MASTER

Transportation fuels from the well of the wheels

development and use of a model to analyse energy consumption and emissions in fuel chains

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Award date:
2004

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Development and use of a model to analyse energy consumption and emissions in fuel chains

Delft, February 2004

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Summary

In the twentieth century, the use of products that are based on crude oil and other fossil fuels has become an aspect of everyday life. Crude oil is used in a range of products, from plastics and cosmetics to transportation fuels. This use is not without disadvantages however. First of all, the use of fossil fuels is a burden to the environment. Carbon dioxide and greenhouse gases that are formed when fossil fuels are burned, contribute to the enhanced greenhouse effect. Second, the supplies of crude oil are finite and crude oil is recovered only in a small number of countries, which makes the world dependent on these countries. Both problems can be diminished by using sustainable fuels and more efficient powertrains. Research institutes and companies all over the world are developing such fuels and powertrains. One of them is TNO Automotive. Within the Environmental Studies & Testing group of TNO Automotive there is a need for information about the consequences of the use of fossil fuels. This study aims to fulfill this need by answering the following research questions:

- How will energy demand and energy availability develop in the first half of this century?
- What are the energy use and greenhouse gas emissions from a selected number of conventional and renewable fuels in the Well To Wheel (WTW) chain?
- What are the production costs of these fuels?

The term WTW in the second research question indicates a type of modelling in which all energies and emissions that are used in the production and use of a fuel are included in the analysis. The analysis assesses all energy flows from the point of extraction of a primary feedstock (the well) to the final use of the fuel (to drive a vehicle, that is to turn the wheels).

In order to determine the development of energy demand in the first half of the 21st century, several energy scenarios are compared. These scenarios are six energy scenarios by Global Energy Perspectives, a scenario that assumes maximum stimulation of renewables named Renewables Intensive Global Energy Scenario, and two scenarios made by Shell, Dematerialisation and Sustained Growth. It turns out that all scenarios expect primary energy use to rise. The estimations vary between 561 EJ/year and 1150 EJ/year (for comparison: in 1990 the worldwide primary energy use equaled 387 EJ/year). The scenarios are not very optimistic about the introduction of renewable fuels: by 2020 the world still heavily depends on fossil fuels. By 2050 however, a transition away from fossil fuels has begun: shares of renewable energy use range from one-quarter up to half the world's energy use.

From an investigation of the availability of reserves it turns out that there is enough oil for the coming decades. However, the reserves in Europe and North America will get exhausted, thereby increasing the dependence on a limited number of oil-producing countries in the Middle East. Besides reserves, there are also resources. Resources are quantities for which it is not yet possible to extract them in an economically and/or technically feasible way. In the case of crude oil, the numbers of resources are gigantic. If they become available, there will be plenty of oil for centuries. The analysis of the reserves of natural gas shows that these will last longer than the reserves of crude oil. Natural gas reserves are also more evenly divided over the world. With resources of natural gas larger than those of crude oil, the amount of natural gas present in the earth's crust is enough to comply with any growth rate in any scenario. In the same way there are no shortages to be expected for coal. The fourth energy carrier included in the analysis is biomass. Unlike fossil fuels, whose presence in the earth's crust diminishes by every use mankind makes of them, biomass can be regrown after it was harvested. The analysis shows that the availability of land for growing biomass and the

growth rate of the biomass are determining factors for the availability of the biomass. However, in the entire first half of this century the potential for biomass is larger than the anticipated use. Therefore no shortages are to be expected.

In order to answer the second research question, a model is developed to calculate Well to Wheel (WTW) energies and emissions. Most WTW models only report on the total energy use in a fuel chain. This model however has the unique property that is shows energy use by primary feedstock. This enables a comparison between fuel chains of, for example, the amount of crude oil used. Because some fuel chains have multiple outputs, the fuel chains can not be compared straight away. First the byproducts have to be accounted for in some way. The model contains four methods of accounting for byproducts. In the first method, byproducts are accounted for according to avoided primary energy and emissions principles. The byproducts that emerge from the production of the transportation fuel replace production of the energy carriers in their usual way. Therefore the byproducts are credited with the energy that would have been used to produce them in the usual way. In the second method, it is assumed that the byproducts are used by another powertrain in another vehicle. For example, the byproduct FT-gasoline that emerges from production of FT-diesel is used in a gasoline fuelled vehicle. The energies and emissions that are needed to produce the fuel and the byproducts are accounted for according to the number of kilometers one can drive with that output. Only the energies and emissions that are accounted to the original transportation fuel are included in the final results. The third and fourth method account energies and emissions according to the energy content of the output. Only those energies and emissions that are accounted to the energy content of the intended fuel are included in the final results. In the third method, this is done in a straightforward way. The fourth method is a variation to the third method that requires more extensive calculations but results in more precise results.

Next, the model is quantified with data. Eight fuel chains of transportation fuels are selected to be modelled. These are:
- Diesel from crude oil;
- Gasoline from crude oil;
- LPG from crude oil;
- CNG from natural gas;
- Fischer-Tropsch diesel from natural gas;
- Fischer-Tropsch diesel from cellulosic biomass;
- Ethanol from cellulosic biomass, and
- Ethanol from sugary biomass.

Besides the fuel chains of the transportation fuels themselves, also the fuel chains of the process fuels are modelled. Process fuels are energy carriers whose fuel chain does not lead to the production of a transportation fuel, but who are needed in order to correctly model the fuel chains of the transportation fuels. Examples of process fuels are coal and electricity.

After the modelling of all fuel chains of transportation fuels and process fuels is completed, the results are presented. This is done according to the four methods of accounting for byproducts that have been developed earlier. The fuel chains are compared at three aspects: total energy use/chain efficiency, fossil energy use and greenhouse gas emissions. From the comparison of total energy use it turns out that the diesel fuel chain is the most efficient. Diesel is followed by LPG, gasoline and CNG respectively. In all methods of accounting for byproducts, the ethanol from cellulosic biomass fuel chain uses the most energy. Furthermore all methods of accounting for byproducts show that it is more efficient to produce FT diesel from natural gas than it is to produce it from cellulosic biomass. In those methods of accounting for byproducts where ethanol from sugary biomass is included, this is the most efficient biomass-based fuel chain.

Besides total energy use, the use of fossil fuels is analysed. In all cases, the biomass-based fuels use the least fossil energy. In all three methods of accounting for byproducts the order is the same: FT diesel from cellulosic biomass uses the least fossil fuels of all, followed by ethanol from cellulosic biomass. Ethanol from sugary biomass uses the most fossil energy of the biomass-based fuels. Ranked from low greenhouse gas emissions to high greenhouse gas emissions, the order among the fossil fuel based fuel chains is diesel, CNG, LPG, gasoline and FT diesel.

The analysis of greenhouse gas emissions shows that these are lowest in the biomass based fuel chains. Of all biomass-based fuels, the ethanol from sugary biomass fuel chain uses the most fossil fuels and consequently emits the most emissions. This means that converting cellulosic biomass to transportation fuels creates fewer emissions than converting sugary biomass to a transportation fuel. However, whether it is better to convert cellulosic biomass to FT diesel or ethanol is not very clear. According to one method of accounting for byproducts, ethanol results in the lowest emissions. With the other methods of accounting for byproducts, conversion to ethanol results in the lowest emissions. Of the fossil fuels, respectively diesel and CNG result in the lowest emissions. In some methods of accounting for byproducts, diesel is followed by FT diesel from natural gas, LPG and gasoline. According to other methods however, FT diesel from natural gas creates the most emissions of all fuels.

Next, a sensitivity analysis is performed on the results of the model. The sensitivity analysis starts by comparing the results of this model with the results from another study performed by General Motors. This analysis shows that the General Motors study consequently estimates the conversion step in the fuel chain to be more efficient than this study does. The comparison confirms what had already become clear from the modelling of individual fuel chains: that there exist great differences in the efficiencies that are assumed in each process step and that these differences lead to different results. In the second part of the sensitivity analysis, some variations to some fuel chains are modelled. For the CNG fuel chain, some alternative compositions of natural gas and some alternative transportation distances are applied. For the biomass-based fuel chains, the locations where the biomass is grown and where it is converted into a transportation fuel are varied. The impact of these variations to the final results in the fuel chains turns out to be small. Finally the impact of variations in emissions of methane and nitrous oxide to the total greenhouse gas emissions is investigated. In all fuel chains but the ethanol from sugary biomass fuel chain, this impact turns out to be small. With the sensitivity analysis, the answer to the second research question is completed.

In order to answer the third research question, the operating costs of the transportation fuels are investigated. The investigation includes production costs and capital costs. It turns out that the operating costs per unit of distance traveled with a fuel are smallest in the diesel fuel chain, followed by the CNG fuel chain, LPG fuel chain and gasoline fuel chain respectively. Next are the operating costs of FT diesel, irrespective of the primary feedstock that is used to create the FT diesel with. The operating costs for ethanol are the highest costs of all costs. The costs for the ethanol from sugary biomass are even more than three times as high as those in the diesel fuel chain or the LPG fuel chain. However, there can be a great difference between the operating costs and the price that a consumer has to pay at the refueling station. In the Netherlands, taxes make up about 70 % of the current fuel prices. Reducing taxes or freeing some fuels from taxes can make all fuels included in this study competitive with the current Dutch fuel prices that have to be paid at the refueling station.

Finally an example is given of how the results of WTW analysis can serve as input for a range of other calculations. The number of cars on the road and the average number of kilometers driven per car are determined for the years 2002 and 2020. These data are combined with WTW data on the emissions per vehicle kilometer, which results in data on the emissions of the total Dutch vehicle fleet in the year 2002 and 2020. For a number of compositions of the Dutch vehicle fleet in the year 2020, the total greenhouse gas emissions are determined. The calculation shows that the only way to maintain emissions at the 2002-level is to introduce fuels that are based on renewable primary inputs.

Preface

Before you lies my Master thesis, the result of 10 months of research performed at TNO Automotive in Delft, the Netherlands. When I came to TNO back in May, I had some vague idea of doing something with exhaust gases of vehicles and the energies needed to produce transportation fuels. Soon these ideas where shaped and a research proposal was written. The most important part of my activities at TNO would be to compose a model to calculate WTW energies and emissions, and to analyse eight case studies to test the model with.

Building a model is one thing, finding the data to fill it with is another. There exist many, many studies and one can get easily overloaded with data. Finding exactly that one number I was looking for turned out to be a tough job. In fact, it turned out to be such a tough job that it took much more time than I had anticipated. But, finally, I pulled it off and looking back at it, it has certainly been worth the effort. The result is one I'm truly proud of.

I would also like to use this place to thank some people. First of all Richard, my supervisor at TNO. We spend quite some time together discussing data from the case studies and formulas and variables for the model. To me, this has been both constructive and enjoyable. I also want to thank my supervisors at the university, Gijs Mom and Rik Baert, for the work they have done. Next, my colleagues of the section EST at TNO, who made my stay at TNO a very pleasant one. I especially enjoyed the lunches in our "office garden". I won't name all of them here, but I do want to reserve some special place for Joep, who was sitting at the desk across my own desk, and who has always had time for a little chat if I needed to clear out my hart of if I simply needed a break. Joep, thank you. Finally I want to thank my boyfriend, Jochem, and my family and friends for the support they've given me, not only during these past months but through all the years of my study.

Margot Buijsse

Delft, February 2004.

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1 Introduction

1.1 Introduction

Ever since the Stone Age, mankind has used energy. At first, this energy was only used to prepare food and to keep oneself warm. Later on, one started using energy to build houses. The development of tools and craftsmanship further increased energy use. After the invention of the wheel, people started to use energy for transportation purposes. And so, during the ongoing development of mankind, energy use has increased. The inventions of the steam engine and of combustion spurred energy use to heights that had not been known before. In the twentieth century, too, energy use has shown a continuous growth. Not only did the use of energy increase as it had never done before, but also the origin of the energy changed. Up until the end of the middle ages, biomass had been the primary source of energy, together with wind energy and water energy. The twentieth century however became the age of fossil fuels. Coal was used first to fuel steam engines. Later on, up until now, coal is primarily used for the production of electricity. Natural gas is used to heat houses, to cook, to generate electricity and in industry. But the fossil fuel that has become the most important is crude oil. Nowadays crude oil is used to produce a range of products, from plastics and cosmetics to transportation fuels.

However, the use of crude oil and other fossil fuels is not without disadvantages. Carbon dioxide and other gases that form when fossil fuels are burned, contribute to the enhanced greenhouse effect. Other emission components adversely affect air quality and cause acid rain. Governments all over the world have come to recognise these problems and have set targets to limit emissions of carbon dioxide and other greenhouse gases. One of the main sources of carbon dioxide emissions is traffic. Therefore, the use of sustainable fuels and more efficient powertrains could make major contributions in achieving the targets set by governments.

A second problem concerning the use of fossil fuels is that the supplies are finite. Fossil fuels are being formed constantly in the earth's crust, but the rate with which this process takes place is so small that it is almost negligible. The rate with which the supplies are consumed however, is far from negligible and still increasing. Some people fear that the world will run out of supplies one day. Due to the dependency on fossil fuels in everyday life, this would seriously affect the world economy and our current (western) way of living. An important contributor in the use of fossil fuels is transportation, because today's transportation fuels are all made of fossil fuels. Using sustainable fuels and more efficient powertrains could therefore diminish the dependency on crude oil.

The above shows the favourable consequences from the use of sustainable fuels and more efficient powertrains. Therefore research institutes and companies all over the world are developing such fuels and powertrains. One of the major Dutch companies in this field is TNO Automotive. TNO Automotive carries out research, development and contract engineering on conventional and advanced powertrains. The Environmental Studies & Testing group of TNO Automotive performs environmental studies and vehicle tests to generate objective information on energy use and emissions of road vehicles. Within this group, there is a need for information about the consequences of the use of fossil fuels. This study is carried out to fulfill that need.

In the first part of this research, the availability of resources and the expected energy use in the first half of the 21st century are determined. This information is combined in order to find out whether or not there are shortages of resources to be expected. The second part of this study is dedicated to an assessment of energy use in the production and use of a number of transportation fuels and of the emissions coming forth from production and use. Analyses of this kind are called Well to Wheel (WTW) analyses. This term indicates that all energies and emissions in the fuel chain, from the point of extraction (the well) to the final use of the fuel (to make the wheels turn) are included. In order to assess the WTW energy flows and emissions, a quantitative model is developed. The model is applied to eight fuel chains of transportation fuels in this study, but has been developed in such a way that is applicable to any other fuel chain, too. The outcomes of the WTW analysis indicate which transportation fuels affect our environment the most and to what extent, and which transportation fuels are environmentally friendly and to what extent they are so. However, which transportation fuels will actually be used now and in the future, does not only depend on energy use and emissions, but also on the costs of the fuel of interest. Therefore an indication of the costs of the transportation fuels included in the model is made too.

1.2 Research objective, research question & methodology

From the description of the research given in the previous section, a research objective can be deduced. The objective is threefold:

- To assess the development of energy use and energy availability in the first half of the 21st century;
- To develop a calculation tool, based on a limited number of cases, to assess WTW energy use and greenhouse gas emissions; and
- To indicate the production costs in the total WTW chain.

The second objective is the most important though. The research objectives can be obtained by answering the following research questions:

- How will energy demand and energy availability develop in the first half of this century?
- What are the energy use and greenhouse gas emissions from a selected number of conventional and renewable fuels in the WTW chain?
- What are the production costs of these fuels?

The first research question is answered by means of study of literature. In order to determine the development of energy use, a number of scenarios on future energy use are selected and compared. From this comparison, general conclusions about future energy use are deducted. The availability of resources is mapped by study of literature.

The second research question is answered partly by study of literature and partly by the development of a quantitative model. In order to determine energy use and greenhouse gas emissions in a structured way, a quantitative model is developed. Through the study of literature the different steps in the chains and the flows of material and energy are mapped, and methodological choices are made concerning e.g. calculation methods, boundary conditions (e.g. which steps to in- or exclude), geographical and temporal aspects (like how to deal with time horizons and developments in technology and production costs over time). The structure of the model is transparent so that calculation steps can be easily verified and the underlying data can easily be accessed, updated, modified or extended with other fuel chains. The results are compared with data from existing studies to evaluate the validity of the model. Sensitivity analyses will be performed to gain insight in how methodological choices, parameter values and presentation methods influence the results of comparative analyses of this kind.

The third research question is answered by means of study of literature. However, reliable, detailed data on costs are very scarce. In the case of existing production processes of conventional transportation fuels, companies are very reluctant in providing data on costs due to reasons of competition. For renewable fuels, no large-size production facilities exist as yet and so all numbers available in literature are based on estimations. The outcomes of the analysis of costs should therefore be taken as an indication only.

1.3 Structure of the report

The first research question will be answered in chapter 2 and 3. In chapter 2, the expected future energy use is mapped by means of a comparison of a number of scenarios. In chapter 3, the availability of the most important fossil and renewable energy sources is mapped. At the end of chapter 3, the energy use and the availability of resources are combined and conclusions are drawn about whether or not there are shortages to be expected.

The second research question is answered in chapters 4 to 11. In order to answer the research question, a model is developed in chapter 4 to map energy flows and emissions in a fuel chain. Chapter 4 draws entirely on the theoretical side of the model and the formulas that are used in it. In chapter 5, the practical aspects of building a model are dealt with. In this chapter methodological choices are made concerning, among others, the time frame, the use of heating values and the application of Global Warming Potentials. In this chapter also the fuel chains to be included in this study are selected. Next, in chapter 6, 7, 8 and 9 the actual modeling of the fuel chains takes place. Chapter 6 is devoted to fuel chains based on crude oil; chapter 7 to fuel chains based on natural gas and chapter 8 to fuel chains based on biomass. In chapter 9, the process fuels are modelled. Although the fuel chains of the process fuels do not lead to transportation fuels and thus don't lead to direct results, it is necessary to model the process fuels in order to correctly calculate the results in the other fuel chains. In chapter 10, the results from the fuel chains of chapter 6, 7 and 8 are collected and presented in four different ways. Finally, the sensitivity analysis of chapter 11 provides insight in the relative importance of various process steps. With the sensitivity analysis the answer to the second research question is completed.

The third research question is answered in chapter 12. In this chapter the production costs of the selected fuel chains are mapped. Chapter 13 takes a look at the consequences of a growing vehicle fleet, improved engines and the use of alternative fuels on the emissions from the Dutch traffic in the period 2020-2030. Finally, in chapter 14 it is time to draw conclusions. This chapter also contains some recommendations for further research.

2 Future energy use

2.1 Introduction

This chapter assesses how the world's future energy demand could develop. It does so by comparing several energy scenarios. Before this can be done, some background information is needed to know what scenarios are, what they can be used for and what different sorts of scenarios there are. This background is presented in section 2. Because there exist many scenarios and it is impossible to look at them all, a selection is made in section 3. Each scenario consists of an underlying framework of methodology and assumptions that determine the output, in this case the projected energy use. In section 4 the frameworks of the selected scenarios will be compared, whereas section 5 contains a comparison of the energy use as predicted by the scenarios. Finally, in section 6, conclusions are drawn about the world's anticipated energy needs.

2.2 *Energy scenarios, what are they and what are they used for?*

The use of energy depends on an almost countless number of variables that all contribute in some way. The exact number is usually not known, nor is the relative importance of each variable exactly known. Therefore it is impossible to formulate a model that correctly describes energy systems and predicts how they will develop in the future. The best option for understanding future developments in energy systems is to use scenarios. Scenarios combine an internally consistent, reproducible set of assumptions and theories with images and stories of the future primarily based on intuition. The ratio between the qualitative theories and the more quantitative storyline can vary greatly. Alcamo has studied many scenarios and found they all contain certain elements [Alcamo, 2001]:

- Driving forces: these are the main determinants that cause the changes described in the scenario. Commonly used driving forces in energy scenarios are population growth and economic growth.
- Base year: the base year is the starting year of the scenario. Usually, it is the most recent year for which all quantitative data are available. Historical trends are based on actual data until the baseyear. From the baseyear on, all numbers are forecasts.
- Time horizon and time steps: the time horizon is the most distant future year covered by the scenario. The distance between the base year and time horizon is usually divided into a number of time steps.
- Description of step-wise changes: a scenario describes an image of how the future might evolve. The transition to the end-state in the scenario is not described continuously but by means of a limited number of intermediary states. Usually these fall together with the time steps.
- Storyline: the descriptive part of the scenario is called the storyline. The storyline is used to visualize the future. Storylines can be newly developed or can be based upon existing storylines form other scenarios.

Scenarios can be categorised in a number of ways:

- Qualitative vs. quantitative: qualitative scenarios describe the future by the storyline. They are easily understandable but lack absolute information to support their statements. Due to this lack of numbers, their internal consistency and feasibility cannot be verified. Quantitative scenarios on the other hand contain lots of numbers and tables, but this 'dry' information makes it hard to imagine what the future will be like. To overcome these problems, most scenarios consist of a combination of the two and contain qualitative as well as quantitative aspects.

- Exploratory vs. anticipatory: exploratory or descriptive scenarios are based on historical trends. They start in the base year and by extending historical trends they try to figure out what the future could look like. Anticipatory or normative scenarios start with a prescribed view of the endpoint, sometimes called utopia, and then count back to describe what should be done in order to reach the desired endpoint.
- Baseline vs. policy: baseline scenarios, also known as reference or benchmark scenarios, describe a future state in which additional regulation does not exist or does not have noticeable influence. In the case of energy scenarios, they describe the future as it could become if there will be no radical policies to constraint or promote energy use. Policy scenarios on the other hand assume a policy or regulation and sketch what the effects could be.

2.3 Selection of energy scenarios

There exist many scenarios and therefore a selection has to be made. First of all, this report tries to assess how the future might evolve from our current situation. This is typical for exploratory scenarios. Therefore only exploratory scenarios will be used and anticipatory scenarios will be disregarded. Second, in order to be able to make a quantitative assessment, all scenarios to be used must contain a quantitative part. Third, it is interesting to look at some baseline scenarios to know what could happen if energy use develops itself without restrictions, but it is also interesting to see what could happen if we assume a maximum stimulation of energy efficiency and the use of renewable energy sources. Therefore both baseline and policy scenarios will be included in this assessment. Fourth, most scenarios are made by governments or governmental institutions and therefore look at the world with the view of policy makers. However, our energy system depends not only on governments but also on the industry. It is interesting to know how they think the world's energy system will develop. Therefore some scenarios made by industry will be included in the selection. Finally, the scenarios have to be regarded by experts as plausible images of how the future might evolve. By applying these criteria to a great number of scenarios, a selection could be made. This selection includes:

- The scenarios from Global Energy Perspectives, developed jointly by the International Institute for Applied Systems Analysis (IIASA) and the World Energy Council (WEC) [Nakićenović, 1998]. This report presents four baseline scenarios and two policy scenarios and is widely seen as one of the best available reports in this field. The scenarios of this report are used throughout the literature in this field.
- Renewables Intensive Global Energy Scenario (RIGES) by Johansson [Johansson, 1993], which was prepared as input for the United Nations Conference on Environment and Development (UNCED) held in Rio de Janeiro in Brazil in 1992. This scenario is a policy scenario. It assumes active policy to promote energy efficiency and the use of renewable fuel sources.
- Dematerialisation and Sustained Growth by Shell [Shell, 1994]; [Shell, 1996]. These scenarios were developed by Shell and provide insight in how the industry thinks our future energy system might evolve. Although Shell has developed other scenarios more recently, the Dematerialisation and Sustained Growth scenarios have received more publicity and are esteemed higher by influential experts. Therefore they have been selected over more recent scenarios.

