution equipment and vehicle production would make the option even less attractive economically.

For the Far East case, the reduction cost is reduced to about 130 FIM/t CO_2(eq) (22 EUR/t CO_2(eq)). This reduction cost is comparable with some other options considered feasible in Finland. However, the cost of methanol sea transportation and costs from changes in local distribution (plus additional production costs of fuel cell vehicles compared to conventional vehicles) would eventually enhance the reduction cost.

For biomass-based hydrogen production in Finland, the reduction cost is about 360 FIM/t CO_2(eq) (60 EUR/t CO_2(eq)). If hydrogen would be produced in the Far East (this case was not considered in this study), the greater biomass potential would allow a higher production capacity and lead to reduced costs [about 90 FIM/t CO_2(eq) or 15 EUR/t CO_2(eq)] assuming the same difference between Finland and the Far East as in the case of methanol production.

Table 56. Summary of estimated GHG reduction costs (based only on fuel production costs (present), i.e. the additional costs of fuel distribution and fuel cell vehicle production are not considered).

FC, biomass-M100, Finland		
MeOH, Finland	98	FIM/GJ
RFG	47	FIM/GJ
Cost difference	51	FIM/GJ
Reduction	82	kg/GJ
Cost of reduction	616	FIM/t CO_2(eq)
FC, biomass-M100, the Far East		
MeOH, the Far East	57	FIM/GJ
RFG	47	FIM/GJ
Cost difference	10	FIM/GJ
Reduction	82	kg/GJ
Cost of reduction	126	FIM/t CO_2(eq)
FC, biomass-H_2, Finland		
H_2, Finland	73	FIM/GJ
RFG	47	FIM/GJ
Cost difference	26	FIM/GJ
Reduction	73	kg/GJ
Cost of reduction	361	FIM/t CO_2(eq)

The implementation of the methanol or hydrogen production concepts considered in this study are technically feasible, but the high production costs are seen as an implementation barrier. To overcome this barrier in near future, either subsidies for methanol/hydrogen production or substantial environmental taxes for oil-derived fuels (or considering Finland reductions in current fuel taxes) would have to be used. For longer term, it could also be possible to reduce the production costs by improving efficiencies and raw material (forest residues) logistics.

5. Conclusions and discussion

In this study new concepts for methanol and hydrogen production from wood-based biomass are presented in order to assess the climate benefits that could be achieved from the use of these fuels in advanced vehicles, with focus on fuel cell vehicles. The process concepts chosen for a closer study integrate methanol or hydrogen production to CHP production in an existing pulp mill. The greenhouse gas emissions for the use of the biofuels in specified vehicle types were estimated and compared to corresponding emissions from the use of gasoline, diesel, methanol made from natural gas, hydrogen derived from electrolysis of water and those of electric vehicles. Estimates for the potential use of the biofuels are given based on estimated availability of biomass resources. Possibilities to integrate the production of the fuels to CHP production of a pulp mill were also assessed. Implications of the estimated production cost for the biofuels were also discussed.

The production of methanol from biomass requires a fairly advanced gasification and gas cleaning process to meet the requirements of the synthesis process. The hydrogen production process is somewhat simpler. However, the evaluation of the hydrogen production processes was based on a more shallow evaluation due to priorities set in the project. The hydrogen production process should, therefore, be studied in more detail to assess, if some additional improvements in the process could be made.

Two methanol production concepts were selected for evaluation: methanol production integrated to an existing pulp mill in Finland and in the Far East. Performance and costs of corresponding hydrogen production were estimated roughly for the Finnish case. The fast growth of wood would allow higher capacities of fuel production in the Far East than in Europe. The capacities were selected based on the availability of the raw material at a moderate price. In the Finnish case (fuel input 100 MW_{th}) the raw material was forest residues (pine) and in the Far East case (500 MW_{th}) short rotation coppices (eucalyptus). The methanol production would be 83 400 t/a in the Finnish case and 439 400 t/a in the Far East case. The production costs in the Finnish case were estimated at around 16 EUR/GJ methanol. In the Far East case the methanol production costs were lower, approximately 10 EUR/GJ methanol. Recently, the world market price of methanol has been about 4.7 EUR/GJ. The scale of the plant has a considerable effect on the fuel production costs. Currently, the largest natural gas based methanol plants have a capacity of > 800 000 t methanol/a.

By combining the fuel, power, and heat production a high total efficiency can be achieved. In this study, it was estimated that by integrating the methanol production to the power plant of the pulp mill, the total efficiency of the methanol plant would be increased to 67–69% (LHV). Employing the district heat production for utilising the low-grade waste heat would increase the total efficiency. Reductions of about 20% were estimated in the methanol production costs by using the existing equipment of the pulp mill. Further improvements in the total efficiency and consequent production cost reductions could be achieved by process optimisation (optimised gasification temperature, minimised oxygen consumption, high carbon conversion in gasification, small hydrocarbon content in gasification gas, optimised methanol synthesis).

All the energy demand of the processes is met by energy produced by biomass. No CO_2 emissions are therefore allocated to the production processes as the biomass is assumed to be of sustainable origin. The integrated production processes do, however, consume biomass resources and have a somewhat lower power output [although increased total energy (power and heat) production] than a non-integrated pulp production process would have. If these biomass resources and power were used to replace fossil energy, the climate benefits of the process would be lowered. This is, however, not considered in the study.