2.4 Scenario outline for the selected scenarios

In the second section, some elements were recorded that are present in every scenario, namely driving forces, baseline, time steps, stepwise changes and storyline. This section describes these elements for the selected scenarios after which section 5 will present a comparison of the actual developments in energy use as foreseen by the scenarios. All scenarios are internally consistent and have been developed both by a bottom-up and a top-down approach. This means that not only the effect of the driving forces on energy use has been measured (bottom-up), but the effect that energy use patterns have on driving forces is also included (top-down).

Global Energy Perspectives

"Global Energy Perspectives" distinguishes six driving forces: population growth, economic growth, energy intensity improvements, technological change, the resource base and the environment. The base year in this report is 1990, with a principle focus on the period 2020-2050 and some extensions to the year 2100. The storyline is quite elaborate. There are three basic scenarios, named A, B and C. In the course of the time span, scenario A diverges into three scenarios A1, A2 and A3. In the same way scenario C diverges into C1 and C2. The A-scenarios are characterised by vigorous technological improvements and high economic growth. Case B also knows technological improvements, but less firmly than the A-scenarios. Economic growth is more moderate. The C1 and C2 scenario show substantial technological enhancements, but oriented more towards environmental protection and increased efficiency. All scenarios have one driving force in common: population growth. In each scenario it is assumed that population will grow to 10,1 billion people in 2050 and nearly 11,7 billion in 2100.

Scenarios A1, A2 and A3

The scenarios of group A show high economic growth with an average of 2,7 percent in the period 1990 to 2020 and 2,6 percent in the period 2020 to 2050. Economic growth is not divided evenly over the world however. In OECD countries it is about 2 percent while it is twice as much in developing countries. By the end of the century the term "developing countries" is hardly applicable anymore. Gross World Product grows from 20 trillion US(1990)$ in 1990 to 100 trillion US(1990)$ in 2050 and even 300 trillion US(1990)$ by the year 2100. This high growth stimulates turnover of capital stock and economic structure. As a result energy intensity, defined as the energy requirements per unit of economic activity, improve at a rate of 0,9 percent per year in the period 1990-2050 and 1,0 percent per year in the period 1990-2100. In the entire scope of the scenario until 2100 there are favourable geopolitical conditions and free markets. Due to high economic growth there is also rapid technological change. This change develops along three alternative trajectories resulting in three different scenarios (A1, A2 and A3) with almost identical end-use of energy but different energy system structures. In scenario A1 the general thought is that there are ample fossil fuels for the 21st century. Until the year 2020 the world relies on conventional oil and gas and afterwards on unconventional resources. Technological developments result in advanced extraction techniques so that unconventional resources can be recovered at competitive prices and without severe efficiency problems or environmental burdens. Only at the end of the century, when unconventional resources are running out, a transition to renewables starts to develop. In scenario A2 on the other hand the general vision of governments is that oil and gas are running out quickly and they have to change their energy systems to prevent disaster. Because technological progress is more general and oriented more towards existing techniques than developing new ones, recovery of unconventional resources is technically not feasible. Renewable energy sources are too expensive and their technologies have not matured and therefore coal turns out to be the fuel of choice. Sulpher and nitrogen emissions can be dealt with, but the mines from which coal is extracted grow deeper every year, which causes new challenges that remain throughout the entire century. In this coal-based era, liquid fuels are obtained by converting coal to liquid synthetic fuels such as synthetic methanol. In scenario A3 technological change is oriented towards renewable and nuclear energy. This scenario is least dependent on fossil fuels of the A group. During the transition to renewable and nuclear energy, natural gas is the fossil fuel of choice. The strategy followed in this scenario leads to a significant degree of decarbonisation. Although primary energy use grows to almost three times today's primary energy use, carbon emissions only increase to be 1,5 times those of today. In all three scenarios of the A group, economical growth is viewed as more important than environmental concern.

Scenario B

Scenario B is a scenario where current trends are expanded in the future. In scenario B, economic growth is modest with an average of 2,2 percent in the period 1990 to 2020 and 2,0 percent in the period 2020 to 2050. The economy experiences some short setbacks but eventually these are all overcome in the longer run. Trade barriers between countries are gradually removed resulting in facilitated international exchange. Gross World Product develops from current 20 trillion US(1990)$ to 75 trillion US(1990)$ in 2050 and 200 US(1990)$ in 2100. Energy intensity improves, but at a slower rate than in the scenarios of group A, with 0,8 percent per year over the entire period of 1990-2100. Energy use depends heavily on fossil fuels. Due to modest economic growth as compared to the scenarios of group A, technological growth is slower. Technological transitions like those in the scenarios from group A, don't occur. Scenario B shows continuous heavy dependence on oil and gas. At the end of the century oil and gas are running out and can only be extracted at higher cost. Because there are still no other fuels available at large scale, the world will have to cope with higher prices. Scenario B can be characterized as "muddling through". There is no clear choice for alternatives to fossil fuels so when fossil fuels are finally running out no fuel system has emerged that is able to replace fossil fuels on a large scale. Some people argue that although this scenario is less attractive in some ways, it is more realistic than other scenarios.

Scenario C1 and C2

Scenarios C1 and C2 are policy scenarios, as opposed to scenarios A1, A2, A3 and B that are baseline scenarios. In scenario C1 and C2, the improvement of energy intensity and the use of non-fossil energy sources are given special attention. These scenarios show almost the same modest economic growth as scenario B, with an average of 2,2 percent in the period 1990 to 2020, but 2,1 percent in the period 2020-2050, where scenario B had an average growth of 2,0 percent in that period. Gross World Product grows to 75 trillion

	Scenario					
	A1	A2	A3	B	C1	C2
Population (billion)						
1990	5,3	5,3	5,3	5,3	5,3	5,3
2050	10,1	10,1	10,1	10,1	10,1	10,1
2100	11,7	11,7	11,7	11,7	11,7	11,7
Economic growth (%/year)						
1990 to 2020	2,7	2,7	2,7	2,2	2,2	2,2
2020 to 2050	2,6	2,6	2,6	2,0	2,1	2,1
Global primary energy intensity improvement (%/year)						
1990 to 2050	0,9	0,9	0,9	0,8	1,4	1,4
1990 to 2100	1,0	1,0	1,0	0,8	1,4	1,4
Technological change	High	High	High	Medium	High	High
Resource base	Conventional and unconventional oil and gas resources	Coal	Nuclear energy and renewables	Conventional oil and gas	First nuclear energy, then renewables	Nuclear energy
Environment						
CO_2 emission constraint	No	No	No	No	Yes	Yes

Table 2.1: summary of driving forces for scenarios of Global Energy Perspectives
Based on [Nakićenović, 1998]

US(1990)$ in 2050 and 220 US(1990)$ in 2100. Policy measures to accelerate energy efficiency improvements and to develop and promote decentralized energy technologies result in energy intensity improvements of 1,4 percent per year in the total period from 1990 to 2100. In addition to local policies, a global regime to control greenhouse gas emissions is established which aims to reduce carbon emissions by 2100 to one third of the 1990 level, at 2 Gigatonne of carbon. In order to reach this target, a transition away from fossil fuels takes place. In 2050 40 percent of energy comes from renewable sources and by 2100 this has increased to 80 percent. In scenario C1 nuclear energy is used a transition fuel. Due to continuous public concerns about safety it does not last. In scenario C2 the safety concerns are overwon and nuclear energy becomes the primary energy source. Table 2.1 shows a summary of the driving forces of all six scenarios.

Renewables Intensive Global Energy Scenario

Like scenario C1 and C2 from "Global Energy Perspectives", RIGES is a policy scenario. RIGES is more vigorous than scenario C1 and C2 though, with an even stronger emphasis on energy efficiency and a transition away from fossil fuels. RIGES is oriented towards renewable energy sources, thereby excluding nuclear energy. Driving forces in RIGES are population growth, economic growth, energy efficiency and the environment. A difference between driving forces of RIGES and the scenarios from Global Energy Perspectives is that Global Energy Perspectives also takes into account technological change and the resource base. The base year in RIGES is 1985 and the time horizon extends to 2050 with an intermediate horizon of 2025. The storyline is very focussed on the environment.

In RIGES, population growth is considerable, although world population grows at a slower pace than in Global Energy Perspectives. World population is expected to grow from 4,87 billion people in 1985 via 8,19 billion people in 2025 to 9,53 billion in 2050. Economic growth is high: Gross Domestic Product grows at a global average rate of 3,5 percent per year between 1985 and 2025 after which the growth slows down a bit to a worldwide average of 3,0 percent in the period 2025-2050. However, there are substantial regional differences: in North America and Western Europe an average growth percentage of 2,4 is expected, while centrally planned Asia is expected to have an average growth of 4,9 percent. These growth levels lead to a Gross World Product that grows from 15,75 trillion US(1989)$ to 130 US(1989)$. This level is higher than that of the scenarios in group A of Global Energy Perspectives. In RIGES, the world is focussed on the environment. Therefore energy efficiency has high priority and energy improvements of an average of 2,0 to 2,1 percent per year are reached, which is very high. This emphasis on energy efficiency facilitates the introduction of new energy carriers such as methanol or hydrogen. In RIGES, a whole range

	RIGES Scenario
Population (billion)	
1985	4,87
2000	6,17
2025	8,19
2050	9,52
Economic growth (%/year)	
1985-2025	3,5
2025-2050	3,0
Global average energy intensity improvements (%/year)	2,0 - 2,1
Environmental policies	Yes

Table 2.2: summary of driving forces for RIGES scenario
Based on [Johansson, 1993]

of new energy technologies become available that are fully competitive with existing energy technologies. The transition to these new technologies will be encouraged by active policies, such as subsidies, tax exemptions, government support for research and development and regulations on efficiency and emissions. Eventually, renewables are used whenever renewable energy is no more expensive on a life-cycle cost than conventional alternatives and the use of renewable technologies at the level indicated will not create significant environmental, land use or other problems. Table 2.2 provides a summary of driving forces of the RIGES scenario.

Dematerialisation and Sustained Growth

The Shell scenarios "Dematerialisation" and "Sustained Growth" are both baseline scenarios. Both scenarios only know three driving forces: population growth, economic growth and energy intensity. The base year is 1990 and the scenarios extend until 2060, with intermediary time horizons of 2030 and 2050. Unfortunately, not all data for all variables are given for the intermediate years. In case data for the year 2050 are missing, data for the year 2060 will be used. The storyline is not very elaborate.

Population growth is the same in both scenarios and follows estimations from the World Bank. World population is expected to grow to 8,5 billion people by 2030 and 10 billion people by 2060. With a continuous high economic growth of 3 percent per year, Gross Domestic Products rises to 73 trillion (1990)US$ in 2030 and even 170 trillion (1990)US$ by 2060, which is considerable higher than Gross Domestic Products as predicted by the other scenarios. In the "Sustained Growth" scenario, energy intensity improves at a rate of 1 percent per year. In the first two decades of the 21st century, the use of fossil fuels increases steadily. By 2020-2030, the production of fossil fuels reaches a maximum. Due to the activities of companies and universities to develop renewable energy technologies, a number of technologies such as wind energy, biomass and solar photovoltaics are ready for large-scale implementation. Therefore there is ample energy at competitive prices and economic growth can be sustained. Around the year 2050, a second wave of renewable technologies is ready for introduction to the market. These include energy from magma, artificial photosynthesis and a surprise energy that has yet to be discovered. In "Sustained Growth" no single energy carrier emerges. In stead, by 2060 our energy will come from perhaps ten or so different sources each having a market share between 5 and 15 percent.

The other scenario, "Dematerialisation", knows the same population growth and economic growth as "Sustained Growth". However, in this scenario energy intensity improves at a rate of 2 percent per year in stead of the 1 percent of "Sustained Growth". This is because the development of new technologies is oriented towards reducing energy input rather than

	Scenario	
	Sustained Growth	Dematerialisation
Population (billion)		
1990	5,2	5,2
2030	8,5	8,5
2060	10,0	10,0
Economic growth (%/year)		
1990-2060	3,0	3,0
Global average energy intensity improvements (%/year)		
1990-2060	1,0	2,0

Table 2.3: summary of driving forces for Shell scenarios
Based on [Shell, 1996], [Shell, 1994]

developing renewable technologies. Efficient technologies and the use of new, light materials improve energy intensity fastly. Due to less attention for renewable energy technologies, it takes longer before they are ready to enter the market. Solar photovoltaics, biomass and wind energy are only introduced on a large scale between 2020 and 2050, while the second wave does not take off at all in within the time horizon of the scenario. Table 2.3 summarizes the driving forces of both Shell scenarios.

2.5 *Future energy needs*

This section compares the energy needs as they are predicted by the various scenarios. Energy needs can be compared at various levels, ranging from primary energy to end-use. In order to make correct comparisons we will first look at the definitions used in each report to see if all definitions used are compatible. After this is done, primary energy needs will be discussed, followed by electricity use and final energy. When possible, final energy is discussed by sector. However, the Shell scenarios are very much oriented towards primary energy use and provide hardly any information on end use. Last of all, predicted carbon emissions will be compared. In all cases, the scenarios from Global Energy Perspectives will be the first to be discussed, then RIGES and finally the Shell scenarios. The scope will be from the base years of the scenarios until the year 2050 because this is the last year that is included by all scenarios. For those scenarios whose time horizon lies beyond the year 2050, all data covering the years after 2050 are disregarded in this section.

Definitions

There exist many slightly different definitions for different forms of energy. In Global Energy Perspectives, primary energy is defined as *"energy recovered of gathered directly from nature"* [Nakićenović, 1998]. For fossil fuels this definition can be applied straightforward. For example, primary energy from coal is the energy contained in mined coal and for oil it is the amount of recovered crude oil. For renewable energy sources the definition comes down to the amount of collected biomass or the solar energy absorbed by collectors. "Secondary energy" refers to the fuels and electricity that exist after conversion. For electricity from renewable energy sources, a conversion efficiency of 38,6 percent is used. Secondary energy is transported, distributed and delivered to the point of consumption as final energy.

RIGES applies the same definition of primary energy as "Global Energy Perspectives". However, for the production of electricity from renewable sources, the average worldwide efficiency for power generators is used. Regrettably, the report does not provide numerical values for this efficiency rate. In RIGES, primary energy is converted to electricity and energy for direct use, where direct use refers to the use of fuels by final consumers. This means that the term "direct use" in RIGES comprises the same as "final energy" in "Global Energy Perspectives. For the sake of unity, the term "final energy" will be used throughout the text.

The Shell report lacks a clear explanation of used definitions. It is assumed that the term "primary energy" covers the same content as the primary energy from Global Energy Perspectives and RIGES. In the case of final energy the report mentions "energy consumption" which is considered here to equal "final energy" as defined by Global Energy Perspectives.

Primary energy

Global Energy Perspectives

In all scenarios, primary energy production is expected to rise, although to different heights. In the scenarios of Global Energy Perspectives, rise in primary energy use varies from 1,5 times to 2,7 times primary energy use of 1990. The scenarios of group A show primary energy

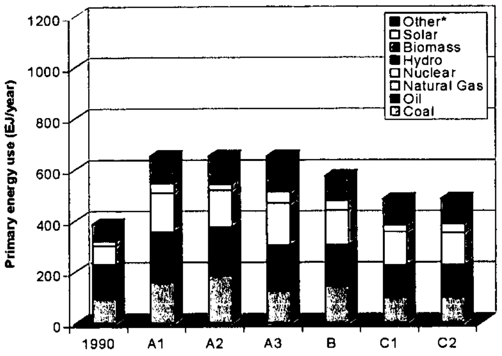

Figure 2.1: composition of primary energy in 2020 and reference year 1990, according to scenarios from Global Energy Perspectives
*: wind, geothermal, waste
Based on [IIASA, 2003]

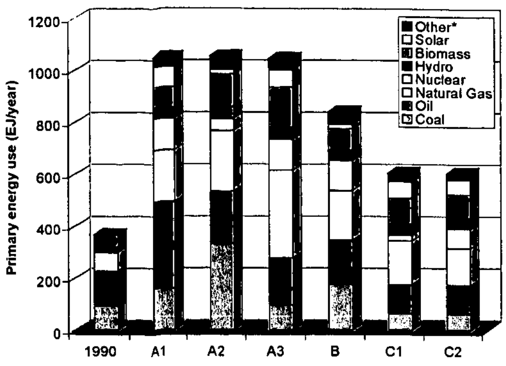

Figure 2.2: composition of primary energy in 2050 and reference year 1990, according to scenarios from Global Energy Perspectives
*: wind, geothermal, waste
Based on [IIASA, 2003]

growth rates as they have been experienced in the past. In scenario B, C1 and C2 growth is less strong. In scenario B this is caused by lower economic growth as compared to group A. In scenario C1 and C2 the emphasis on efficiency and the environment result in a decoupling of economic growth and primary energy growth.

The composition of primary energy use by source in the years 2020 and 2050 is shown in figure 2.1 and figure 2.2 respectively. In both figures, 1990 is shown as a reference. The fraction of coal, oil and gas varies between 71,8 percent (scenario A3) and 79,6 percent (scenario A2), which is almost equal to the fraction of 1990 which was 77,7 percent. In absolute values there are more differences. In scenarios C1 and C2 much attention is paid to energy efficiency, which leads to an increase in fossil fuel use of only 17 and 18 percent as compared to 1990. In scenario B, which extends historical trends into the future, fossil fuel use is almost 1,5 times that of 1990, whereas the high growth scenarios of group A show even higher growths. Scenario A2 leads with an increase of 73% percent as compared to 1990. Nuclear and renewable energy sources, which accounted only for 22,3 percent of primary energy in 1990, are still of minor importance in 2020. Nuclear energy, hydro energy and biomass are the most important non-fossil energy sources. The role of solar energy and other sources like wind energy, geothermal energy and energy from waste is almost negligible. In 2050, the picture is much more differentiated. In scenario A1, oil is still the main resource accounting for 31,8 percent of primary energy use, which is 334 EJ on a yearly basis. Oil is followed by coal and gas. Out of the non-fossil fuels, nuclear energy is the only source worth mentioning, with 123 EJ, or 11,7 percent. In scenario A2 the main focus lies on coal, with oil only occupying a third place. In this scenario, biomass is the most important non-fossil fuel source. Scenario A3 shows natural gas to be the most important energy source. Coal, nuclear energy and biomass are about equally important. In all three scenarios of group A, total primary energy use has risen to about 1050 EJ, which is more than 2,7 times the reference use of 1990. In scenario B, economic growth is more limited than in scenario A, which leads to a smaller increase in energy use. In this scenario, the emphasis is still on fossil fuels, although the main fossil fuel is now natural gas instead of oil. Coal, oil and natural gas together account for a little more than 64%. Of non-fossil sources, biomass is the most important, although its share only amounts about 14 percent. In scenarios C1 and C2 a transition away from fossil fuels is most successful: non-fossil energy accounts for almost half of primary energy use. Because in these scenarios there is much attention for energy efficiency, total energy use grows the least fast of all scenarios. In both scenarios the use of coal and oil has decreased as compared with 1990, both in fractions and in absolute values.

Use of oil is limited to about 80 percent of the 1990 level while use of coal is expected to be only two-third of contemporary levels. The use of natural gas on the other hand is expected to double between 1990 and 2050. Both scenarios show high levels of non-fossil fuels as compared to the other scenarios, but the distribution differs greatly. In scenario C1, biomass and solar energy are important whereas nuclear energy has the lowest share of all fuel sources. In scenario C2, nuclear energy is the most important non-fossil fuel, followed by biomass and solar. In all scenarios, hydro energy is the least important, followed by other renewable sources like wind energy, geothermal energy and energy from waste.

Riges

In RIGES, which looks at the maximum potential for renewable energy sources, primary energy production rises between 1985 and 2050, but at a much slower speed than in any scenario of Global Energy Perspectives. Primary energy production is expected to have risen only to 561 EJ per year by 2050, which is an increase of 74 percent as compared to 1985, or 33 percent compared to 1990. This small increase is explained by the strong focus on energy efficiency. Only 43 percent, 243 EJ/year, of primary energy comes from fossil fuels. The emphasis on renewable energy sources and the active policy to use them whenever possible leads to a situation with less fossil fuel use than in any of the scenarios of Global Energy Perspectives. Renewable energy comes primarily from biomass (206 EJ/year) and intermittent renewables such as wind energy and solar energy (together accounting for 64 EJ/year). Hydropower, electrolytic hydrogen and geothermal energy will have only minor contributions by 2050 but the last two are expected to grow afterwards and eventually replace the intermittent renewables (wind, solar energy and photovoltaic energy). The distribution of primary energy sources is shown in figure 2.3. Table 2.4 gives a more detailed insight in the origin of the biomass. It shows that in this scenario by 2050, about half of the biomass is grown on plantations. The other half comes from a variety of waste streams. However, the amount of waste that can be used for biomass is limited. As the table shows, there is hardly any growth in residues between 2020 and 2050. When the use of biomass is to increase further, this growth will come from plantations.

Shell

Like the other scenarios, the Shell scenarios show a growth in primary energy use as compared to 1990. In the "Sustained Growth" scenario, primary energy rises from about 400 EJ per year in 1990 to 800 EJ per year in 2030 and 1150 EJ per year by 2050, which is even more than predicted by the scenarios of group A from Global Energy Perspectives. "Dematerialisation" shows a more moderate picture: 700 EJ per year in 2030 and 800 EJ per year by 2050.

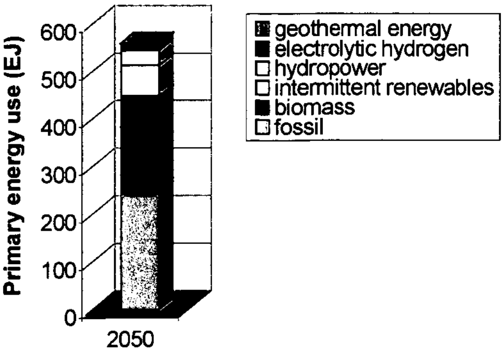

Figure 2.3: distribution of primary energy sources in 2050 according to RIGES
Based on [Johansson, 1993]

	biomass production (EJ/year)	
	2020	2050
Plantations	79,9	128,2
Residues		
forests	23,6	24,3
sugar cane	10,2	12,1
dung	17,0	25,3
cereals	10,9	13,0
urban refuse	3,1	3,1
total	144,7	205,9

Table 2.4: sources of biomass according to RIGES
Based on [Johansson, 1993]

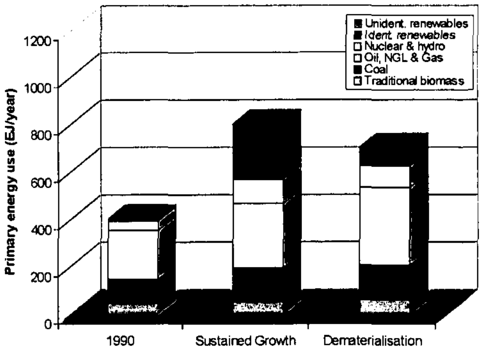

Figure 2.4: composition of primary energy in 2030 and reference year 1990, according to Shell scenarios

Based on [Shell, 1994], [Shell, 1996]

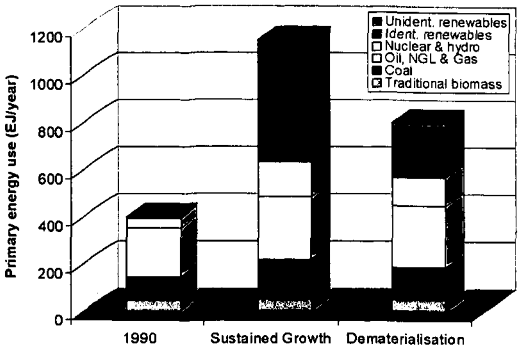

Figure 2.5: composition of primary energy in 2050 and reference year 1990, according to Shell scenarios

Based on [Shell, 1994], [Shell, 1996]

Figure 2.4 and 2.5 show the distribution of primary energy in 2030 and 2050 respectively. Both figures show 1990 as a reference. By the year 2030, the distribution is quite similar for both scenarios. Through economic development in currently lesser developed regions of the world, the share of traditional biomass has decreased from over 10 to 6-8 percent. The share of coal is in both scenarios about 20 percent, while nuclear energy and hydro-energy account for 13 percent. The difference between both scenarios lies in renewable energies. In "Sustained Growth" renewables are taking off and account for almost 30 percent (220 EJ/year) of total energy. In "Dematerialisation" this take off has not yet started and instead natural gas is used.

By 2050 the use of traditional biomass has declined further. The share of coal has declined in both scenarios, but due to the high growth of energy use in "Sustained Growth" the use has increased in absolute values. Fossil fuels such as oil and natural gas liquids have reached a maximum production level and have stabilised. In "Dematerialisation" the first wave of renewables has taken off, substituting natural gas with renewables. In both scenarios, renewables have experienced the biggest growth. In "Sustained Growth" the renewables of the second wave are being introduced.

Distribution of end use

Global Energy Perspectives

In Global Energy Perspectives, three sectors are distinguished within final energy: transport, industry and residents and commerce. In 1990, residents and commerce used 40,3 percent of final energy, industry used 37,1 percent and transport accounted for 22,6 percent. In 2020, the share of industry is expected to be almost equal to that of 1990, varying between 36 and 38,7 percent. The share of transport will have increased somewhat at the cost of residents and commerce. In absolute numbers final energy use by residents and commerce increases with 23 to 50 percent, industrial use with 28 to 84 percent and transport with 54 to 120 percent. For all sectors, the increase is smallest in scenario C1 and C2 and largest in the scenarios of group A.

By 2050 the relative importances of the sectors are still fairly the same. Industry accounts for about 40 percent of final energy, and residents and commerce and transport both for about 30. In all scenarios except A1, the share of residents and commerce is just above that of transport. In scenario A1 it is the other way round. In absolute numbers, the scenarios of group A show the highest levels of final energy use. Total final energy use will be about 2,6 to 2,7 times as high as in 1990, equaling more than 700 EJ per year. In scenario B, final energy use is just below 600 EJ whereas scenarios C1 and C2 foresee the lowest increase, with only

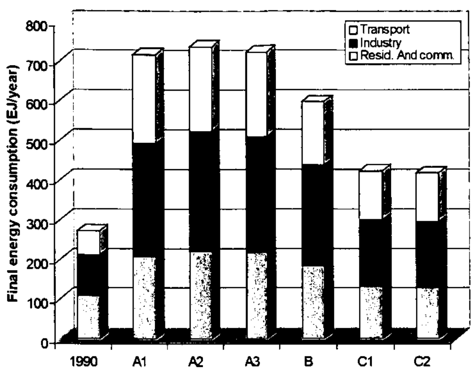

Figure 2.6: final energy distribution in 2050 according to Global Energy Perspectives
Based on [IIASA, 2003]

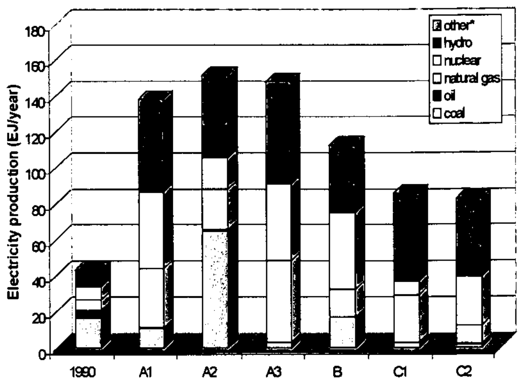

Figure 2.7: electricity production by source in 2050 according to Global Energy Perspectives
Based on [IIASA, 2003]

about 420 EJ. Figure 2.6 shows the distribution of final energy over sectors in the year 2050. 1990 is shown as reference.

Total end use is not only made up by final energy but also by electricity. In 1990, the world consumed 43 EJ of electricity, or about 12 000 TWh. The most important source for electricity production was coal, accounting for 38 percent. Second and third most important were hydro energy and nuclear energy, while biomass, wind energy and solar energy only accounted for 2,6 percent, or 1,1 EJ. By 2020, coal is still the most important source for electricity, but renewable sources are catching up. The use of oil, which was already a minor source for electricity, has become negligible. In the scenarios of group A, electricity production almost doubles. The largest increase is in renewable energy sources like wind energy and biomass. All other sources are growing more or less relatively. In scenario B, electricity use in absolute numbers is smaller than in the scenarios of group A, but the division over the various sources is comparable. Scenarios C1 and C2 show smaller fractions for coal and energy from wind and biomass, which is counterbalanced by an emphasis on natural gas, nuclear energy and hydro energy. By 2050 all scenarios except A2 show a transition away from coal. The use of coal is either at the level of 1990 (scenario B) or lower. Instead, electricity comes from natural gas, nuclear energy and renewable sources like wind energy, solar energy and biomass. The use of hydro energy has increased in absolute numbers but decreased in shares. Only in scenario A2 coal is still heavily used, which leads to lower fractions of all other sources. Figure 2.7 shows the electricity production by source in 2050.

RIGES

RIGES calculates data on final energy by world region and unfortunately does not distinguish any sectors. Final worldwide energy is shown to increase from about 220 EJ in 1985 to just below 300 EJ in 2025 and to stabilize at that level until 2050. This is substantially lower than predicted by the scenarios of Global Energy Perspectives, where even the scenario with the least increase in final energy predicts 418 EJ per year. The use of coal and gas remains more or less equal, but the use of oil diminishes, in favour of biomass. The use of solar energy and wind energy develops only slowly. A visualisation of these numbers is provided in figure 2.8. Electricity production as predicted by RIGES is more in accordance with the predictions from Global Energy Perspectives. Electricity use grows to 3,5 times the 1990 level, from 33 EJ to 117 EJ. The emphasis on coal shifts away in favour of natural gas, wind energy, solar energy and biomass. The contribution of hydro energy remains moderate with the biggest growth before 2025. These figures are shown in figure 2.9.

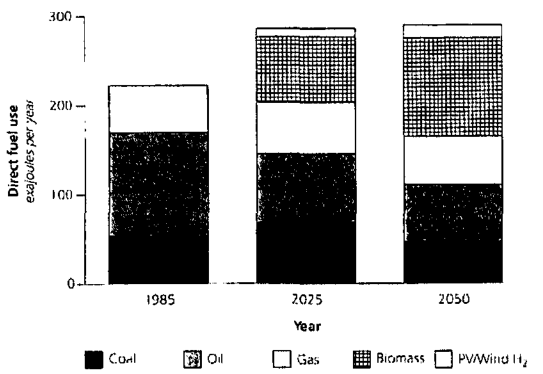

Figure 2.8: final energy distribution according to RIGES
Source: [Johansson, 1993]

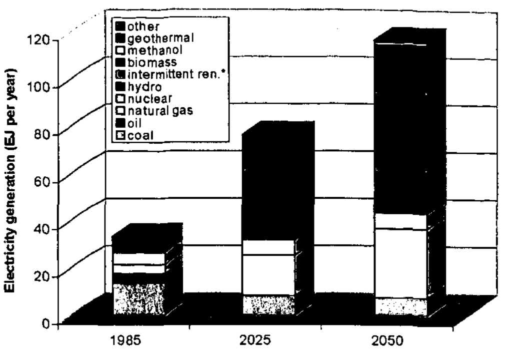

Figure 2.9: electricity production by source according to RIGES
Based on [Johansson, 1993]

Shell

Because of their strong focus on primary energy use, the Shell scenarios provide very little information about end use. In "Sustained Growth", energy consumption by consumers in 2060 will amount 550 EJ per year. This would be between the level of scenario B and C1 from Global Energy Perspectives, although it is not certain whether these numbers are comparable. For the "Dematerialisation" scenario an energy consumption by consumers of 330 EJ per year is mentioned, which would be between the level of scenario C2 from Global Energy Perspectives and RIGES. For both scenarios, demand for transport fuels has increased as compared with 1990, due to expanding economic activity. From 2020 onwards synthetic fuels are introduced, first natural gas and later on biomass. The use of electricity becomes increasingly important.

Emissions

Global Energy Perspectives

As we have seen, all scenarios predict increases in primary and final energy use. In 2020, the main sources of this energy are fossil fuels. As a consequence, CO_2 emissions are expected to rise, as is shown in table 2.5. Scenarios C1 and C2 of Global Energy Perspectives show the least increase in fossil fuel use and therefore the least increase in CO_2 emissions. In these scenarios, emissions are expected to be almost 7000 MtC, which is an increase of 11 and 12 percent respectively as compared to 1990. The other scenarios expect higher growths of fossil fuel use and correspondingly higher levels of CO_2, up to an increase of 71 percent. By 2050 the fossil fuel-intensive scenarios A1, A2, A3 and B show further increase in CO_2 emissions, but scenario C1 and C2 are able to cut back on emissions. Their emissions are below the 2020 level, and in the case of scenario C2 they are even below the 1990 level.

scenario	CO_2 emission (MtC/year)		
	1990	2020	2050
A1	6234	10280	13749
A2	6234	10658	15999
A3	6234	9211	11124
B	6234	8914	10762
C1	6234	6995	6377
C2	6234	6923	5929

Table 2.5: CO_2 emissions according to Global Energy Perspectives
Based on [IIASA, 2003]

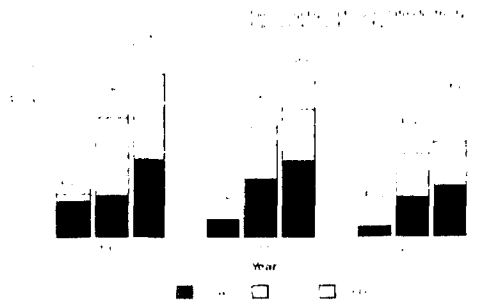

Figure 2.10: CO_2 emissions according to RIGES
Source: [Johansson, 1993]

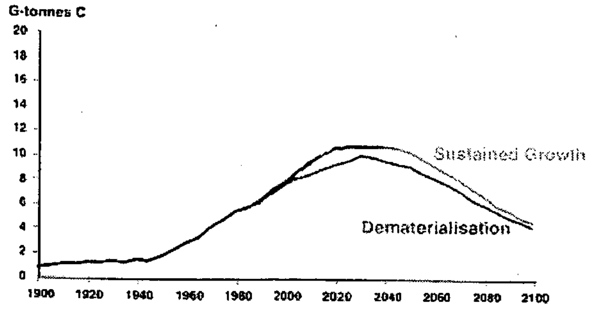

Figure 2.11: CO_2 emissions according to the Shell scenarios
Source: [Shell, 1996]

RIGES
The renewables intensive scenario RIGES foresees a decline in CO_2 emissions. Where scenario C2 from Global Energy Perspectives expects an increase in 2020 and only afterwards a decrease, RIGES expects already a decline by 2025. Emissions are expected to decline from about 5800 MtC in 1985 to 4900 MtC by 2025 and 4200 MtC by 2050. CO_2 emissions according to RIGES are depicted in figure 2.10.

Shell
According to the Shell scenarios, emissions will rise until about the year 2030. For "Sustained Growth", the maximum will be 11.000 MtC per year, for "Dematerialisation" it will be around 10.000 MtC per year. These numbers are comparable to scenarios A1 and A2 from Global Energy Perspectives. These are also the scenarios whose primary energy use is closest to that as predicted by the Shell scenarios. However, in the scenarios from Global Energy Perspectives the emissions continue to rise, while the Shell scenarios predict a decline to start. By 2050, emissions are back to 10.000 and 9.000 MtC per year for "Sustained Growth" and "Dematerialisation" respectively.

2.6 Summary and conclusions

In this chapter, a comparison of several energy scenarios has been made. The scenarios from Global Energy Perspectives were chosen because this report is a leading publication in this field. Global Energy Perspectives contains three high growth scenarios, one medium growth scenario and two environmentally oriented scenarios. These six scenarios have been compared with the Renewable Intensive Global Energy Scenario (RIGES), which is a policy scenario. This scenario assumes strong political efforts to increase energy efficiency and to stimulate the use of renewable energy sources. Finally, two scenarios from Shell were selected to include the vision of industry.

The scope of the scenarios ranges from 1985 or 1990 to 2050. In all scenarios, primary energy use is expected to rise, although to different heights. The lowest increase is reported by RIGES, namely 561 EJ/year by 2050. The highest value is reported by "Sustained Growth", one to the Shell scenarios, which measures 1150 EJ/year, more than twice as much as the lowest. An overview of the values mentionned by all scenarios is presented in table 2.6. By 2020, the world is still heavily dependent on fossil fuels. Coal, oil and natural gas together account for more than 70 percent of primary energy. Of non-fossil fuels, biomass is expected to have the largest fraction, ranging from 8,5 to 12,7 percent. By 2050 the dependence on fossil fuels has decreased somewhat. In the most optimistic views 43 percent of primary energy comes from fossil fuels (RIGES); on the other side of the scale this is still 73 percent (scenario A2). Important non-fossil energy sources are nuclear energy, biomass and solar energy.

Scenario	Total primary energy use (EJ)	Final energy use for transportation purposes (EJ)
Global Energy Perspectives:		
A1	1050	225
A2	1054	214
A3	1047	214
B	841	160
C1	605	124
C2	604	123
RIGES	561	Not specified
Dematerialisation	800	Not specified
Sustained Growth	1150	Not specified

Table 2.6: overview of total primary energy use and final energy use for transportation purposes in the year 2050 in all scenarios

Final energy and electricity production are expected to rise in accordance with primary energy use. Final energy use equaled 272 EJ/year in 1990. Predictions for 2050 range from 290 EJ/year (RIGES) to 737 EJ/year (scenario A2). As far as the scenarios provide a division of final energy over sectors, industry is expected to use most energy, accounting for 40 percent of final energy. Residents and commerce and transport hold almost equal shares of about 30 percent. Electricity production is expected to grow with a factor 1,9 to 3,5. In almost all scenarios the current emphasis on coal in electricity production shifts away to renewable sources, natural gas and nuclear energy. There's only one scenario that predicts an increase in the use of coal (A2).

The energy use as predicted by the different scenarios leads to very different carbon emissions. The high and medium growth scenarios from Global Energy Perspectives foresee an increase in carbon emissions. By 2050, total carbon emissions are expected to be doubled or even more than doubled in comparison with 1990. However, the low growth scenario and the renewables intensive scenario foresee a stabilisation at the 1990 level or even a decrease. The Shell scenarios combine high growth with stabilising and afterwards declining emissions. This can be explained by the extensive use of renewable fuels.

3 Availability of energy sources and carriers

3.1 *Introduction*

In the previous chapter, we have seen that world energy demand is expected to grow and that different scenarios anticipate different energy systems. Some scenarios predict a world that is heavily dependent on fossil fuels while others foresee a transition to biomass. In this chapter, we will investigate what quantities of energy sources and carriers exist and what quantities are, or could become, potentially available for use. Section 2 presents a set of definitions and a classification of reserves and resources. In section 3 reserves and resources of oil are mapped. Sections 4 and 5 do the same for natural gas and coal, whereas section 6 deals with biomass. Finally, in section 7, conclusions are drawn.

3.2 *Classification of reserves and resources*

Fossil fuels comprise oil, gas and coal. For each of these the total quantity can be divided in a conventional and an unconventional part. The conventional part consists of reserves, those quantities that can be recovered economically using current technology. The unconventional part consists of resources, which are quantities that are not economically extractable, not extractable using current technology, or both. The border between reserves and resources is dynamic. Prices and available technology change continuously and therefore resources of today can be reserves tomorrow, or the other way around. Unfortunately, there is no globally accepted set of definitions for reserves and resources. There are many slightly different versions in use, which makes it hard to compare various studies. The definitions followed here are those of a report by the World Energy Assessment, “Energy and the challenge of sustainability” [WEA, 2000]. In this report, resources are defined as '*concentrations of naturally occurring solid, liquid or gaseous material in or on the earths crust in such form that economic extraction is potentially feasible*' [WEA, 2000]. Resources are divided according to two criteria: their economic feasibility and their geological assurance. On the scale of economic feasibility they can be either economic or subeconomic. On the scale of geological assurance they can be identified or undiscovered. Identified resources are deposits with '*known location, grade, quality, and quantity that can be estimated from geologic evidence*' [WEA, 2000]. They can be measured, indicated, or inferred. Undiscovered resources are quantities expected to exist but for which no generally accepted proof exists. They can be hypothetical or speculative. Only those resources that are both economical and identified at the time of assessment are reserves [WEA, 2000]. Besides resources, there are 'other occurrences'. These are defined in the World Energy Assessment as '*materials that are too low-grade of for other reasons not considered technically or economically extractable*' [WEA, 2000]. The categories of reserves and resources and their relationships are visualised in the McKelvey box in figure 3.1. The arrows in this figure indicate that the borders between the various categories are dynamic.

Assessments on quantities of reserves and resources are usually accompanied by a debate about depletion. The so-called 'optimists' believe that technical developments will continuously push the borders between reserves and resources outwards, so that new reserves come available and the world is assured of a continuous flow of cheap energy. They confirm their view with developments like deep-offshore techniques and the exploitation of tar sands. Pessimists on the other hand emphasize that fossil fuels are not renewable so that every use brings the world closer to their exhaustion. They underpin their opinion with

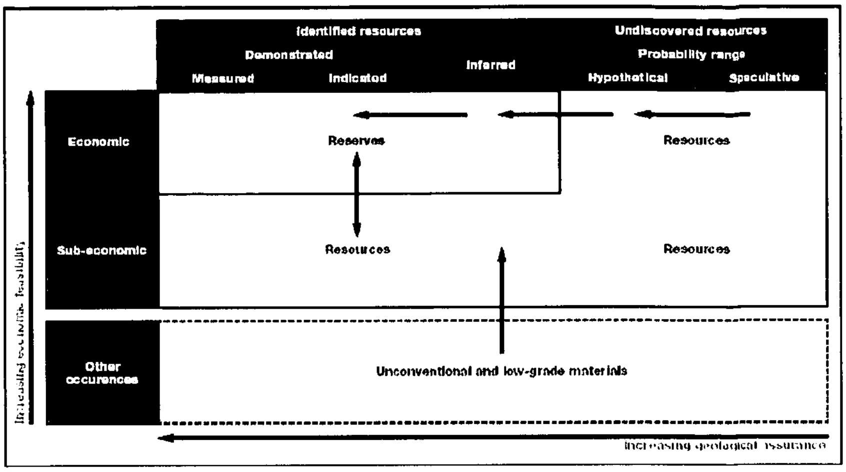

Figure 3.1: McKelvey box
Source: [WEA, 2000]

statistics of past discoveries and argue that all major oil fields have been found at least 15 years ago and that increases in reserves have come primarily from re-estimations of already known reservoirs. This report will try to remain neutral in this debate by giving an overview of the opinions of optimists as well as pessimists.

3.3 Oil

Reserves

Reserves of crude oil are assessed by many institutions. By the end of 2001, BP estimated reserves to be 6.400 EJ [BP, 2002], whereas OPEC estimated the reserves to be 6.550 EJ [OPEC, 2002]. The bars in figure 3.2 show the development of oil reserves in the period 1981-2001 as recorded by OPEC. The increase in reserves in the later half of the eighties is due to revaluation of reserves in countries in the Middle East. There are rumours that this revaluation took place for political reasons and that there is no actual oil to support the increase. However, these rumours have never been confirmed. If we assume that all recorded data are correct, we see that the amount of oil reserves is still increasing. Because the reserves decline each year with the amount consumed in the past year, this means that up until now each year more oil has been found than produced. For the coming years, new reserves are expected to be found in deep offshore areas. The application of new technologies in recent years makes it possible to recover oil from the bottom of the ocean at increasing depths. Recently discovered oil fields before the coastlines of Angola in Africa and Venezuela in Latin America suggest there is yet more oil to be found [IEA, 2001].

The blue line in figure 3.2 shows the share of reserves located in OPEC-countries. OPEC is an organisation of 11 countries whose economies rely heavily on oil exportation[1]. OPEC decides on the output level and prices for the oil of their member states [OPEC, 2003]. As figure 3.2 shows, OPEC's share in reserves has increased from 65,4% in 1981 to 78,7% in 2001. These numbers indicate the dependence of the world on a limited number of countries. Many governments in the world, especially the government of the United States, are actively seeking ways to decrease this dependence. The uneven distribution of reserves over various regions in the world is confirmed by figure 3.3. This figure shows that the Middle East holds almost two thirds of all reserves. All other regions hold less than 12% each.