The greenhouse gas emissions from the use of biomass-based methanol and hydrogen were estimated for some selected powertrain and vehicle types, and compared to the use of other fuels (gasoline, methanol from natural gas, and hydrogen from electrolysis using fossil or biomass-based electricity). The total fuel chain greenhouse gas emissions (emissions from fuel production and distribution + emissions from the use in the vehicles) are significantly lower (approximately 80–90%) for the biomass-based methanol and hydrogen fuels than for the other alternatives. Only battery electric vehicles using electricity produced from biomass have emissions that are as low (see Ch. 3.4.9 for more detailed summary of different fuel chain greenhouse gas emissions). Extensive use of battery-electric vehicles using biomass electricity would, however, require even larger biomass resources, as the energy efficiency of electricity production is lower than that of methanol production.

The implementation of biomass-based methanol and hydrogen as transportation fuels has technical and economic barriers. The biomass resources are limited and the amounts of biomass needed for substituting conventional fuels with biofuels would be large. Estimates on the availability of raw material (forest residues or eucalyptus) for the concepts studied showed that the entire fuel demand of light-duty vehicles would be difficult to meet by the concepts considered, even if the fuels were used in advanced vehicles. Large land areas would be needed for the production of the raw material, and there are many competing uses for it. The possibilities to integrate methanol and hydrogen production to existing pulp mills are also limited.

The greenhouse gas emission reductions that could be achieved in Finland by methanol or hydrogen produced from forest residues, taking the limited availability of the resources into account, were estimated for the years 2010–2020. The use of these fuels was estimated to give maximally reductions of the order 10–20% compared to gasoline use in LDVs of family car type (description in Ch 3.3). The use in methanol in fuel cell or hybrid-ICE vehicles was estimated to give almost equal reductions (~15%), whereas the use in ICE-SI vehicles gave smaller reductions (~10%). The use of hydrogen in fuel cell vehicles gave a few percentage units higher emission reductions than methanol. In a vehicle fleet with a large share of urban commuter type cars (description in Ch. 3.3) using biomethanol or biohydrogen the emissions would be much smaller. Methanol from biomass could also be used for MTBE production. In Finland the whole LDV vehicle fleet could be supplied with MTBE using methanol made from forest residues. The emission reduction achieved would, however, be much less, only one tenth of what could be achieved by methanol use in fuel cell or hybrid vehicles.

The costs of producing wood-based methanol and hydrogen were, depending on the concept chosen (fuel input 100–500 MW_{th}), of the order of 2 to 4 times higher than those of gasoline or methanol made from crude oil and natural gas. Subsidies or tax incentives would be needed to introduce the wood-based fuels to the market.

The use of the biomass-based fuels in advanced and, especially, fuel cell vehicles, is promising. The fuel cell vehicles will likely be introduced to the market within a few years. The market share of these vehicles will be minor still long, partly because of the time lag in the renewal of the vehicle fleet. The availability of sustainable hydrogen and hydrogen carrier fuels is scare and could in the long run become the main obstacle for the success of the fuel cell vehicles. Sustainable hydrogen production technology based on chemical or biological processes or electrolysis utilising renewable energy, or production of hydrogen from fossil fuels combined with CO_2 recovery and disposal, are not expected to be of commercial technology until in the mid of the century, if even then. Biomass-based methanol, or hydrogen, could therefore play a role in enhancing the introduction of the fuel cell vehicles to the market before other sustainable concepts for, e.g., hydrogen production are developed. The foreseen growth in the transportation volume and decreasing oil resources could also increase the attractiveness of biomass-based methanol, or hydrogen, as transportation fuels in the future. Environmental benefits are seen especially in urban transportation, where the use of the fuels in fuel cell vehicles could also improve the local air quality substantially.

This study addresses only the greenhouse gas emissions for the chosen biomass-based methanol and hydrogen production processes and the use of the fuels in mainly light duty vehicles. The implications of system changes (distribution, storage) needed to introduce the fuels to the markets would also need to be analysed. The estimates of achievable greenhouse gas emission reductions, taking the biomass resources into account, would also need to be extended to heavy-duty vehicles. Other environmental impacts and safety aspects should also be assessed. To be able to fully assess the greenhouse impact of the introduction of the fuels and new vehicle technologies to the market, system studies on the impact on energy and industrial (vehicles) manufacturing, and also agricultural and forestry sectors, would be needed.

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Title

New concepts for biofuels in transportation

Biomass-based methanol production and reduced emissions in advanced vehicles

Abstract

New production concepts for biomass-based methanol and hydrogen for use as transportation fuels were evaluated. The fuel chain greenhouse gas emissions for these biofuels were estimated and compared with corresponding emissions for gasoline and some other fuels.

Concepts with methanol or hydrogen production integrated with pulp and paper production were studied more closely. These concepts were found to increase the total efficiency and lower the production costs compared to stand-alone plants. However, the costs were estimated still to be 2 to 4 times higher than those of fossil transportation fuels on average.

The estimation of the fuel chain emissions included emissions from production and distribution of the fuels to end use in selected vehicle types. The estimated total fuel chain greenhouse gas emissions were significantly lower (approximately 80–90%) for the biomass-based methanol and hydrogen fuels than for most of the other considered alternatives. The availability of biomass resources for the production of biomethanol or biohydrogen and the high production costs were estimated to limit the implementation of the process concepts and use of the fuels in transportation. Most promising prospects for biomass-derived methanol or hydrogen were seen as fuels for fuel cell vehicles in urban transportation.

Keywords
biomass, biofuels, wood, liquefaction, gasification, methanol, costs, emissions, greenhouse gases, engine fuels

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