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[1] For a list of OPEC member states see appendix A.

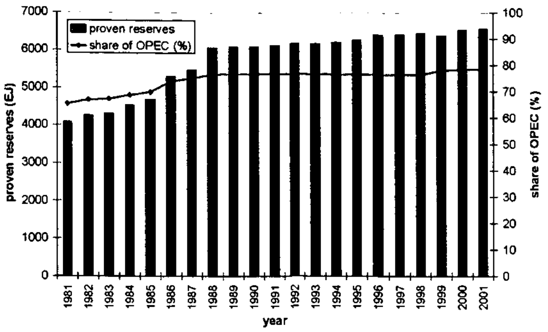

Figure 3.2: development of oil reserves 1981-2001

Based on [OPEC, 2002]

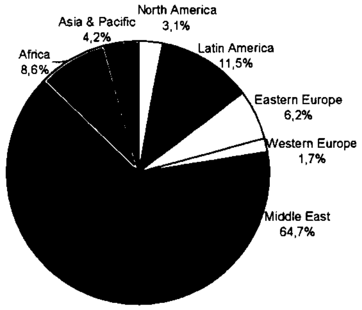

Figure 3.3: regional distribution of oil reserves[2]

Based on [OPEC, 2002]

region	reserves	production	R/P ratio
	(EJ)	(EJ/year)	(years)
North America	203,41	15,33	13,3
Latin America	755,77	19,89	38,0
Eastern Europe	407,42	17,60	23,1
Western Europe	110,58	13,13	8,4
Middle East	4247,19	44,35	95,8
Africa	566,06	14,15	40,0
Asia & Pacific	274,38	15,39	17,8
World	6556,59	139,84	46,9

Table 3.1: R/P ratios for reserves of crude oil[2]

Based on [OPEC, 2002]

A common way to estimate how long the reserves will last, is the R/P ratio, where R stands for reserves and P for production. However, by simply dividing the reserves by the production, one assumes that there will be no additional reserves found and that production will stabilise at the current level. In history this was not the case and therefore R/P ratios should be reviewed critically. In the past they have shown to be underestimations [WEA, 2000]. R/P ratios for the different regions in the world as well as the whole world are shown in table 3.1. The table shows that the first regions to be out of reserves are Western Europe, North America and Asia & the Pacific. These are also the regions that have the largest oil consumption [OPEC, 2002]. Therefore we may expect that oil dependence will only increase in the coming years. The worldwide R/P ratio currently equals 46,9 years. However, as we have seen in this section it is likely that more reserves will be found and from the previous chapter it can be deduced that production is likely to increase. It is not certain whether these effects will counterbalance each other or that one will outscore the other, thereby increasing or decreasing the R/P ratio.

Some people argue that the world's biggest problem won't be the depletion of oil, but the stagnating production rate at which oil can be recovered. It is known from already exhausted oil fields that production reaches a maximum when the field is about 50% depleted, after which production gradually slows down while production costs go up. By applying this knowledge to all important oil fields in the United States, dr. Hubbert correctly forecasted a

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[2] For a classification of countries over regions, see appendix B

peak in the United States oil production in the beginning of the seventies of the last century [Deffeyes, 2001]. Others have extended his calculations to the whole world. Their forecasted production peaks range from the year 2005 to the year 2058 [Hubbert, 2003]; [WRI, 2004], depending on the assumed growth rate of oil consumption, and the assumed amount of reserves that is yet to be found. Besides the uncertainties in growth rates and reserves, there are two more factors that hamper calculations of this kind: first, the extend by which new production techniques (such as secondary and tertiary extraction) will improve the rate at which oil can be recovered, thereby postponing a production peak. Second, the influence of politics and organisations like OPEC, which could either speed up the production peak or postpone it.

Resources & other occurrences

The World Energy Assessment distinguishes three categories of unconventional oil: oil shale, heavy crude oil and oil sands & extra-heavy oil [WEA, 2000]. Oil shale consists of rocks containing kerogen, which can be converted to synthetic oil. Oil sands are mixtures of natural bitumen, sand, water and clay. The difference between heavy crude oil, extra heavy oil and natural bitumen is vague and there exist many definitions. In most of them, heavy crude oil is defined as oil with a density between 943 and 1000 kg/m^3 and viscosity below 10.000 mPa*s. Extra heavy crude oil has a density over 1000 kg/m^3 and viscosity below 10.000 mPa*s whereas natural bitumen has a density over 1000 kg/m^3 but viscosity over 10.000 mPa*s [WEA, 2000], [Hanson, 1998].

Oil shale

Oil shale consists of sedimentary rocks containing kerogen. They have low calorific value and high ash and mineral content. The weight percentage of organic material varies from 2 or 3 up to 13 percent [Wiser, 2000]. Oil shales are found in many countries, but Brazil, Russia and the United States are the most important, together accommodating 86% of world oil shale resources [Brendow, 2002].

Oil shales have since long been known and in the past have simply been burned to produce heat and electricity. At this moment, oil shales are used in Estonia, where they are used both for electricity production and production of oil. Australia is preparing some pilot projects on oil production. In some other countries, shales are used for production of cement or chemicals, but these are all small-sized projects. In America much research to extract oil shales was carried out after the oil crisis of 1973, but eventually all projects were abandoned. Reasons are the organic content, which varies greatly even over a few meters, the unprofitable extraction techniques and the waste problems. Oil shales have to be fractioned and heated underground to be able to pump them up. Because shales contain kerogen, which actually is no oil but coal, hydrogen has to be added to convert the kerogen to oil. Because of the high sulphur and heavy metals content a lot of processing is required. This takes a lot of water and energy while the final product is synthetic oil of only medium quality. After processing, the waste takes up about 30 percent more space than before, causing severe spatial problems [Wiser, 2000].

The proven amount in place is estimated to be in the order of 20.000 EJ [WEC, 2001], [WEA, 2002], which is about three times as much as the proven reserves of oil at the end of 2001. However, except for some niche markets like those in Estonia, these supplies are not looked upon as economically feasible and are therefore classified as other occurrences.

Heavy crude oil

Heavy crude oil reservoirs are often situated near conventional oil fields or in the bottom of the ocean. Most resources are situated in Venezuela, the former Sovjet Union, Kuwait, Iraq, Mexico and China [WEA, 2000]. The recovery efficiency and productivity are low compared to oil fields with medium or light oil. The oil is too viscous too be pumped up using regular extraction techniques and therefore in-situ steam-injection and cracking are necessary to reduce viscosity. Because they are often situated near conventional oil fields, it is expected that heavy crude oil will only be developed commercially once the nearby conventional oil fields are at depletion. According to the World Energy Assessment, total occurrences are estimated to be 13.200 EJ of which 4.000 EJ would be feasible for future recovery and is classified as resources [WEA, 2000].

Oil sands (natural bitumen) & extra heavy oil

Natural bitumen and extra heavy oil are often treated together in resource studies. The difference between them is their viscosity. Both, however, are too viscous to be pumped up under normal reservoir conditions. Natural bitumen is found in oil sands, in the United States also known as tar sands, which are a mixture of bitumen, sand, water and clay. The world's most important source of oil sands in the world is the province of Alberta in Canada. This province accommodates almost 85% of the world's estimated oil sands resources. Since the late sixties of the former century, these fields are exploited commercially. Oil sands are recovered either by open pit mining or, when they are positioned too deep to be mined, by steam injection.

Currently oil sands account for about one-third of Canadian oil production. By the end of 2005, this is expected to have grown to half of the Canadian oil production. Out of the total resources in Alberta of 9.760 EJ, almost 1.900 EJ is considered ultimately recoverable using current economically feasible techniques. This equals about 29% of the world wide proven reserves of crude oil at the end of 2001. From December 2002 onwards, the Oil and Gas Journal, which is the leading source in reserves estimates, has upgraded the Alberta oil sands to reserves instead of resources. This gives Canada the second greatest reserves in the world. Oil sands outside Alberta are too scattered and exist in too small accumulations to be considered economically extractable.

While Alberta accommodates almost all oil sands resources, the Orinoco River area in Venezuela accommodates almost all extra heavy oil resources. Here the extra heavy oil is deposited too deep to be recovered with open pit mining techniques and therefore techniques like steam injection are used. After extensive processing a product called Orimulsion® originates. A lot of research has been done and a lot of investments have been made but Venezuela has problems finding product markets. All in all exploitation is not as developed as in the case of oil sands. Out of 8.000 EJ of occurrences, 1.650 EJ is considered economically recoverable which equals 25 percent of proven crude oil reserves worldwide.

Summary of reserves, resources and other occurrences

Table 3.2 provides a summary on the occurrences of oil, both conventional and unconventional.

All values in EJ	Reserves	Resources	Other occurrences	Total
Crude oil	≈ 6.500	-	-	6.500
Oil shale	-	≈ 0	20.000	20.000
Heavy crude oil	-	4.000	9.200	13.200
Oil sands	1.900	-	9.600	11.500*
Extra heavy oil	-	1.650	6.350	8.000

Table 3.2: summary of reserves, resources and other occurrences of all forms of oil

3.4 Natural gas

Reserves

Until recently, natural gas was considered less valuable than oil. Currently this view is changing. Due to a higher hydrogen/carbon ratio, combustion of natural gas causes less CO_2 than combustion of oil and therefore increased use of natural gas at the cost of oil could help constraining global CO_2 emissions. BP estimated natural gas reserves to be 6.050 EJ at the end of 2001 [BP, 2002]. OPEC estimated reserves to be 6.950 EJ at the end of 2001 [OPEC, 2002]. The size of oil reserves estimates varies round 6.500 EJ, which means there is almost as much energy available from natural gas as from oil. As the bars in figure 3.4 show, reserves of natural gas are growing at a much higher rate than oil. Mean growth over the period 1981-2001 equals 3,60 %, whereas mean growth of crude oil reserves in the same period equaled 2,45%. As the blue line in figure 3.4 and the chart in figure 3.5 indicate, gas is much more evenly divided among regions than oil. The share of OPEC of natural gas reserves has risen from 36,5% in 1981 to 49,3% in 2001 but there is hardly any production in OPEC countries so the influence of OPEC on worldwide natural gas production is limited.

Figure 3.5 shows the distribution of natural gas reserves over various regions in the world. This figure shows that next to the Middle East, Eastern Europe has great reserves. Table 3.3 shows regional R/P ratios and a R/P ratio for the total world. The latter equals 69,5 years. However, this number is based on current production. Many expect production of natural gas to increase in the near future, which means that the R/P ratio would be an overestimation. As far as world regions are concerned, North America is expected to be the first region fully dependent on imports from other regions. North America is also the biggest consumer of natural gas, together with Eastern and Western Europe [BP, 2002].

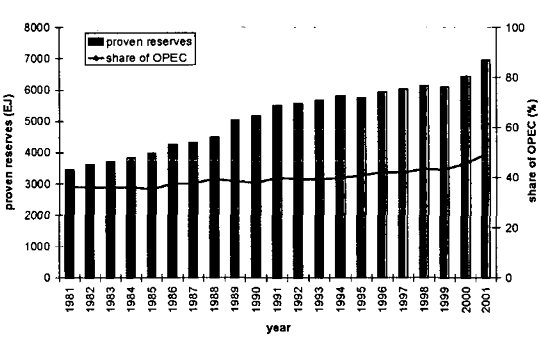

Figure 3.4: development of natural gas reserves
Based on [OPEC, 2002]

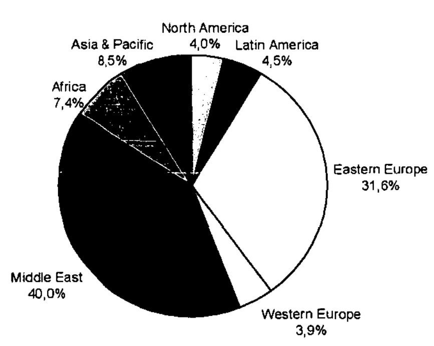

Figure 3.5: regional distribution of natural gas reserves[2]
Based on [OPEC, 2002]

region	reserves (EJ)	production (EJ/year)	R/P ratio (years)
North America	274,64	28,75	9,6
Latin America	315,20	5,36	58,8
Eastern Europe	2198,70	28,87	76,2
Western Europe	274,09	11,12	24,7
Middle East	2782,88	9,41	295, 8
Africa	511,17	5,20	98,3
Asia & Pacific	593,78	11,30	52, 6
World	6950,42	100,01	69,5

Table 3.3: regional R/P ratios and R/P ratio for the whole world (natural gas)[2]
Based on [OPEC, 2002]

Resources & other occurrences

The World Energy Assessment mentions four categories of unconventional natural gas occurrences: coalbed methane, tight formation gas, gas hydrates and aquifer gas [WEA, 2000]. Because natural gas reserves are expected to last longer than oil reserves, there is less research into resources of natural gas than resources of oil. As far as information is available, each resource will be discussed.

Coalbed methane

Coalbed methane is a mixture of gases containing more than 90 percent methane which occurs in coal. It has since long been known as mine gas, a gas dangerous to mineworkers because of its explosive potential. It used to be removed with air ventilation systems but in the seventies of the twentieth century one started capturing it. The supplies released in this way are quite small however. To increase production, separate holes have to be drilled. Because coal has a greater internal surface than conventional gas reservoirs, coal can contain up to seven times as much gas. In order to capture the gas safely, the pressure has to be released first. This can be done by removing water that is present in fractions in the coal. However, the amounts of water released in this way are enormous, and because the water is contaminated with salts, it causes a severe environmental burden [Rice, 1997].

Commercial production occurs currently only in the United States but Australia, China, India and the United Kingdom are planning some projects. Other regions possessing coalbed methane but currently not planning production are the former Sovjet Union and parts of Asia. Because the occurrence of the gas varies greatly within basins, worldwide occurrence is uncertain. Estimates range from 3.300 EJ to 10.000 EJ [WEA, 2000]. In comparison: the world proven reserves of natural gas amounted 6.950 EJ by the end of 2001 [OPEC, 2002]

Tight formation gas

Tight formation gas, or shortly tight gas, is natural gas trapped in reservoirs of hard rock, sandstone or limestone, which are impermeable and non-porous [natural gas, 2002]. Because of this impermeability, production of tight gas requires advanced techniques. Gas flow rates of two to three times higher than those of conventional wells can be achieved, but production is very expensive. In the United States, production takes place on a limited scale, but it is heavily supported by tax breaks and financial incentives. It is estimated to last till at least 2015 before production techniques can become economically feasible. Occurrence is estimated at 4.450 EJ [WEC, 2001].

Gas hydrates

Gas hydrates or clathrates consist of methane molecules trapped in a cage of frozen water molecules. Cages of this kind can contain all sorts of naturally occurring small-sized gas molecules, such as carbon dioxide and hydrogen sulfide, but methane is most common [Woodshole, 2003]. Gas hydrates were first discovered in permafrost regions. Later on indirect evidence through geochemical and geophysical investigations indicated that hydrates cover a significant portion of the ocean floor. However, there is no scientific evidence for the quantities that might be involved, nor are there techniques available or foreseeable to extract them. Estimations are highly uncertain and vary from 350.000 EJ to 750.000 EJ [WEA, 2000].

Aquifer gas

Aquifer gas (geopressured gas, hydropressured gas, brine gas) is found in natural underground formations that are under unusually high pressure for their depth. Typically the content of gas increases at greater depths. Usually aquifer gas zones are found 3.500 to 8.000 meters below the surface of the earth [natural gas, 2002]. Currently some aquifer gas is produced in shallow reservoirs but in all cases the gas is a byproduct of the recovery of trace elements present in the gas. There are no detailed assessments about the volume of reserves, only estimates. These vary from 90.000 to 1.200.000 EJ.

All values in EJ	Reserves	Resources	Other occurrences
Natural gas	6.000-7.000	-	-
Coalbed methane	-	≈ 0	3.300-10.000
Tight formation gas	-	≈ 0	4.450
Gas hydrates	-	-	350.000-750.000
Aquifer gas	-	-	90.000-1.200.000

Table 3.4: summary of reserves, resources and other occurrences of all forms of natural gas

Summary of reserves, resources and other occurrences

Table 3.4 provides a summary on the occurrences of natural gas, both conventional and unconventional.

3.5 Coal

Reserves

At present, coal is mostly used for production of electricity. However, in the future it could well be used to produce gaseous or liquid fuels such as hydrogen or methanol and therefore it is by many seen as a resource with great potential. Coal is divided in classes according to its calorific value and coal content. These are anthracite, bituminous coal, sub-bituminous coal and lignite, with carbon content and calorific value ranging from high (anthracite) to low (lignite). Sub-bituminous coal and lignite are also adressed as brown coal, as opposed to black coal for anthracite and bituminous coal.

Currently coal provides about 22 percent of the world primary energy supply. About 40 percent of global electricity is produced in coal-fuelled power stations [WEA, 2000]. Countries with important coal reserves are Australia, China, India, South Africa and the United States. As can be seen in figure 3.6, coal reserves are distributed much more evenly over the earth than oil and gas resources, with three regions accommodating about a quarter of reserves and the other four regions sharing the last quarter. Table 3.5 shows regional R/P ratios and the R/P ratio for the whole world. The R/P ratio for the Middle East is extremely high due to the fact that there is almost no production. For the whole world the R/P ratio equals 216 years. Because reserves and production are fairly stable in the case of coal, this number is viewed as much more reliable than R/P ratios for oil or natural gas. According to BP coal reserves equal about 29.000 EJ [BP, 2002]. About 85% of this amount consists of hard coal, the remainder of brown coal.

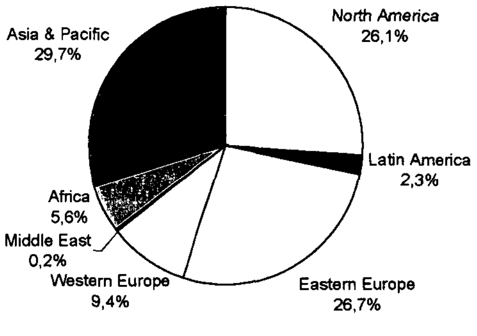

Figure 3.6: distribution of coal reserves over world regions[2]
Adapted from [BP, 2002]

region	reserves (EJ)	production (EJ/year)	R/P ratio (years)
North America	7517,56	32,22	233,3
Latin America	672,82	1,68	401,5
Eastern Europe	7708,19	21,68	355,6
Western Europe	2704,16	13,10	206,4
Middle East	50,10	0,02	2137,5
Africa	1622,25	6,79	239,1
Asia & Pacific	8569,40	58,23	147,2
World	28844,47	133,72	215,7

Table 3.5: regional R/P ratios and R/P ratio for the whole world (coal)[2]
Adapted from [BP, 2002]

Resources

The total amount of coal in the world is estimated to equal about 187.000 EJ. This number includes both reserves and resources. Because reserves take up 29.000 EJ, resources are estimated to be 158.000 EJ.

3.6 *Biomass*

Biomass is a renewable fuel that has been used for ages, primarily for traditional purposes like heating and cooking. Currently biomass accounts for about 11 percent of global primary energy, being most important in developing countries. Until recently, biomass was deemed inferior as compared to fossil fuels, but advanced technologies enable the efficient use of biomass for production of electricity and gaseous or liquid fuels. This has renewed the interest for biomass and today many experts look upon biomass as a high potential renewable energy source. Biomass is a collective term for many different materials. They have in common that they are organic materials with a short carbon cycle. That is, as opposed to fossil fuels that were captured millions of years ago, the CO_2 that is released by the use of biomass was only recently captured. Therefore it does not add to the net amount of carbon in the earth's carbon cycle, as the carbon released from fossil fuels does. Biomass has many sources. [Eurec, 2002] distinguishes the following:

- Short rotation forestry (willow, poplar, eucalyptus)
- Herbaceous ligno-cellulosic crops (miscanthus)
- Sugar crops (sugar beet, sweet sorghum)
- Starch crops (maize, wheat)
- Oil crops (rape seed, sunflower)
- Wood wastes (forest residues, wood processing waste, construction residues)
- Agricultural residues and waste (straw, animal manure, etc.)
- Organic fraction of municipal solid waste and refuse
- Sewage sludge
- Industrial residues (e.g. from wood and paper industries)

Biomass can be divided in waste materials and energy crops. Waste materials are supplies that are leftovers or byproducts of other processes, whereas energy crops are plants that are grown with the purpose of production of energy or fuels. The availability of biomass is subject to other characteristics than fossil fuels. Biomass is renewable so it won't get depleted and there is no matter of reserves or resources. However, biomass has to be either recovered from waste streams or it has to be grown. The potential of waste streams is limited for there is only a limited amount of organic waste material that can be recovered. The amount of waste depends on world population and energy efficiency. As we have seen in the previous chapter estimations for these variables vary greatly, and so do estimations of the potential of waste streams. Hall estimated as a broad rule of thumb that energy contents of residues are about one third of global commercial energy use [Hall, 1993]. About 30 percent of this stream is organic material that could potentially be recovered for energy purposes. This comes down to 10 percent of the global commercial energy use. In the scenarios from the previous chapter, final energy in the year 2050 is estimated to range between 290 and 740 EJ per year. If we assume final energy use to equal commercial energy use, the potential for waste streams ranges between 29 and 74 EJ per year.

The potential of energy crops for primary energy depends primarily on the amount of land that can be used to grow crops, the productivity of the land, availability of water and environmental implications. For final energy use, also technical performances of conversion technologies are added to these factors [WEA, 2000]. The amount of land available to grow crops depends on the world population and the efficiency of food production. The globally available total amount of land equals 13,1 billion hectares. Most of this land consists of permanent pastures, forests, woodlands and cropfield for food production. When the world population increases, more land

Region	Maximum area for biomass production (10^6 hectare)	Maximum additional amount of energy from biomass[a] (EJ/year)	
		yield=8,5[b]	yield=15[b]
Industrialized countries	100,0	15,3	27,0
Latin America	665,0	101,7	179,6
Africa	484,0	74,1	130,7
Asia	33,0	5,0	8,9
China	-	1,8	1,8
Total	1282,0	197,9	347,9

[a]: the additional amount of energy is calculated by multiplying the maximum area for biomass production with the yield and a lower heating value of 18 GJ per oven dry tonne

[b]: yield in oven dry tonnes per hectare per year

Table 3.6: energy crop potential in 2050

Adapted from [WEA, 2000]

will be needed to fulfill the need for food, leaving less potential for energy crops. Only when the efficiency of food production increases, this effect can be (partially) undone. In order to give quantitative estimates of the potential of energy crops, most studies identify a reference year and a predicted global population. In the previous chapter the time horizon was the year 2050. In order to be able to compare the numbers in this section with those from the previous chapter, the year 2050 will also be used in this section. In 1990 the potential for energy crops amounted 1,6 to 1,8 Gha, with a global population of 5,3 billion people. The World Energy Assessment expects world population to have risen to 8,3 billion people by 2050 [WEA, 2000], leaving 1,28 Gha of land for the production of energy crops. For the productivity of the land, the World Energy Assessment uses a high estimate and a low estimate. In the high estimate, each hectare yields 15 oven dry tonnes of biomass per year. In the low estimate, this is only 8,5 oven dry tonnes per hectare per year. It is assumed that as much water is available as needed. Under these conditions, the potential for energy crops ranges from almost 200 EJ per year to almost 350 EJ per year, as is shown in table 3.6.

The total potential for biomass both from waste streams and energy crops ranges from 230 EJ per year to 420 EJ per year in the year 2050. From the comparison of scenarios in the previous chapter it appeared that the use of biomass for primary energy is expected to lie between 78 and 206 EJ per year by 2050. These values show that the potential availability of biomass is high enough to satisfy the need. The reader should keep in mind though that this research has only looked at potential availability and that other factors concerning the use of biomass like available technology and production costs have not been taken into account.

3.7 Summary and conclusions

After having investigated the anticipated energy need in the previous chapter, this chapter has investigated the availability of energy sources. Four energy sources have been included in the investigation: crude oil, natural gas, coal and biomass.

Reserves of crude oil are investigated by many institutions. Their recorded values show some differences but report an order of magnitude of 6.500 EJ. Over three-quarters of these reserves are located in only 11 countries, which causes the world to be heavily dependent on these countries. The regions in the world consuming the most oil will be the first to face depleted reserves, thereby further increasing the dependence. By the end of 2001, the R/P ratio for crude oil amounted 46,9 years. This number isn't very reliable however because both reserves and production are expected to increase. Rather than running out of oil, some people fear that oil production will reach a maximum followed by a rapid decline. According to their calculations, the peak in oil production will come between 2005 and 2010. However, there are arguments to counterbalance these calculations. Besides reserves, there are also resources of oil. These include oil shales, heavy crude oil, oil sands and extra heavy oil. Together they comprise 51.000 EJ of energy, of which 5.650 EJ is regarded to be economically extractable (4.000 EJ from heavy crude oil, 1.650 EJ from oil sands) and 1.900 EJ has recently been upgraded to reserves (Alberta oil sands).

Natural gas reserves are less precisely recorded than oil reserves. Reported global reserves vary between 6.050 and 6.950 EJ, which means that there is about as much energy available in oil as in natural gas. Natural gas is more evenly distributed around the world than oil, which gives it the advantage over oil that there is less dependence on exporting countries. The worldwide R/P ratio amounts 69,5 years, but when the production increases, as many expect, this will be an overestimation. North America is the only region expected to be depleted in the short term. Resources include coalbed methane, tight formation gas, gas hydrates and aquifer gas. The occurrence of these resources contains a higher degree of uncertainty than that of oil. Estimations of total resources vary between 450.000 EJ and 19.550.000 EJ. Most of these resources are regarded non-extractable in the foreseeable future, however. Only small quantities of coalbed methane and aquifer gas are currently produced.

Coal is currently used for production of electricity but many experts see potential for the production of liquid fuels and hydrogen. Current reserves amount 29.000 EJ. Of all fossil fuel reserves, coal reserves are most evenly distributed over the world. The R/P ratio amounts 216 years and is more reliable than R/P ratios for oil and natural gas because of more stable reserves and production. Besides reserves, there are 166.000 EJ resources of coal.

At this moment biomass contributes primarily to global energy use in traditional ways, but it has great potential for production of electricity and liquid or gaseous fuels. Biomass can be recovered from residues or can be purposely grown. The potential from residues is estimated to amount 10 percent of commercial energy use. According to the predictions from the scenarios in the previous chapter, the potential in the year 2050 lies between 29 and 74 EJ. The potential for the growing of crops depends on the availability of land, the production capacity of this land, the availability of water and environmental implications. Estimations of the potential availability of energy crops vary between 200 EJ per year and 350 EJ per year. As the scenarios from the previous chapter show, this potential is not expected to be completely used.

4 Development of a model to calculate WTW energy use and emissions

4.1 *Introduction*

In this chapter a calculation method is developed to assess how much energy is used in the production and use of a fuel, and to calculate the size of the emissions that are released during production and use. The calculation method is developed according to the Well to Wheel concept, which is explained in section 2. In section 3 the energy flows in the production of the fuel are modelled while section 4 is dedicated to the greenhouse gas emissions that emerge from the production of the fuel. Section 5 is dedicated to energy use and emissions during the use of the fuel (driving the car). In section 6, the information on production and use is combined, for both energy flows and emissions. Finally, section 7 is dedicated to the ways in which the results can be presented. In appendix C, an overview of the nomenclature used in this study is presented.

4.2 *The Well to Wheel concept*

The framework that is used in this study has been developed according to the Well to Wheel (WTW) concept. The term Well to Wheel indicates that all energies embedded in the fuel or used at any point in the production of the fuel are included, from the point of extraction (the well) to the final use of the fuel in a vehicles engine (to drive the wheels). In the case of alternative fuels it is strictly speaking not always justified to speak of a well because not all alternative fuels are recovered from a well. However, the term Well to Wheel is very appealing and therefore has become common to use anyway. The Well to Wheel chain can be split in a Well to Tank (WTT) part and a Tank to Wheel (TTW) part. The WTT part covers the WTW chain from the point of extraction to the point where the fuel is in the tank of a vehicle. The TTW part covers the burning of the fuel in the vehicles engine, or other types of conversion on board of the vehicle (e.g. fuel cell).

A schematic overview of a generalised WTW fuel chain is depicted in figure 4.1. The part of the figure from A to B constitutes the WTT part, while the part from B to C constitutes the TTW part. As the picture shows, the WTT part of a fuel chain can be subdivided in the actual fuel chain and the WTT system. The production of the fuel takes place in several steps in the fuel chain, depicted by the black boxes in the figure. In each step, several process energies are used to convert the ingoing energy into the output product of the production stage. The process fuels are input in the fuel chain. The process fuels themselves have also been produced by fuel chains. Their production is portrayed by the red boxes. Each of these boxes stands for a complete WTT system including a fuel chain with multiple steps, but for the sake of simplicity these chains are depicted by a single box. The production of the process fuels is not a part of the fuel chain itself. It is a part of the WTT system though and the energy use should be included in WTT calculations. The production of a process fuel requires the use of different primary energy inputs, as is depicted by the dashed blue lines in figure 4.1. One of the primary inputs is also used as feedstock in the fuel chain. By summing all the quantities of a primary input that are used either in the fuel chain or in the WTT system of the fuel chain, the total amount of each primary input can be determined. The sum of all primary inputs denotes the total amount of primary energy used in the WTT system. In most steps of most fuel chains, only one product is created. However, in some steps also byproducts are formed. In figure 4.1, the byproducts emerging from the fuel chain are denoted by the solid green

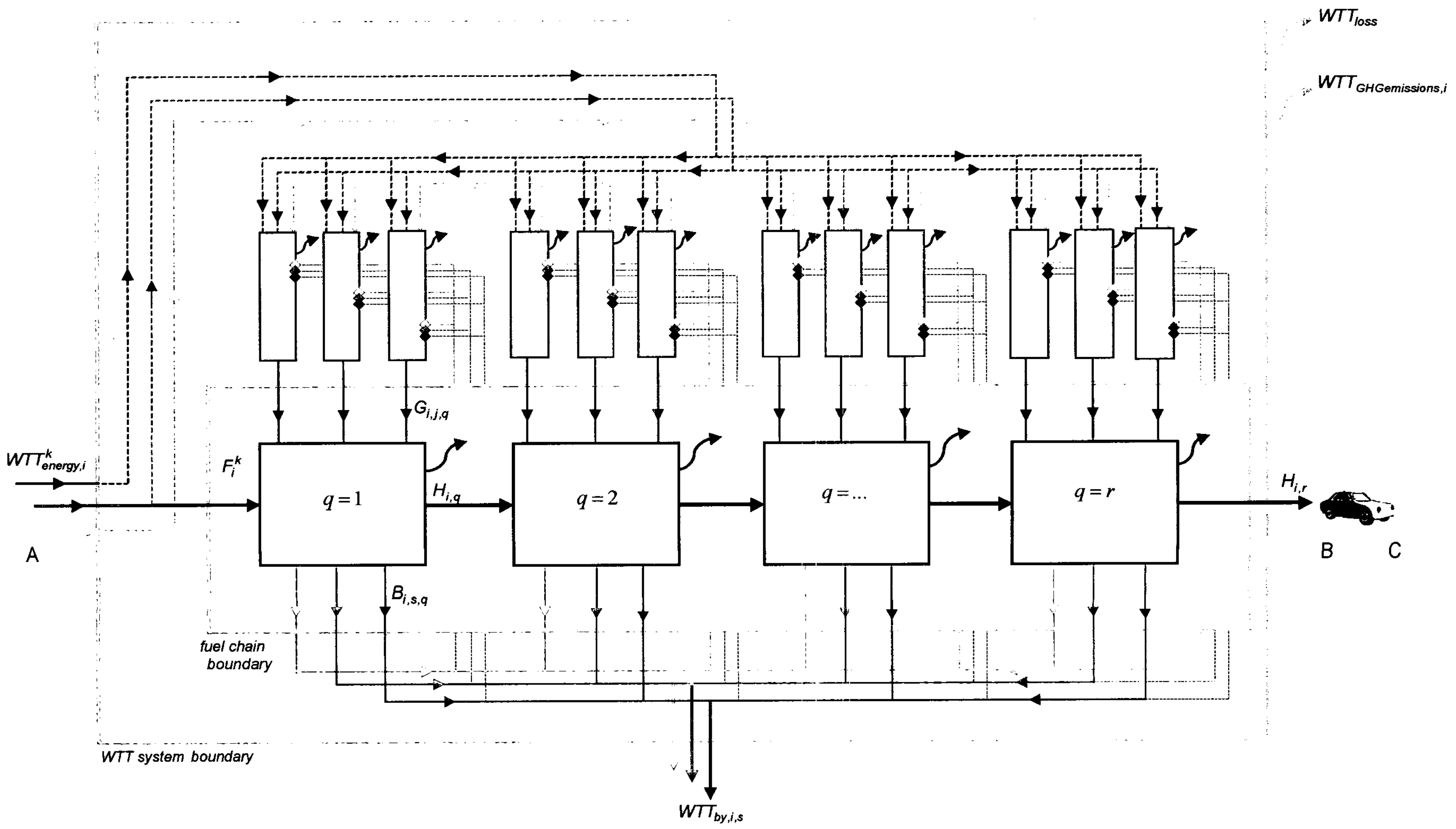

Figure 4.1: schematic overview of a fuel chain and associated energy flows

lines. As the figure shows, one step can produce multiple byproducts. Byproducts are not only produced in the fuel chains themselves, but also in the fuel chains of the process fuels. These byproducts, denoted by the dashed green lines, are no part of the fuel chain but only of the WTT system. Because they are a part of the WTT system they have to be included in WTT calculations. By summing all the amounts of a byproduct produced in the fuel chain itself and in the WTT system of the fuel chain, one obtains for each byproduct the total amount produced. The curved arrows leaving the process steps and the fuel chains of the process fuel depict energy losses and emissions. The second part of the chain, the TTW part, is much less complicated. In the TTW part, the fuel is taken from the tank of the vehicle and converted into mechanical energy by the powertrain of the car, which causes the wheels to turn. The TTW part makes no use of process fuels or primary feedstocks. It only uses the output of the WTT part as input. The output of the TTW part of the fuel chain consists of the traveled distance and of emissions.

4.3 Modeling of energy flows in the WTT fuel chain

In this section, the energy flows in the WTT fuel chain are modelled. First a single step is modelled after which this model is expanded to a whole fuel chain. To each fuel in the fuel chain and each associated fuel chain to be modelled a label is assigned, namely i, with $i = \{1,2,...,m-1,m\}$. The model is able to contain not only fuels, but also energy carriers of all kinds, for example electricity. For the sake of simplicity, we only talk about fuels here. Whenever the word "fuel" is used in this chapter, this term includes all energy carriers that are contained in the model. The steps in the fuel chain are numbered q, with $q = \{1,2,...,r-1,r\}$. To the process energies a label j is assigned, with $j \in i$. Byproducts are labelled s, with $s = \{1,2,...,t-1,t\}$. Finally, energy losses are labelled E_{loss}. With this information, step q of fuel chain i can be schematically drawn as shown in figure 4.2.

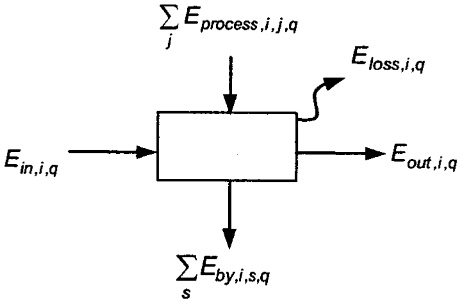

Figure 4.2: step *q* of fuel chain *i*

With:

$E_{in,i,q}$: ingoing energy in step q of fuel chain i. In the course of the fuel chain, a primary feedstock enters the fuel chain in the first step, $E_{in,i,1}$, and is converted to fuel i.

$E_{out,i,q}$: outgoing energy of step q of fuel chain i. Like the ingoing energy, the type of outgoing energy changes in the course of the fuel chain.

$\sum_j E_{process,i,j,q}$: sum of the process energies of type j in step q of fuel chain i.

$\sum_s E_{by,i,s,q}$: sum of byproducts of type s in step q of fuel chain i.

$E_{loss,i,q}$: energy losses in step q of fuel chain i. The energy loss in a step is the difference between all ingoing energies and all outgoing energies:

$$E_{loss,i,q} = E_{in,i,q} + \sum_j E_{process,i,j,q} - (E_{out,i,q} + \sum_s E_{by,i,s,q})$$

In order to be able to easily compare the energy balances between steps and fuel chains, all energies in a step are normalised by dividing them with $E_{out,i,q}$, the outgoing energy of that step:

$$f_{i,q} = \frac{E_{in,i,q}}{E_{out,i,q}} \tag{1}$$

$$g_{i,j,q} = \frac{E_{process,i,j,q}}{E_{out,i,q}} \tag{2}$$

$$b_{i,s,q} = \frac{E_{by,i,s,q}}{E_{out,i,q}} \tag{3}$$

With:

$f_{i,q}$:	normalised ingoing energy. This number denotes how much ingoing energy is needed to create 1 unit of energy leaving step q.
$g_{i,j,q}$:	normalised process energy. This number denotes how much process energy of a process fuel of type j is needed to create 1 unit of energy leaving step q.
$b_{i,s,q}$:	normalised energy contained in byproduct of type s. This number denotes how much byproduct of type s is produced per unit of output energy.

When all the separate steps in the fuel chain are placed behind each other, they can be connected so that they constitute an entire fuel chain, as is shown in figure 4.3.

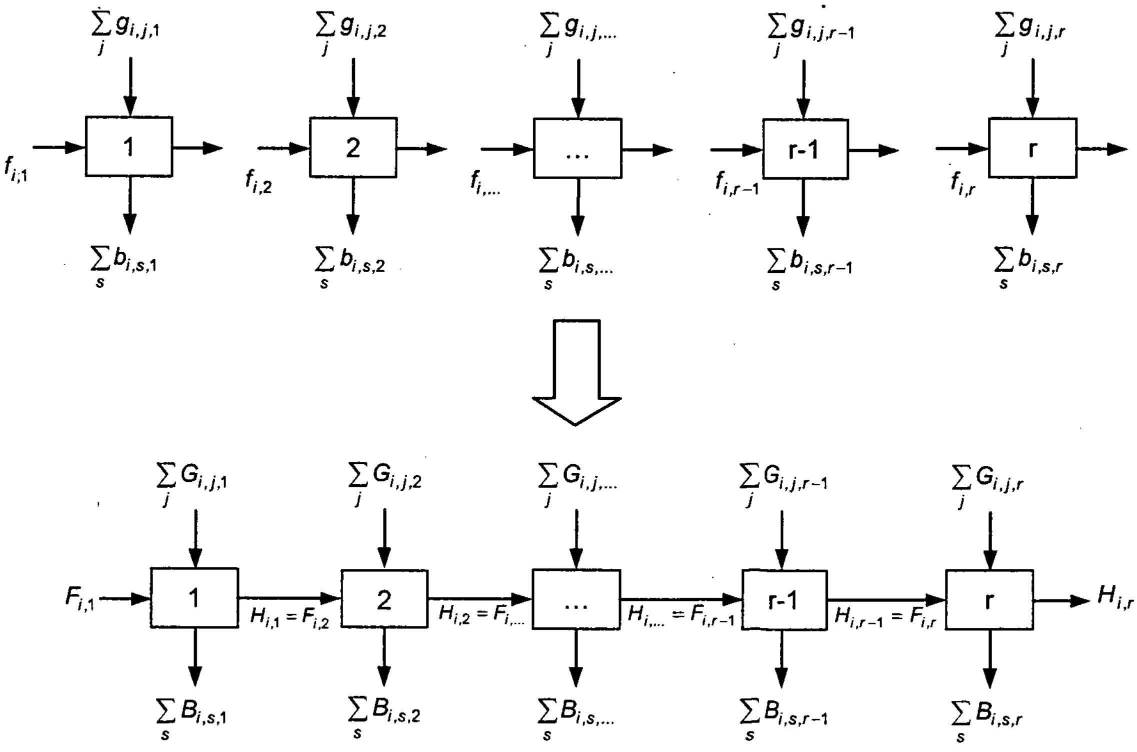

Figure 4.3: fuel chain *i*

In order to describe an energy chain producing a certain absolute amount of output $H_{i,r}$, the absolute values of all energy flows in the chain can be expressed as a function of the normalised step characteristics. To this end these absolute flows are labelled:

$H_{i,q}$: outgoing energy of step q of fuel chain i.
$F_{i,q}$: ingoing energy in step q of fuel chain i.
$G_{i,j,q}$: process energy of process fuel of type j in step q of fuel chain i.
$B_{i,s,q}$: amount of byproduct of type s produced in step q of fuel chain i.

In the case of the last step of the fuel chain, the ingoing energy of the step equals the outgoing energy of the step times the normalization factor $f_{i,r}$ of that step, and therefore:

$$F_{i,r} = f_{i,r} \cdot H_{i,r} \tag{4}$$

In the last but one step of the fuel chain, step *(r-1)*, the output of this step must be equal to the input of the last step, step r:

$$H_{i,r-1} = F_{i,r} \tag{5}$$

Combining formula (4) and (5) gives:

$$H_{i,r-1} = f_{i,r} \cdot H_{i,r} \tag{6}$$

The ingoing energy of step *(r-1)* can be calculated with:

$$F_{i,r-1} = f_{i,r-1} \cdot H_{i,r-1} = f_{i,r-1} \cdot f_{i,r} \cdot H_{i,r} \tag{7}$$

The expressions for the ingoing energy can be generalized in the following equation:

$$F_{i,q} = H_{i,r} \cdot \prod_{q=q}^{r} f_{i,q} \tag{8}$$

In the same way the process energies can be calculated. A process energy of type j in the last step is denoted $G_{i,j,r}$ and can be calculated as follows:

$$G_{i,j,r} = g_{i,j,r} \cdot H_{i,r} \tag{9}$$

The process energy of type j of the last step but one can be calculated by multiplying the process energy relative to the output of that step with the normalization factor of the last step and the output of the last step:

$$G_{i,j,r-1} = g_{i,j,r-1} \cdot f_{i,r} \cdot H_{i,r} \tag{10}$$

The process energy in the last step but two equals:

$$G_{i,j,r-2} = g_{i,j,r-2} \cdot f_{i,r-1} \cdot f_{i,r} \cdot H_{i,r} \tag{11}$$

In generalized form this formula becomes:

$$G_{i,j,q} = g_{i,j,q} \cdot H_{i,r} \cdot \prod_{q=q+1}^{r} f_{i,q} \tag{12}$$

In the same way, a formula for the byproducts can be deduced. This formula becomes:

$$B_{i,s,q} = b_{i,s,q} \cdot H_{i,r} \cdot \prod_{q=q+1}^{r} f_{i,q} \tag{13}$$

The fuels used in the fuel chain and the WTT system are made from different primary inputs such as crude oil or biomass. Primary inputs are labelled k, with $k = \{1,2,\ldots,n-1,n\}$. A primary energy input of type k in fuel chain i is depicted as F_i^k. From all primary energy inputs that are used throughout the WTT system, only one is used as feedstock in the first step of the fuel chain. This primary input is assigned the label $k{=}a$. In this case, $F_i^a = F_{i,1}$. For all other values of k (i.e. $k \neq a$), $F_i^k = 0$.

Calculation of primary energy inputs

The fuel chain itself is now modelled. The primary feedstock input, the energy input and output in each step, the direct process energies and the direct byproducts are all known. In figure 4.1, these are respectively the blue-black line entering the first black box, the black boxes and the arrows that connect them, the red arrows entering the black boxes and the green arrows leaving the black boxes. However, as we see in the figure, there is also a WTT system. This includes not only the fuel chain itself, but also the dashed blue lines entering the red boxes and the dashed green lines leaving the red boxes. These are the primary inputs and the byproducts from the fuel chains of the process fuels. They are part of the WTT system and have to be taken into account. For taking into account the primary energies of the process fuels in the total amount of primary energy, the following formula is applied:

$$WTT_{energy,i}^{k} = F_i^k + \sum_{j=1}^{m}\left(\sum_{q} G_{i,j,q} \cdot wtt_{energy,j}^{k}\right) \tag{14}$$

$$F_i^k = 0, \text{ if } k \neq a$$
$$F_i^k = F_{i,1}, \text{ if } k = a$$

With:

$WTT_{energy,i}^{k}$:	the total amount of primary input of type k used in the WTT system of fuel chain i.
F_i^k:	the primary input of type k entering the fuel chain in step $q{=}1$.
$wtt_{energy,j}^{k}$:	the amount of primary input of type k used in the WTT system of fuel chain j needed to produce 1 unit of process fuel of type j. This normalised WTT energy can be calculated by dividing the WTT energy of fuel chain j with the amount of energy leaving fuel chain j: $wtt_{energy,j}^{k} = \dfrac{WTT_{energy,j}^{k}}{H_{j,r}}$
$\sum_{q} G_{i,j,q}$:	the amount of process fuel of type j used in fuel chain i (summed over all steps in the fuel chain)
$\sum_{q} G_{i,j,q} \cdot wtt_{energy,j}^{k}$:	the amount of primary input of type k that is used to produce the amount of process fuel of type j that is used in the WTT system of fuel i.

Formula (14) contains terms that are formulas in themselves. By writing these down as far as possible and normalising the formula to the output of the fuel chain $H_{i,r}$, the following formula emerges:

$$wtt^{k}_{energy,i} = f^{k}_{i} + \sum_{j=1}^{m}\left(wtt^{k}_{energy,j} \cdot \sum_{q=1}^{r}\left(g_{i,j,q} \cdot \prod_{q=q+1}^{r} f_{i,q}\right)\right) \qquad (15)$$

$$f^{k}_{i} = 0, \text{ for } k \neq a$$

$$f^{k}_{i} = \prod_{q=1}^{r} f_{i,q} \text{ , for } k = a$$

As we see in formula (14) and (15), the WTT energy of type *k* used in the WTT system of fuel chain *i* depends on the primary feedstock input of type *k* in fuel chain *i*, on the amount of process fuel use of all process fuels, from *j=1* to *j=m*, and on the amount of WTT energy of type *k* that is needed to create 1 unit of each process fuel. The amount of WTT energy that is needed to create 1 unit of a process fuel is calculated in itself by formula (15), only with different values for *i* and *j*. This means that the WTT energy use of type *k* in each fuel chain has to be known before the WTT energy use of type *k* in fuel chain *i* can be calculated. However, there is a fair chance that the endproduct of fuel chain *i* is used in one or more fuel chains of the process fuels. In this case, the WTT energy use of type *k* in fuel chain *i* has to be known before the WTT energy use of type *k* in each fuel chain can be calculated. For this reason formula (15) can generally only be solved by means of iteration. Because all fuel chains are connected to each other, the calculation can only be resolved by calculating the WTT energy use of type *k* in all fuel chains at once.

In the first step of the iteration, a set of values has to be assumed for all values of $wtt^{k}_{energy,j}$ from *j=1* to *j=m*. All values are assumed to equal 1, which means that this step in the iteration comes down to $wtt^{k}_{energy,i} = f^{k}_{i} + \sum_{j=1}^{m}(\sum_{q} g_{i,j,q} \cdot 1)$. The result of the first step is a set of values for the $wtt^{k}_{energy,i}$ for all values of *i* from *i=1* to *i=m*. This set is entered as $wtt^{k}_{energy,j}$ in the second step of the iteration, which results in a new set of values for $wtt^{k}_{energy,i}$. Each value in this set is then entered as $wtt^{k}_{energy,j}$ in the third step of the iteration. By repeating this process a number of times the values of $wtt^{k}_{energy,i}$ and $wtt^{k}_{energy,j}$ converge as the difference between them approaches zero. From this process, the WTT energy use of type *k* in all fuel chains from *i=1* to *i=m* emerges.

By summing all the primary inputs *k* from *k=1* to *k=n* in a fuel chain, the total primary energy input needed to create 1 unit of output is calculated:

$$wtt_{energy,i} = \sum_{k=1}^{n} wtt^{k}_{energy,i} \qquad (16)$$

With:

$wtt_{energy,i}$: normalised primary energy input in the WTT system of fuel chain *i*. This number denotes how much primary energy is needed to create 1 unit of fuel leaving fuel chain *i*.

Calculation of byproducts

With formula (14) to (16) the primary energy inputs of the fuel chains of the process fuels are included in the model. Now only the byproducts from the fuel chains of the process fuels have to be included to complete the model. This can be done with formula (17):

$$WTT_{by,i,s} = \sum_{q} B_{i,s,q} + \sum_{j=1}^{m}\left(\sum_{q} G_{i,j,q} \cdot wtt_{by,j,s}\right) \qquad (17)$$

With:

$WTT_{by,i,s}$: the total amount of byproduct of type *s* produced in the WTT system of fuel chain *i*.

$\sum_{q} B_{i,s,q}$: the amount of byproduct of type *s* produced in fuel chain *i*.

$\sum_{q} G_{i,j,q}$: the amount of process fuel *j* used in fuel chain *i*.

$wtt_{by,j,s}$: the amount of byproduct of type *s* produced during the production of 1 unit of process fuel of type *j* in the WTT system of fuel chain *j* . This normalised WTT energy can be calculated with $wtt_{by,j,s} = \frac{WTT_{by,j,s}}{H_{j,r}}$

$\sum_{q} G_{i,j,q} \cdot wtt_{by,j,s}$:the amount of byproduct of type *s* that emerges from the production of the amount of process fuel of type *j* that is used in the WTT system of fuel chain *i*.

This formula still contains terms that have to be calculated themselves. By integrating these calculations in the formula and normalising the formula to the output of the fuel chain, the formula becomes:

$$wtt_{by,i,s} = \sum_{q=1}^{r}\left(b_{i,s,q} \cdot \prod_{q=q+1}^{r} f_{i,q}\right) + \sum_{j=1}^{m}\left(wtt_{by,j,s} \cdot \sum_{q=1}^{r}\left(g_{i,j,q} \cdot \prod_{q=q+1}^{r} f_{i,q}\right)\right) \tag{18}$$

Formula (17) and (18) tell us that the amount of byproduct of type *s* produced in the WTT system of fuel chain *i* depends on the amount of byproduct of type *s* produced in the fuel chain, on the amount of process fuel use of all process fuels, from *j=1* to *j=m*, and on the amount of byproduct of type *s* produced in the WTT systems of the process fuels. This tells us that the amounts of byproduct of type *s* produced in the WTT systems of all process fuels that are used in fuel chain *i* must be known before the amount of byproduct of type *s* produced in the WTT system of fuel chain *i* can be calculated. However, there is a chance that some of the fuel chains of the process fuels produce byproduct of type *s*, too. In this case, the amount of byproduct of type *s* produced in the WTT system of fuel chain *i* is needed to calculate the amount of byproduct of type *s* produced in the WTT system of fuel chain *i*. In this situation the term $wtt_{by,i,s}$ appears on both sides of the equation. Similar to formula (15), such an equation can only be solved by iteration. It is important to note that, because all fuel chains are connected to each other, they all have to be solved at once in order to obtain the right outcome. The working of the iteration process has been explained in detail before and will only be repeated shortly here. In the first step of the iteration, all values of $wtt_{by,j,s}$ are assumed to equal 1. This results in a set of values for $wtt_{by,i,s}$ for all values of *i*, from *i=1* to *i=m*. Next these values are entered as new values for $wtt_{by,j,s}$ in the right side of the equation. This results in new values for $wtt_{by,i,s}$. By repeating this process a number of times, a valid set of data for the amounts of byproduct produced in the fuel chains is found. This process can be repeated for each byproduct, from *s=1* to *s=t*.

The amount of byproduct produced in a fuel chain is calculated by summing the amounts per individual byproduct:

$$wtt_{by,i} = \sum_{s=1}^{t} wtt_{by,i,s} \tag{19}$$

With:

$wtt_{by,i}$: the sum of all byproducts produced in the WTT system of fuel chain *i* per unit of energy leaving the WTT system of the fuel chain.

With these calculations, the modeling of all energy flows in the fuel chain system is complete. However, one of the purposes of this study is to build a model with which different fuel chains can be compared. For a fair comparison, the output of all fuel chains has to be comparable. At this point, all fuel chains have different outputs due to the different amounts of byproducts that are produced. These outputs can not be compared just like that and therefore some additional operations have to be performed on the byproducts. How this is done, is explained in section 7 of this chapter.

4.4 Modeling of emissions in the WTT chain

In this section, the emissions generated by the fuel chain will be modelled. Emissions are generated both in the process steps of the fuel chain and in the production processes of the process fuels. In the calculation of the magnitude of the emissions, a distinction is made between CO_2 and other emissions. This section starts with an overview of the calculation for CO_2 emissions after which the calculation of other emissions will be discussed.

CO_2 emissions

So far, the modeling of process energies and byproducts has been oriented towards describing singular steps and connecting these steps. However, data on CO_2 emissions emerging from individual steps contain high levels of uncertainty. To sum and multiply these emissions in the way the energy flows are summed and multiplied, would result in outcomes with large confidence intervals. This is not necessary. From a carbon balance over the WTT system of a fuel chain, we learn that the amount of carbon entering the WTT system equals the amount of carbon leaving the fuel chain, either contained in the fuel, contained in byproducts or as emissions, primarily as carbon dioxide. The carbon content of all fuels entering the fuel chain and of all fuels and byproducts leaving the fuel chain is known and can be expressed in carbon dioxide equivalents. This leaves only the carbon dioxide emissions as unknown variable. With one unknown variable and one formula, the unknown variable can be calculated. Rewriting the carbon dioxide balance in order to isolate the emissions results in the required formula:

$$WTT_{emissions,i,CO_2} = \sum_{k=1}^{m}\left(WTT_{energy,i}^{k}\cdot\sigma_k\right) - \sum_{s=1}^{t}\left(WTT_{by,i,s}\cdot\sigma_s\right) - H_{i,r}\cdot\sigma_i \tag{20}$$

With:

$WTT_{emissions,i,CO_2}$:WTT carbon dioxide emissions produced in fuel chain *i*.

$WTT_{energy,i}^{k}$: amount of primary feedstock *k* used in the WTT system of fuel chain *i*.

σ_k: CO_2 content of primary feedstock *k*.

$WTT_{by,i,s}$: Total amount of byproduct *s* produced in the WTT system of fuel chain *i*.

σ_s: CO_2 content of byproduct *s*.

$H_{i,r}$: Energy leaving the last step of fuel chain *i*.

σ_i: CO_2 content of fuel *i*.

The carbon dioxide emissions per unit of energy leaving the fuel chain can be calculated by normalising formula (20) on the output of the fuel chain $H_{i,r}$:

$$wtt_{emissions,i,CO_2} = \sum_{k=1}^{m}\left(wtt_{energy,i}^{k}\cdot\sigma_k\right) - \sum_{s=1}^{t}\left(wtt_{by,i,s}\cdot\sigma_s\right) - \sigma_i \tag{21}$$

With:

$wtt_{emissions,i,CO_2}$: WTT carbon dioxide emissions produced in fuel chain i per unit of energy leaving the fuel chain.

Other emissions

The modeling of other emissions is done similar to the modeling of process energies and byproducts. Emissions are indicated by Z. The specific substance is indicated with the subscript v, with $v = \{1,2,\ldots,u-1,u\}$. Figure 4.4 presents a schematic drawing of the emissions of a process step.

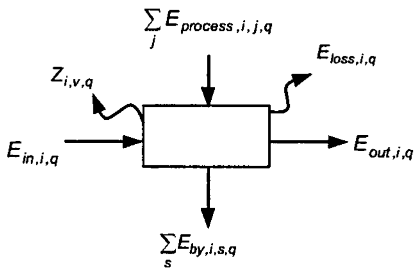

Figure 4.4: emissions in step *q* of fuel chain *i*

With:

$E_{in,i,q}$: ingoing energy of step q of fuel chain i.

$E_{out,i,q}$: outgoing energy of step q of fuel chain i.

$\sum_j E_{process,i,j,q}$: sum of the process energies of type j in step q of fuel chain i.

$\sum_s E_{by,i,s,q}$: sum of byproducts of type s in step q of fuel chain i.

$E_{loss,i,q}$: energy losses in step q of fuel chain i.

$Z_{i,v,q}$: emission of substance of type v in step q of fuel chain i.

The emissions can be related to the output of the step by dividing them with the outgoing energy:

$$w_{i,v,q} = \frac{Z_{i,v,q}}{E_{out,i,q}} \tag{22}$$

With:

$w_{i,v,q}$: normalised emissions of substance of type v. w is related to 1 unit of energy leaving step q.

Several steps can be connected to constitute a fuel chain. In this case, the emissions have to be related to the output leaving the fuel chain. In order to be able to do so, a new unit has to be introduced:

$W_{i,v,q}$: emission of substance of type v in step q of fuel chain i.

In the last step of the fuel chain, $W_{i,v,q}$ is equal to the normalised emissions times the normalization factor of the last step:

$$W_{i,v,q} = w_{i,v,q} \cdot H_{i,r} \tag{23}$$

In the last step but one, the emissions related to the output of the step have to be multiplied with the normalised outgoing energy of the last step but one and the normalization factor of the last step in order to relate them to the output of the last step:

$$W_{i,v,r-1} = w_{i,v,r-1} \cdot f_{i,r} \cdot H_{i,r} \tag{24}$$

The emissions of the last step but two can be related to the output of the fuel chain by multiplying them with the normalised outgoing energy, the normalization factor of the last step and the last step but one. From these equations, a general formula can be deduced:

$$W_{i,v,q} = w_{i,v,q} \cdot H_{i,r} \cdot \prod_{q=q+1}^{r} f_{i,q} \tag{25}$$

With this formula, the emissions in the fuel chain are known. However, these are not the only places in the fuels WTT system where emissions are created. Emissions also emerge from the fuel chains of the process fuels in the WTT system of the fuel chain. In order to take these emissions into account, the following formula can be applied:

$$WTT_{emissions,i,v} = \sum_{q} W_{i,v,q} + \sum_{j=1}^{m} \left(\sum_{q} G_{i,j,q} \cdot wtt_{emissions,j,v} \right) \tag{26}$$

With:

$WTT_{emissions,i,v}$: emissions of substance of type v in the WTT system of fuel chain i.

$\sum_{q} W_{i,v,q}$: the amount of emissions of substance of type v emerging from fuel chain i.

$\sum_{q} G_{i,j,q}$: the amount of process fuel of type j used in fuel chain i

$wtt_{emissions,i,v}$: emissions of substance of type v that emerge from the production of 1 unit of process fuel of type j in the WTT system of fuel chain j.

$\sum_{q} G_{i,j,q} \cdot wtt_{emissions,j,v}$:the total amount of emissions of substance of type v that result from the use of process fuel of type j in the WTT system of fuel chain i.

This formula contains some terms that have to be calculated by themselves. By writing these down and normalising the formula to the output of the fuel chain, the following formula emerges:

$$wtt_{emissions,i,v} = \sum_{q=1}^{r} \left(w_{i,v,q} \cdot \prod_{q=q+1}^{r} f_{i,q} \right) + \sum_{j=1}^{m} \left(wtt_{emissions,j,v} \cdot \sum_{q=1}^{r} \left(g_{i,j,q} \cdot \prod_{q=q+1}^{r} f_{i,q} \right) \right) \tag{27}$$

We see in equation (26) and (27) that the WTT emissions in the WTT system of fuel chain i depend on the emissions in the fuel chain, the amount of process fuel use of each process fuel from $j=1$ to $j=m$, and the emissions that result from the WTT production of the process fuels. This means that the WTT emissions in the WTT system of all fuel chains have to be known in order to be able to calculate the WTT emissions in the WTT system of fuel chain i. However, the chances are quite high that one or more WTT systems of the process fuels use the output of fuel chain i as process fuel. In this case, the WTT emissions from the WTT system of fuel chain i have to be known in order to be able to calculate the WTT emissions in the WTT system of the process fuel. In this situation, the emissions in the WTT system of each fuel chain depend on the emissions in the WTT system of all the other fuel chains. Such a situation requires iteration in order to be solved. Also, the results for all fuel chains must be calculated in one iteration process. In the first step, the values of the $wtt_{emissions,j,v}$ are assumed to equal 1 for all values of v from $v=1$ to $v=u$. This results in a set of values for $wtt_{emissions,i,v}$.

The values for the WTT emissions in the WTT system of each fuel chain are entered as new values of $wtt_{emissions,j,v}$ in the second step of the iteration, which results in a new set of values for $wtt_{emissions,i,v}$. If this process is repeated a number of times, a solution is found for the values of $wtt_{emissions,i,v}$ for all values of *v* from *v=1* to *v=u*.

Emissions can not be summed in the way energies can be summed. For emission components other than carbon dioxide that are contributing to the enhanced greenhouse effect, a Global Warming Potential (GWP) is assigned. This GWP is expressed in CO_2-equivalents and is a measure for the relative input on global warming of the emission as compared to carbon dioxide. By multiplying each emission with its GWP, the emissions can be summed:

$$wtt_{emissions,i} = wtt_{emissions,i,CO_2} + \sum_{v=1}^{u} \left(wtt_{emissions,i,v} \cdot GWP_v \right) \tag{28}$$

With:

$wtt_{emissions,i}$: total emissions in CO_2-equivalents that emerge from the WTT system of fuel chain *i* in the production of 1 unit of energy leaving the fuel chain.

GWP_v: Global Warming Potential of emission component *v*.

More information about the background of GWP potentials, the emissions and the accompanying GWPs that are used in this study can be found in section 5.5.

4.5 Modeling of energy flows and emissions in the TTW chain

The second part in the WTW chain is the tank to wheel (TTW) chain. This part of the WTW chain covers the end use of the fuel, where the fuel is taken from the tank of the vehicle and converted to mechanical energy by the powertrain in order to make the vehicle move, or, stated differently, to make the wheels turn. In figure 4.1, this is the part of the fuel chain between point B and C.

For each fuel a suitable type of engine must be determined, for example Spark Ignition or Compression Ignition. It is important that all engines that are included in a study meet a specified program of demands, to ensure that their performance is comparable. If this is not the case, no fair comparison can be made. For each combination of fuel, engine and vehicle characteristics such as mass, rolling resistance, air resistance and area, a representative fuel consumption is determined. The distance that is traveled with fuel *i* is labelled DD_i, the driving distance with fuel *i*. The amount of energy consumed on this distance is labelled $TTW_{energy,i}$, where *i* refers to the fuel chain. By dividing the energy use with the distance, the energy use per unit of fuel can be calculated:

$$ttw_{energy,i} = \frac{TTW_{energy,i}}{DD_i} \tag{29}$$

With:

$ttw_{energy,i}$: energy use of fuel *i* per unit of distance traveled.

$TTW_{energy,i}$: absolute energy use of fuel *i*.

DD_i: driving distance of fuel *i*. This is the number of kilometers one can drive with an amount of energy $TTW_{energy,i}$.

The TTW energies that are used in this study are obtained from an extensive study performed by TNO [TNO, 2003]. In the TNO study, that maps many environmental effects of modern passenger cars, one aspect that is measured is fuel economy. In studies of this kind, fuel economy and emissions are determined by means of standardised driving cycles. In the TNO study, two driving cycles are used, namely the European Driving Cycle (EDC) and the Common Artemis Driving Cycle (CADC). The first contains an urban part and an extra-urban part, to model vehicle behaviour in different environments with different driving characteristics. For the same reason, the CADC contains an urban part, a country part and a motorway part. In the TNO study, three driver profiles are distinguished: a business driver, a local driver and an average driver. The results used in this study are those of the average driver. This driver reflects a trip of average distance and average driving environments. The average driver results have been determined by a combination of one total CADC driving cycle, two times the urban part of the CADC cycle and a surplus for the cold start effect [TNO, 2003].

The TTW carbon dioxide emissions can be expressed in two ways: as emissions per unit of distance traveled or as emissions per unit of fuel consumed. In the first case, the emissions can be calculated by dividing the total emissions by the distance traveled

$$ttw^{*}_{emissions,i,CO_2} = \frac{TTW_{emissions,i,CO_2}}{DD_i} \tag{30}$$

With:

$ttw^{*}_{emissions,i,CO_2}$:CO_2 emissions produced in the TTW part of fuel chain *i*, expressed in g/km.

$TTW_{emissions,i,CO_2}$: CO_2 emissions produced in the TTW part of fuel chain *i* produced over a distance DD_i.

In the second case, the emissions are identical to the carbon dioxide content of the fuel that was introduced in equation (20):

$$ttw_{emissions,i,CO_2} \equiv \sigma_i \tag{31}$$

With:

$ttw_{emissions,i,CO_2}$:CO_2 emissions produced in the TTW part of fuel chain *i*, expressed in g/MJ.

The $ttw_{emissions,i,CO_2}$ and the $ttw^{*}_{emissions,i,CO_2}$ are related by means of the following equation:

$$ttw^{*}_{emissions,i,CO_2} = ttw_{emissions,i,CO_2} \cdot ttw_{energy,i} \tag{32}$$

The difference between $ttw_{emissions,i,CO_2}$ and $ttw^{*}_{emissions,i,CO_2}$ is denoted by an asterix. All values of emissions that are expressed per unit of fuel are denoted without asterix whereas all values of emissions that are expressed per unit of traveled distance are denoted with asterix.

Emissions other than carbon dioxide are not directly linked to fuel consumption. They have to be determined experimentally, as was also done in the study by TNO [TNO, 2003]. They are labelled $ttw_{emissions,i,v}$ or $ttw^{*}_{emissions,i,v}$, depending on whether they are related to the energy content of the fuel or the distance traveled with the vehicle.

4.6 Combination of WTT chain and TTW chain

Now that all information regarding the WTT chain and the TTW chain is complete, the chains can be combined into the WTW chain. The total amount of primary energy used in the WTW chain can be calculated by multiplying the total amount of primary energy use per unit of fuel in the WTT chain with the mileage from the TTW chain:

$$wtw_{energy,i} = wtt_{energy,i} \cdot ttw_{energy,i} \tag{33}$$

With:
$wtw_{energy,i}$: amount of primary energy used in the total WTW fuel chain of fuel *i*.

With the values of $wtw^{k}_{energy,i}$ it can be calculated how much of each feedstock is used in the WTW energy:

$$wtw^{k}_{energy,i} = wtt^{k}_{energy,i} \cdot ttw_{energy,i} \tag{34}$$

With:
$wtw^{k}_{energy,i}$: amount of energy of primary feedstock *k* used in the total WTW fuel chain *i*.
Like the carbon emissions in the TTW part of the fuel chain, the carbon dioxide emissions in the WTW fuel chain can be expressed in g/MJ and g/km:

$$wtw_{emissions,i,CO_2} = wtt_{emissions,i,CO_2} + ttw_{emissions,i,CO_2} \tag{35}$$

$$wtw^{*}_{emissions,i,CO_2} = wtt_{emissions,i,CO_2} \cdot ttw_{energy,i} + ttw^{*}_{emissions,i,v} \tag{36}$$

With:
$wtw_{emissions,i,CO_2}$: CO_2 emissions produced in the total WTW fuel chain *i*, expressed in g/MJ.
$wtw^{*}_{emissions,i,CO_2}$: CO_2 emissions produced in the total WTW fuel chain *i*, expressed in g/km.

Other emissions can be calculated in a way very similar to equation (35) and (36):

$$wtw_{emissions,i,v} = wtt_{emissions,i,v} + ttw_{emissions,i,v} \tag{37}$$

$$wtw^{*}_{emissions,i,v} = (wtt_{emissions,i,v} + ttw_{emissions,i,v}) \cdot ttw_{energy,i} \tag{38}$$

With:
$wtw_{emissions,i,v}$: emissions of substance *v* produced in the WTW fuel chain *i*, expressed in g/MJ.
$wtw^{*}_{emissions,i,v}$: emissions of substance *v* produced in the WTW fuel chain *i*, expressed in g/km.

4.7 Different methods of presenting the results

As we have seen in the third section, some fuel chain systems have multiple outputs and some have not. This implies that these fuel chains are of different types and can not be compared straight away. A part of the primary inputs and produced emissions should be attributed to the main product and a part should be attributed to the byproducts. Before a fair comparison can be made, all fuel chains must have equal outputs. To obtain these equal outputs, the byproducts have to be accounted for in some way. Four ways of doing so are presented in this section. This section is constrained to a description of the theoretical side of the methods. The advantages and disadvantages of each method are discussed in chapter 10.

Avoided primary energy and emissions (APEE)

A common way to represent byproducts is to credit them with the energy that would normally have been used to create them, would they have been created by other production processes. The thought behind this method is that because the fuel is produced, there are also other products produced which replace products based on fossil fuels. For example, in the Fischer-Tropsch diesel from natural gas fuel chain, some electricity is produced. This electricity replaces electricity from the grid, and therefore the amount of energy that would have been needed to produce the electricity from the grid can be subtracted from the total WTT energy use in the Fischer-Tropsch diesel from natural gas fuel chain. For the emissions, avoided emissions are calculated. Due to the production of the byproduct in the fuel chain system, the product didn't have to be made in the ordinary way. The emissions that would have arisen from production are thus avoided and therefore can be subtracted from the emissions in the fuel chain system.

The amount of avoided primary energy of feedstock *k* is calculated with:

$$ape_{i,s}^{k} = wtt_{by,i,s} \cdot wtt_{energy,ap}^{k} \tag{39}$$

With:

$ape_{i,s}^{k}$:	amount of primary energy of type *k* that is avoided through the production of byproduct of type *s* in fuel chain *i*. This is the amount of energy that is saved because the avoided product did not have to be made in its ordinary way.
$wtt_{by,i,s}$:	amount of byproduct of type *s* produced in the WTT system of fuel chain *i*, per unit of fuel.
$wtt_{energy,ap}^{k}$:	amount of primary energy of type *k* needed to create 1 unit of the avoided product of type *ap* in the WTT system of its fuel chain.

The new WTT result is obtained by subtracting the sum of the avoided primary energies of all primary feedstocks from all byproducts from the total WTT energy:

$$wtt_{energy,i}^{APEE,k} = wtt_{energy,i}^{k} - \sum_{s=1}^{t} ape_{i,s}^{k} \tag{40}$$

With:

$wtt_{energy,i}^{APEE,k}$:	WTT energy use of primary feedstock of type *k* in fuel chain *i*, whereby byproducts are subtracted from the fuel chain according to the Avoided Primary Energy and Emissions method.

Summing the values of $wtt_{energy,i}^{APEE,k}$ over all values of *k* from *k=1* to *k=n* results in the total WTT energy use in fuel chain *i*. The WTW result can be obtained by applying formula (33), whereby the term $wtt_{energy,i}$ is replaced by $wtt_{energy,i}^{APEE}$. The new WTW result is labelled $wtw_{energy,i}^{APEE}$, the WTW energy use in fuel chain *i*, whereby byproducts are subtracted from the fuel chain according to the APEE method.

The amount of avoided CO_2 emissions can be calculated with:

$$aem_{i,s}^{CO_2} = wtt_{by,i,s} \cdot wtt_{emissions,ap}^{CO_2} \tag{41}$$

With:

$aem_{i,s}^{CO_2}$:	amount of CO_2 emissions that are avoided through the production of byproduct *s* in fuel chain *i*.

$wtt^{CO_2}_{emissions,ap}$: WTT CO_2 emissions that are the result of the production of 1 unit of the avoided product.

The new WTT result is obtained by subtracting the avoided emissions from the total WTT emissions:

$$wtt^{APEE}_{emissions,i,CO_2} = wtt_{emissions,i,CO_2} - \sum_{s=1}^{t} aem^{CO_2}_{i,s} \tag{42}$$

With:

$wtt^{APEE}_{emissions,i,CO_2}$: WTT CO_2 emissions in fuel chain *i*, whereby avoided emissions are calculated according to the Avoided Primary Energy and Emissions method.

Other avoided emissions are calculated in the same way, only with the subscript *v* in stead of the subscript CO_2:

$$aem^{v}_{i,s} = wtt_{by,i,s} \cdot wtt^{v}_{emissions,ap} \tag{43}$$

With:

$aem^{v}_{i,s}$: amount of emissions of substance of type *v* that are avoided through the production of byproduct *s* in fuel chain *i*.

$wtt^{v}_{emissions,ap}$: WTT emissions of substance type *v* that are the result of the production of 1 unit of the avoided product.

The total amount of avoided greenhouse gas emissions can be obtained by multiplying the amount of avoided emission of each substance with its GWP and then subtracting these values from the total WTT emissions:

$$wtt^{APEE}_{emissions,i} = wtt_{emissions,i} - wtt^{APEE}_{emissions,i,CO_2} - \sum_{v=1}^{u} \left(wtt^{APEE}_{emissions,i,v} \cdot GWP_v \right) \tag{44}$$

The new WTW results can be calculated by applying equations (35) and (37) whereby the terms $wtt_{emissions,i,CO_2}$ and $wtt_{emissions,i,v}$ must be replaced with $wtt^{APEE}_{emissions,i,CO_2}$ and $wtt^{APEE}_{emissions,i,v}$ respectively. The new WTW results are labelled $wtw^{APEE}_{emissions,i,CO_2}$ and $wtw^{APEE}_{emissions,i,v}$.

Multiple Vehicle Kilometers (MVK)

A second way to represent the byproducts is called the Multiple Vehicle Kilometers (MVK) method. In this method it is supposed that byproducts from a fuel chain system are used in another powertrain in another vehicle, and thus that the total number of kilometers driven by an amount of primary input increases. However, only the primary energy needed to travel 1 unit of distance with fuel *i* is included in the WTT results. Therefore the new WTT results are lower and as a consequence the WTW results are lower.

The number of kilometers that can be driven with one unit of output of fuel *i* from the WTT system of the fuel chain equals the inverse of the TTW energy:

$$dd_i = \frac{DD_i}{TTW_{energy,i}} = \frac{1}{ttw_{energy,i}} \tag{45}$$

With:

dd_i: driving distance of fuel *i*. This is the number of kilometers a vehicle can drive with 1 unit of fuel *i*.

The extra number of kilometers that can be driven thanks to the byproducts, can be calculated with formula (46):

$$dd_{extra,s} = \frac{wtt_{by,i,s}}{ttw_{energy,s}} \tag{46}$$

With:

$dd_{extra,s}$: extra number of kilometers that can be driven thanks to byproduct *s*.

$ttw_{energy,s}$: energy consumption of byproduct *s* in a powertrain.

The part of primary input of feedstock of type *k* that is assigned to fuel *i*, is assigned according to the ratio between the driving distance of fuel *i* and the total number of kilometers driven:

$$wtt^{MVK,k}_{energy,i} = \frac{dd_i}{dd_i + \sum_{s=1}^{t} dd_{extra,s}} \cdot wtt^{k}_{energy,i} \tag{47}$$

With:

$wtt^{MVK,k}_{energy,i}$: WTT energy use of primary feedstock of type *k* in fuel chain *i*, whereby byproducts are subtracted from the fuel chain according to the Multiple Vehicle Kilometers method.

The TTW results do not change and therefore the new WTW results can be calculated according to:

$$wtw^{MVK,k}_{energy,i} = wtt^{MVK,k}_{energy,i} \cdot ttw_{energy,i} \tag{48}$$

The total amount of primary feedstock according to the MVK method can be calculated by summing the contributions of the individual feedstocks:

$$wtw^{MVK}_{energy,i} = \sum_{k=1}^{n} wtw^{MVK,k}_{energy,i} \tag{49}$$

With:

$wtw^{MVK,k}_{energy,i}$: WTW energy use in fuel chain *i*, whereby byproducts are subtracted from the fuel chain according to the Multiple Vehicle Kilometers method.

The original WTW emissions in fuel chain *i* as depicted in $wtw_{emissions,i,CO_2}$ and $wtw_{emissions,i,v}$ are related to dd_i, the number of kilometers a vehicle can drive with 1 unit of fuel *i*. However, as we have just seen, more vehicle kilometers can be assigned to the primary energy input that was needed to create 1 unit of fuel *i*. Therefore the new WTW emissions are only a part of the original WTW emissions:

$$wtw^{MVK,*}_{emissions,i,CO_2} = \left(\frac{dd_i}{dd_i + \sum_{s=1}^{t} dd_{extra,s}} \cdot wtt_{emissions,i,CO_2} + ttw_{emissions,i,CO_2} \right) \cdot ttw_{energy,i} \qquad (50)$$

and

$$wtw^{MVK,*}_{emissions,i,v} = \left(\frac{dd_i}{dd_i + \sum_{s=1}^{t} dd_{extra,s}} \cdot wtt_{emissions,i,v} + ttw_{emissions,i,v} \right) \cdot ttw_{energy,i} \qquad (51)$$

With:

$wtw^{MVK,*}_{emissionsi,CO_2}$: WTW CO_2 emissions in fuel chain *i* expressed in g/km, whereby avoided emissions are calculated according to the Multiple Vehicle Kilometers method.

$wtw^{MVK,*}_{emissionsi,v}$: WTW emissions of substance *v* in fuel chain *i* expressed in g/km, whereby avoided emissions are calculated according to the Multiple Vehicle Kilometers method.

Ratio of Energy Contents 1 (REC1)

The third and fourth method used here resemble each other closely and are named Ratio of Energy Contents 1 and 2 respectively. In the first Ratio of Energy Contents method (REC1), the total primary energies and emissions are attributed to products and byproducts by ratio of their energy content. If the output of the WTT system of a fuel chain consists of fuel and byproducts in a ratio of 2:1, then two-thirds of all primary inputs and emissions are assigned to the fuel and one-third of all primary inputs and emissions is assigned to byproducts. This method is straightforward and easy to perform. However, it is a bit simplistic. It treats byproducts as if they pass trough the entire fuel chain, which they don't in most cases. In order to incorporate for the smaller amount of steps that are passed by the products, the first Ratio of Energy Contents method is extended into a second Ratio of Energy Contents method (REC2) in the next section. In this section, the first Ratio of Energy Contents method is discussed.

In REC1, the ratio between the output of fuel *i* of the WTT system of fuel chain *i* and the sum of all byproducts of type *s* from *s=1* to *s=t* is provided by:

$$fdp_i = \frac{H_{i,r}}{\left(H_{i,r} + \sum_{s=1}^{t} WTT_{by,i,s} \right)} \qquad (52)$$

With:

fdp_i: the fraction of the desired product *i* in the total output of fuel chain *i*.

All primary energies entering the fuel chain are multiplied with the fraction of the desired product so that they only account for the production of the desired fuel *i* and no longer for the production of the byproducts:

$$wtt^{REC1,k}_{energy,i} = fdp_i \cdot wtt^{k}_{energy,i} \qquad (53)$$

With:

$wtt_{energy,i}^{REC1,k}$: WTT energy use of primary feedstock of type k in fuel chain i, whereby byproducts are accounted for according to the first Ratio of Energy Contents method.

The total recalculated WTT energy use summed over all primary feedstocks k from $k=1$ to $k=n$ can be calculated with:

$$wtt_{energy,i}^{REC1} = \sum_{k=1}^{n} wtt_{energy,i}^{k,REC1} \tag{54}$$

With:

$wtt_{energy,i}^{REC1}$: total primary energy use in the WTT system of fuel chain i according to the first Ratio of Energy Contents method.

The WTW energy becomes:

$$wtw_{energy,i}^{REC1} = fdp_i \cdot wtt_{energy,i} \cdot ttw_{energy,i} \tag{55}$$

With:

$wtw_{energy,i}^{REC1}$: amount of primary energy used in the WTW fuel chain of fuel i according to the first Ratio of Energy Contents method.

The WTT carbon dioxide emissions become:

$$wtt_{emissions,i,CO_2}^{REC1} = fdp_i \cdot wtt_{emissions,i,CO_2} \tag{56}$$

With:

$wtt_{emissions,i,CO_2}^{REC1}$: the WTT carbon dioxide emissions in fuel chain i, calculated according to the first Ratio of Energy Content principle.

By adding the TTW carbon dioxide emissions, the WTW carbon dioxide emissions expressed per unit of energy can be calculated. Multiplying this value with the TTW energy of fuel chain i results in a value for the WTW carbon dioxide emissions expressed per unit of distance that is traveled.

Emissions other than carbon dioxide can be calculated in the same way as the carbon dioxide emissions:

$$wtt_{emissions,i,v}^{REC1} = fdp_i \cdot wtt_{emissions,i,v} \tag{57}$$

With:

$wtt_{emissions,i,v}^{REC1}$: the WTT carbon dioxide emissions of substance of type v in fuel chain i, calculated according to the first Ratio of Energy Content principle.

The WTW emissions of substance of type v in fuel chain i expressed in g/MJ can be calculated by summing the values of $wtt_{emissions,i,v}^{REC1}$ and the TTW emissions of substance of type v in fuel chain i. Multiplying the value of the WTW emissions per unit of energy with the TTW energy of fuel i results in a value for the WTW emissions per unit of distance traveled.

Ratio of Energy Contents 2 (REC2)

If one takes a closer look at the description of the Ratio of Energy Contents method, one will find out that the method implies a simplification of the truth. In the fuel chain as it has been modelled in this study, the byproducts leave the fuel chain at the end of the step in which they are produced. The transportation fuel on the other hand passes trough all succeeding steps in the fuel chain. We see here a situation that is comparable to a refinery for crude oil: some products require more processing than others do. In the case of the refinery, this unequal distribution of processing is accounted for in the way process energies are attributed to products. If a product needs much processing, like gasoline, a large part of the process energies is subscribed to that product. If a product needs little processing, like heavy fuel oil, then only a small part of the process energies are subscribed to that product. In fuel chains where byproducts are produced the same situation exists, with some outputs of the fuel chain passing trough more steps than others do. However, this is not accounted for in the subscription of process fuels to endproducts in the REC method. Only the energy content of the output out of the fuel chain is accounted for. This is a simplification of the truth. It treats byproducts as if they pass through the entire fuel chain, which they don't. Therefore the amount of process energy that is assigned to the byproducts is larger than it is in reality. This means that too much energy is subtracted from the WTT results and that the results for the transportation fuel are an underestimation of the real results. The earlier byproducts are produced in the fuel chain, the larger this effect is. To overcome this effect, a new calculation method is applied. In this method, a fraction of desired product is determined in each step. This makes it possible to calculate the results more precisely.

The fraction of desired product is defined as:

$$fdp_{i,q} = \frac{H_{i,q}}{\left(H_{i,q} + \sum_{s=1}^{t} B_{i,s,q}\right)} \tag{58}$$

With:

$fdp_{i,q}$: the fraction of desired product in step q of fuel chain i.

In steps where no byproducts are produced, the value of $\sum_{s=1}^{t} B_{i,s,q}$ equals 0. In such a case, the output of the step $H_{i,q}$ is divided by itself and the fraction of desired product equals 1.

The new value for the ingoing energy can be calculated with:

$$f_{i,q}^{REC2} = fdp_{i,q} \cdot f_{i,q} \tag{59}$$

With:

$f_{i,q}^{REC2}$: amount of ingoing energy in step q of fuel chain i that is needed to create the fraction of desired product in step q of fuel chain i.

By multiplying the amount of ingoing energy in all steps with one another, it can be determined how much primary feedstock is needed to produce 1 unit of desired product at the end of the WTT system:

$$F_{i,q}^{REC2} = H_{i,r} \cdot \prod_{q=q}^{r} f_{i,q}^{REC2} = H_{i,r} \cdot \prod_{q=q}^{r} \left(fdp_{i,q} \cdot f_{i,q}\right) \tag{60}$$

With:

$F^{REC2}_{i,q}$ amount of primary feedstock attributed to 1 unit of desired product leaving step *q* of fuel chain *i*.

The amount of process energies becomes:

$$G^{REC2}_{i,j,q} = g_{i,j,q} \cdot H_{i,r} \cdot \prod_{q=q}^{r} fdp_{i,q} \cdot \prod_{q=q+1}^{r} f_{i,q} \qquad (61)$$

With:

$G^{REC2}_{i,j,q}$: amount of process energy of type *j* attributed to 1 unit of desired product leaving step *q* of fuel chain *i*.

After normalising the values of $F^{REC2}_{i,q}$ and $G^{REC2}_{i,j,q}$ to the output of the fuel chain $H_{i,r}$, the WTT energy per primary feedstock can be calculated:

$$wtt^{REC2,k}_{energy,i} = f_i^{k,REC2} + \sum_{j=1}^{m}\left(wtt^{k}_{energy,j} \cdot \sum_{q}\left(g_{i,j,q} \cdot \prod_{q=q}^{r} fdp_{i,q} \cdot \prod_{q=q+1}^{r} f_{i,q} \right)\right) \qquad (62)$$

$$f_i^{k,REC2} = 0 \text{, for } k \neq a$$

$$f_i^{k,REC2} = \prod_{q=1}^{r}\left(fdp_{i,q} \cdot f_{i,q}\right) \text{, for } k = a$$

With:

$wtt^{REC2,k}_{energy,i}$: WTT energy use of primary feedstock of type *k* in fuel chain *i*, whereby byproducts are accounted for according to the second Ratio of Energy Contents method.

The TTW results do not change and therefore the new WTW result becomes:

$$wtw^{k,REC2}_{energy,i} = wtt^{k,REC2}_{energy,i} \cdot ttw_{energy,i} \qquad (63)$$

By summing the values of $wtw^{k,REC2}_{energy,i}$ for all values of *k* from *k=1* to *k=n* the total WTW energy use of fuel chain *i* according to the second Ratio of Energy contents method can be calculated. This is labelled $wtw^{REC2}_{energy,i}$.

In order to calculate the carbon dioxide emissions, the carbon balance has to be adjusted. The value of the WTT energy has changed and there are no longer byproducts included in the WTT system. The new carbon balance becomes:

$$wtt^{REC2}_{emissions,i,CO_2} = \sum_{k=1}^{m}\left(wtt^{k,REC2}_{energy,i} \cdot \sigma_k \right) - \sigma_i \qquad (64)$$

With the value of the TTW carbon dioxide emissions, the new WTW carbon dioxide emissions can be calculated in the way described in equation (35) and (36). These are labelled $wtw^{REC2}_{emissions,i,CO_2}$ or $wtw^{REC2,*}_{emissions,i,CO_2}$, depending on whether they are related to the energy content of the fuel or the distance traveled with the vehicle.

In the case of emissions other than carbon dioxide, the emissions in the fuel chain have to be recalculated before WTT emissions can be calculated. The emissions in the fuel chain can be calculated according to:

$$W_{i,v,q}^{REC2} = w_{i,v,q} \cdot H_{i,r} \cdot \prod_{q=q}^{r} fdp_{i,q} \cdot \prod_{q=q+1}^{r} f_{i,q} \qquad (65)$$

With:

$W_{i,v,q}^{REC2}$: emissions of substance of type v attributed to the production of 1 unit of desired product leaving step q of fuel chain i. Byproducts are accounted for according to the second Ratio of Energy Contents method.

Once the emissions in the fuel chain are normalised to the output of the fuel chain $H_{i,r}$, the new WTT emissions in the entire WTT system can be calculated:

$$wtt_{emissions,i,v}^{REC2} = \sum_{q=1}^{r}\left(w_{i,v,q} \cdot \prod_{q=q}^{r} fdp_{i,q} \cdot \prod_{q=q+1}^{r} f_{i,q}\right) + \sum_{j=1}^{m}\left(wtt_{emissions,j,v} \cdot \sum_{q=1}^{r}\left(g_{i,j,q} \cdot \prod_{q=q}^{r} fdp_{i,q} \cdot \prod_{q=q+1}^{r} f_{i,q}\right)\right) \qquad (66)$$

With:

$wtt_{emissions,i,v}^{REC2}$ WTT emissions of substance of type v in fuel chain i, whereby emissions are attributed according to the second Ratio of Energy Contents method.

With the value of the TTW emissions and the TTW energy, the WTW emissions can be calculated. The WTW emissions per unit of fuel are labelled $wtw_{emissions,i,v}^{REC2}$ while the emissions per unit of distance travelled are labelled $wtw_{emissions,i,v}^{REC2,*}$.

5 A deeper look at the WTW model

5.1 Introduction

The previous chapter has described the theory behind the model to calculate WTW energies and emissions. This chapter is devoted to the practical side of the model. In section 2, the fuels that are included in the analysis are selected. In section 3, the time frame under consideration is determined. Section 4 looks at the differences between several heating values and explains which heating value is used in this study and why. In section 5, a background to emissions coming from transportation is provided, together with information about the global warming potentials that are used by this study. Section 6 states what unit system is used in this study after which section 7 gives a clear overview of the borders of the model, what data are in- or excluded and why. The remaining sections take a little distance from the model. First, in section 8 the model is compared to other models and the most important advantages and disadvantages are described. Finally, section 9 takes a look at the societal added value of WTW models and tries to answer the question what benefits society has from research like this.

5.2 Selection of fuel chains

In this section, the fuel chains that are included in the model are selected. First of all the model includes the diesel fuel chain, the gasoline fuel chain and the LPG fuel chain. These three fuel chains lead to transportation fuels that are currently used on a large scale in the Netherlands. By modeling these three fuel chains a reference situation is modelled to which the other fuel chains can be compared. The model is supplemented with a number of alternatives for the current transportation fuels. One of the criteria in the selection of these alternatives has been the comparability of the fuel chain of the alternative with the fuel chains of diesel, gasoline and LPG. By this criteria hydrogen pathways, electricity pathways and fuel cells have been excluded from the study. Furthermore, the selection has been made in such a way that a feedstock can be used by more than one conversion technique and that a conversion technique can be fed with more than one primary feedstock. For example, natural gas can be used to produce compressed natural gas or to produce Fischer-Tropsch diesel. However, Fischer-Tropsch diesel can not only be produced from natural gas but also from cellulosic biomass. In this way it is possible to determine which production process is most efficient for a certain feedstock and which feedstock is best suited for a production process. The final selection contains 8 fuel chains. In the following list these fuel chains are presented with a short description of the fuel chain. The number between brackets indicates in which chapter a more elaborate description can be found.

- Diesel from crude oil: crude oil is extracted, prepared for transportation and transported by ocean tanker from the place of extraction to the port of Rotterdam. In Rotterdam, it is refined to diesel and distributed. In the TTW part of the fuel cycle, diesel is burned in a compression ignition engine. (Chapter 6)

- Gasoline from crude oil: the gasoline fuel chain partly overlaps the diesel fuel chain. The first two steps in the fuel chain, extraction of crude oil and transportation of crude oil to the refinery in Rotterdam, are identical to the diesel fuel chain. In the third step, crude oil is refined to gasoline. The WTT part is completed by distributing the gasoline. In the TTW part, gasoline is burned in a spark ignition engine. (Chapter 6)

- LPG from crude oil: LPG can be made from two sources: it can be produced as product from the refinery, in which case it is based on crude oil. LPG can also be produced from natural gas from associated gas fields. In this study, the LPG fuel chain that is based on crude oil is considered. In this fuel chain, the first two steps are identical to the first two steps in the diesel fuel chain and the gasoline fuel chain. In the third step, the crude oil is refined to LPG. This is distributed and burned in a spark ignition engine. (Chapter 6)

- Compressed Natural Gas (CNG) from natural gas: natural gas is extracted from a gas field and processed to pipeline quality. Next it is transported to refueling stations and compressed. In the TTW part of the fuel chain the CNG is burned in a spark ignition engine. In the description of the fuel chain, average Dutch natural gas is used. This is low-calorific natural gas that is only transported over relatively short distances. In the sensitivity analysis, some calculations will be made on high-calorific natural gas and on imported natural gas. (Chapter 7)

- Fischer-Tropsch (FT) diesel from natural gas: A lot of research is done into producing FT diesel from natural gas. In many oil fields, associated natural gas is found. This natural gas lacks commercial markets and is therefore valueless. Building a FT plant and converting the natural gas to FT diesel would be an attractive way to produce diesel: the input has zero value. Many oil companies find this very attractive. In such a process, the fuel chain consists of recovery of the natural gas, converting the gas to FT diesel, transporting the FT diesel to the Netherlands and distributing it. However, this is not the fuel chain that will be discussed here. In this study, a fuel chain in which Dutch natural gas is used has been chosen. This natural gas is recovered from the Groningen gas field and from the North Sea. It is processed to pipeline quality and transported to a central plant in the Randstad area. There it is converted to FT diesel, after which the FT diesel is distributed. In the TTW part of the fuel chain, the FT diesel is burned in a compression ignition engine. The choice for this fuel chain rather than the fuel chain that uses remote natural gas is based on the resemblance between this fuel chain and the fuel chains of CNG and diesel from crude oil. (Chapter 7)

- FT diesel from cellulosic biomass: FT diesel can not only be produced from natural gas but also from cellulosic biomass. Woody biomass such as poplar or willow is grown on plantations. The base case of this study assumes that all biomass is grown in the Netherlands. After harvesting, the wood is cut into chips and transported to a central plant in the Randstad area. The wood is converted to syngas, which is converted to FT diesel. Finally the diesel is distributed and used in a compression ignition engine. The sensitivity analysis of chapter 11 includes two alternative cases with biomass that is grown abroad. (Chapter 8)

- Ethanol from cellulosic biomass: cellulosic biomass can also be used to produce ethanol. Like in the FT diesel fuel chain, the biomass is grown al over the Netherlands, harvested, cut into chips and transported to a central plant in the Randstad area. By saccharification and fermentation processes the biomass is converted to ethanol after which the ethanol is distributed. Ethanol is used in spark ignition engines. For this fuel chain too, there are two cases with biomass from abroad included in the sensitivity analysis. (Chapter 8)

- Ethanol from sugary biomass: In stead of woody biomass one can also use sugar rich biomass for the production of ethanol. Sugar rich biomass consists of crops like corn, wheat or sugar beet. This study uses wheat in its base case. Wheat is grown in the Netherlands, transported to a central plant in the Randstad area and by means of fermentation converted to ethanol. Finally the ethanol is distributed and used in a spark ignition engine. Chapter 11 includes two cases in which the biomass is grown abroad. (Chapter 8).

5.3 Scope of the study

The scope of this study lies between the year 2000 and the year 2005. This means that if efficiencies are used, they are either current efficiencies or efficiencies for the very near future. In some cases, especially in the fuel chains of the renewable fuels, technologies are not yet introduced on a large scale. In these cases there are no actual data available. Instead, data have been estimated.

5.4 Heating values

When an organic substance is burned, the main products are heat, carbon dioxide and water. Due to the heat that is released in the burning process, both carbon dioxide and water are released in gaseous form. However, under standard conditions (T=298 K, p=1 atm.), water is not a vapour but a liquid. In large, closed processes like the generation of electricity, it is possible to collect the water and to cool it so that the vapourisation heat is released. In this case, the total amount of heat released is the heat released directly in the burning process, plus the heat that is released in the condensation of water. The heating value that can be determined from such a process is referred to as higher heating value (HHV) or gross heating value (GHV). In open processes on the other hand, the water vapour is dispersed in the air, which makes it impossible to obtain the heat that is released by the condensation of the water. The only heat that can be recovered is the heat that is released directly in the burning process. The heating value that comes forth from such a process is referred to as lower heating value (LHV) or net heating value (NHV).

The production of a fuel takes place in large-scale, closed processes that would justify the use of HHVs. However, when the final product, the fuel, is burned in the engine of a car, the water vapour vanishes in the air and is lost. Therefore it is best to use LHVs, which this study does.

5.5 Global Warming Potentials

The earth is heated by radiation coming from the sun. Part of the radiation is absorbed by oceans, trees, buildings etc., thereby warming up the surface of the earth and enabling life. This is known as the greenhouse effect. The radiation that is not taken up by the surface of the earth is reflected back into the atmosphere. Some of it is absorbed by a number of gases, by which these gases become excited. When the gases fall back to their ground state, the radiation is emitted again. However, the radiation that was originally absorbed was entirely oriented outwards, leaving the atmosphere. The radiation that is emitted by the gases in the air is oriented in all directions. Part of it is oriented towards the earth's surface, thereby increasing the total amount of radiation reaching the earth. This effect is known as the enhanced greenhouse effect. In figure 5.1, the radiation causing the greenhouse effect and the enhanced greenhouse effect is visualised.

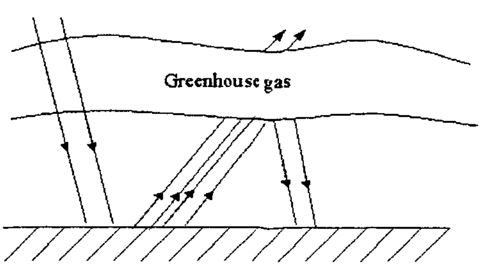

Figure 5.1: radiation in the atmosphere
Source: [Gabi, 2004]

The number of compounds in the atmosphere that are able to take up and re-emit radiation is limited. They are referred to as greenhouse gases. Each gas has a different ability to take up radiation. Except one, all the gases are chemically active. After some time in the atmosphere they react into other compounds. The mean time for a molecule to survive in the atmosphere is known as its lifetime. The only chemically inert gas is carbon dioxide. Carbon dioxide is not removed from the atmosphere through chemical reaction, but through uptake by forests, vegetation and oceans. Since the industrial revolution mankind has used huge amounts of fossil fuels. The emissions coming forth from this use have led to an increase in the concentration of most greenhouse gases. Due to this increase, more radiation is absorbed and emitted again. Consequently, more radiation reaches the earth and the enhanced greenhouse effect is reinforced. To date, a debate is going on whether or not the increased amount of radiation reaching the earth's surface leads to a significantly higher temperature on earth and, if so, what the effects will be to our ecosystems. The magnitude of the effect and its consequences are heavily debated.

To support the debate, a lot of research is done. One aspect of this research is to determine the greenhouse effect of each greenhouse gas in a so-called global warming potential (GWP). The effect that one molecule of carbon dioxide has is defined as a GWP of 1. The GWPs of other greenhouse gases are determined as a function of the radiation absorption coefficient of a gas and its concentration in the atmosphere as a function of time, relative to the radiation absorption coefficient and concentration in the atmosphere of carbon dioxide. The radiation absorption coefficient is a measure for the ability to take up and re-emit radiation whereas the concentration of the gas over time depends on the lifetime of the gas. Because one of the variables that determine the GWP changes with time, a GWP is always determined for a specified timeframe. The most common used timeframe equals 100 years, however sometimes a 20-year timeframe, 200-year timeframe or a 500-year timeframe are used. This study uses the 100-year timeframe.

There are a number of different greenhouse gases, but the main greenhouse gases coming from the use of fossil fuels in transportation are carbon dioxide, methane and nitrous oxide. Therefore these three gases will be discussed in this study. Some characteristics of these gases are shown in table 5.1. Each of them will be discussed shortly.

Chemical species	Chemical formula	Lifetime (year)	100-yr GWP
Carbon dioxide	CO_2	50-200	1
Methane	CH_4	12	23
Nitrous oxide	N_2O	120	296

Table 5.1: characteristics of some greenhouse gases
Source: [IPCC, 2001]

Carbon dioxide

Carbon dioxide is a chemically inert gas. It doesn't react with other compounds in the air and it can't be destroyed by ultraviolet light. However, CO_2 can be removed by uptake through woods, vegetation and oceans. Carbon dioxide is created whenever a carbon-containing compound is burned. This means that both the use of transportation fuels based on fossil fuels and the use of transportation fuels based on renewable sources leads to carbon dioxide emissions. However, when transportation fuels based on fossil fuels are burned, CO_2 is released into the air that has been embedded in the soil for centuries. This CO_2 is added to the amount of CO_2 circulating on earth, and the net amount increases. When transportation fuels based on renewable fuels are burned, an amount of CO_2 is released into the air that was taken up from the air some years previously. There is no net increase in the total amount of

CO_2 and the fuel is said to be climate neutral. Because of the zero net outcome, many studies set the carbon dioxide content of fuels to zero. Although this doesn't affect the final outcome of calculations through the entire fuel chain, it does not provide insight into the amount of CO_2 that is used in different pathways. Therefore this study assigns CO_2 contents to each and every fuel used. In fuel chains where biomass is used, the biomass takes up carbon dioxide from the air to grow. This carbon dioxide is calculated as negative emissions. When the biomass is used, the carbon that is released is converted to a carbon dioxide equivalent and counted as positive emissions. At the end of the Well to Wheel chain, all biomass has either been used or is contained in byproducts. Therefore the sum of the emissions in the WTT part of the fuel chain, the TTW part of the fuel chain and the carbon dioxide equivalent content of the byproducts equals the carbon dioxide uptake at the beginning of the fuel chain and the net emissions are zero.

Methane

The second greenhouse gas involved with transportation is methane. Methane is removed from the atmosphere by chemical reaction. This reaction takes place in the troposphere, the lower part of the atmosphere, and is activated by hydroxyl radicals. The reaction mechanism starts with ozone, which is split by ultraviolet light into an oxygen molecule and an excited oxygen atom [Borrell,1998]:

$$O_3 + hv \rightarrow O_2 + O\bullet \tag{67}$$

The excited oxygen atom, also called oxygen radical, is very reactive. If it collides with water two hydroxyl radicals are formed [Borrell, 1998]:

$$O\bullet + H_2O \rightarrow 2OH\bullet \tag{68}$$

A hydroxyl radical can react with many compounds. If it reacts with methane, a water molecule and a methane radical are formed [Borrell, 1998]:

$$CH_4 + OH\bullet \rightarrow H_2O + CH_3\bullet \tag{69}$$

This reaction is followed by a reaction with oxygen:

$$CH3\bullet + O_2 \rightarrow CH_3O_2\bullet \tag{70}$$

In the last reaction, a methylperoxy radical is formed. This is a highly reactive radical that can easily react further with a number of other compounds in the atmosphere. Eventually, however, all reactions result in the formation of carbon dioxide and water vapour. Most methane in the atmosphere is removed from the atmosphere in the way just described, but a small part reacts according to a second reaction mechanism. In this mechanism, methane is removed directly trough oxygen radicals, without the intermediary formation of hydroxyl radicals [Borrell, 1998]:

$$O\bullet + CH_4 \rightarrow OH\bullet + CH3\bullet \tag{71}$$

This reaction too, is followed by a reaction between the methane radical and oxygen, as depicted in equation (70). Eventually, all the carbon contained in methane is converted to carbon dioxide.

The reactions show that the first, most important route to remove methane from the atmosphere consumes hydroxyl radicals. The formation of hydroxyl radicals to fulfill the need is limited. Hydroxyl radicals are formed from ozone, which is scarce in the troposphere[3]. Also, the amount of hydroxyl radicals formed by reaction (71) is very limited. The removal of methane from the atmosphere lowers the concentration of hydroxyl radicals, thereby lowering the chance of other methane molecules to react and thus increasing the average lifetime. The more methane is emitted, the longer each molecule stays in the atmosphere. Besides this negative effect methane has on its own lifetime, the lowered hydroxyl concentration also lowers the chances for other greenhouse gases to react. Therefore their average lifetimes increase too. This indirect effect has only recently been taken into account. The IPCC has changed the GWP of methane from 21 CO_2-equivalents to 23 CO_2-equivalents. Although most literature up until now has calculated with the old value of 21, this study uses the new value of 23 CO_2-equivalents.

Nitrous oxide

The third relevant greenhouse gas is nitrous oxide, also known as dental gas or laughing gas. Its chemical formula is N_2O. Nitrous oxide is released in small quantities from combustion processes. However, the emissions coming from transportation are small in comparison with the emissions coming from agriculture. Many fertilizers that are used in agriculture contain nitrogen. This nitrogen is deposited in the soil, after which it is taken up by the roots of plants. A small part of it however, is not taken up by plants but converted to nitrous oxide by microbes and emitted to the air.

Nitrous oxide, as other components that do not contain hydrogen atoms, is not removed from the air by hydroxyl radicals. In stead, it is transferred from the troposphere to the higher located stratosphere. This process is very slow. All components that are transferred to the stratosphere before they are removed, have lifetimes of at least 20 years [IPCC, 2001]. In the troposphere, 9 out of 10 nitrous oxide molecules are removed by photodissociation, ignited by ultraviolet light. This reaction results in nitrogen and an oxygen radical [Princeton, 2002]:

$$N_2O + h\nu \rightarrow N_2 + O\bullet \qquad (72)$$

The molecules that are not removed by photodissociation react with oxygen radicals, either into nitrogen oxide or into nitrogen and oxygen [Borrell, 1998]; [Princeton, 2002]:

$$N_2O + O\bullet \rightarrow 2NO \qquad (73)$$

$$N_2O + O\bullet \rightarrow N_2 + O_2 \qquad (74)$$

The GWP of nitrous oxide was originally estimated by the IPCC to be 310 CO_2-equivalents. However, recent investigation has shown this to be an overestimation. Therefore the GWP has been adjusted to 296 CO_2-equivalents. In this study, the latter number is used.

5.6 Units

This study uses SI-units to calculate with. If sources from literature used other units than the units from the SI-system, they have been converted using Perry [Perry, 1997].

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[3] The atmosphere consists of two layers: the troposphere and the stratosphere. In the higher located stratosphere, ozone is abundant. In the lower located troposphere it is not. There are only two small sources of ozone in the troposphere: reactions of greenhouse gases and migration of ozone from the stratosphere [Borrell, 1998].

5.7 *Data collection*

All data have been determined from literature. In the WTT part of the fuel chains, a number of WTW studies have served as input, as well as case studies that focus on one particular fuel chain. For the TTW part of the fuel chains, data have been used from a study performed by TNO [TNO, 2003]. All WTW data have been calculated from the combination of WTT and TTW data. No additional input has been used.

In the modelling of the WTT part of the fuel chains, one recent study has been purposely left beyond consideration. This study is used later on in this report, in chapter 11, as benchmark to which all results are compared. The study that has been left beyond consideration is a report by General Motors [GM Europe, 2002].

5.8 *Delimitations*

Throughout the modeling of energy flows and emissions, a set of delimitations is applied. This set will be discussed shortly here. First of all, this study only takes into account so-called 'first level' energies. These are primary energies or process energies that are used directly in the fuel chain, such as diesel, natural gas or electricity. These primary energies and process energies can only be applied by means of machinery or equipment. The energy that was used to construct, build or fabric the machinery or equipment is called second level energy. This energy is depreciated during the lifetime of the machinery or equipment. Most machinery and pieces of equipment have long lifetimes and are used numerous times. Consequently the amount of energy that would have to be depreciated per unit of process energy in a fuel chain is virtually very low or even negligible. Therefore it is common practice in Well to Wheel studies to include only first level energies. This practice is followed by this study.

Second, the machinery and equipment used in the fuel chains may fail, resulting in leakages, spills of energy and leaks of emissions. Sometimes accidents occur. The energy that is lost during irregular leakages and accidents and the emissions resulting from these events, are left beyond consideration. They are too irregular in size and frequency to be correctly modelled. Only those losses that occur regularly, such as evaporative losses or losses due to processes with imperfect efficiencies, are taken into account. With respect to the energy losses and emissions due to accidents and irregular leakages one must keep in mind that they may be quite substantial in some cases and that their effect can be quite large in reality.

5.9 *Advantages and disadvantages of the model*

This section gives a short description of some advantages and disadvantages of this model in comparison with other models. First the advantages are discussed, followed by the disadvantages.

Advantages

Very precise calculation of WTT energy use

Many studies calculate the WTT energy use by determining an efficiency for each individual step in the fuel chain, multiplying the efficiencies of the individual steps to obtain a WTT efficiency and taking the inverse of the WTT efficiency as the WTT energy use per unit of output. In this method, it is very often very unclear what process energies are used and how the production of the process fuels is accounted for. In the model that has been developed in this study, all energy flows are separately mapped. Only at the end of the calculation they are summed to obtain a total WTT result. Also, the production of each process fuel that is used in the fuel chain is accounted for with its own WTT energy use. This provides information with a much greater level of detail than the studies working with a product of chain step efficiencies.

Primary feedstocks are mapped individually
In the studies that multiply the efficiencies of individual steps in order to obtain a WTT result, information on the level of individual feedstocks is lost. In studies of this kind it is not possible to tell how much energy comes from individual feedstocks such as crude oil or natural gas. There is even no information about the ratio between fossil fuels and renewables. Especially in fuel chains that use renewable feedstocks, this results in a twisted picture of reality. In fuel chains that use renewable energy sources the energy use tends to be rather high. However, the use of fossil fuels in these chains tends to be low. This information is lost if one simply multiplies stage efficiencies. In this study on the other hand, each primary feedstock is mapped individually. This gives a much better insight in the energy use in a fuel chain, and provides the type of information mentioned above.

Products and byproducts are mapped individually
In many studies byproducts are accounted for in calculations that are not shown to the reader. The text accompanying the calculations does not always make it clear how the accounting was done. This makes it impossible for the reader to find out all energy flows that occur in a fuel chain. In this model, all products and byproducts are modelled individually. Only at the end of the calculation they are accounted for. This provides not only good insight into the fuel chains but it also provides the possibility to account for the byproducts in different ways and to compare the results of the different presentations.

Disadvantages

Of course the model has not only advantages, but also some disadvantages:

Confidence intervals
The way in which the model is constructed requires the use of one specific value at a time. This makes it hard to indicate that data are uncertain or to calculate with confidence intervals. The fact that all calculations result in one value does not imply that this value is the absolute truth. At many points in many calculations estimates are used. The real value of a result could well be somewhat higher or somewhat lower. The model as it is as yet does not provide the opportunity to reflect this uncertainty easily.

Level of detail
The biggest advantage of this model is sometimes a disadvantage. Applying this model to a fuel chain results in very detailed information. However, it also requires very detailed information as input. It is sometimes hard to find this information. Especially in the case of process fuels it is sometimes hard to find information about the way a fuel is produced and what process fuels are used during production and in what quantities. This problem can in many cases be overcome by making assumptions or educated guesses.

6 Crude oil based fuel chains: diesel, gasoline & LPG

6.1 Introduction

This chapter is the first in a series of four chapters in which the modelling of specific fuel chains is described in detail. Except for the last of the four, the chapters are arranged by primary feedstock. The first chapter of the series, this one, is devoted to fuel chain systems based on crude oil. Chapter 7 is devoted to fuel chain systems based on natural gas and in chapter 8 fuel chain systems with biomass as direct primary feedstock are modelled. Finally, in chapter 9, the fuel chain systems of process fuels are modelled. These fuel chains are different from the others because they only contain a WTT part and no TTW part. The four chapters present the modeling of energy flows and emissions as described in section 3 to 6 of chapter 4. The different ways in which the results can be represented, as described in section 7 of chapter 4, are shown in chapter 10. That chapter shows and compares the results of all fuel chains.

In this chapter fuel chains are modelled that use crude oil as direct primary input. Crude oil constitutes the basis for three transportation fuels: diesel, gasoline and LPG. The three fuel chains start with the extraction of the crude. After extraction and some preparation, the crude is transported. Most crude is shipped in oil tankers but a small fraction is transported by pipeline. Once the crude has arrived at the point of destination, it is refined. The refining process results in a lot of products, some of which are diesel, gasoline and LPG. For each product, separate efficiencies and emissions can be determined. After refining, the transportation fuels are in principle ready to be used; they only need to be distributed. This is usually done by truck. This short description of the three fuel chains shows that the extraction and transportation step are identical for diesel, gasoline and LPG. The last two steps in the chains, production and distribution, are unique for each fuel. The diesel fuel chain is modelled in section 2, the gasoline fuel chain in section 3 and the LPG fuel chain in section 4. In section 5, a summary of the most important results is presented.

6.2 The diesel fuel chain

In this section, the diesel fuel chain is modelled. The section starts by modeling the energy flows in the Well to Tank chain. First the energy flows in the separate steps are described after which the steps are combined. The analysis is completed by including the energy flows in the production of the process fuels. Then the Tank to Wheel part of the fuel chain is described after which the WTT and TTW part are combined in the Well to Wheel part. Finally, emissions of carbon dioxide, methane and nitrous oxide are modelled.

The Well to Tank chain

The Well to Tank part of the diesel fuel chain consists of four steps: extraction of crude oil, transportation of crude oil, refining of crude oil to diesel and finally distribution of the diesel. These steps are described one by one after which they are combined and the energy flows in the production of the process fuels are added.

Reference	Efficiency	Comments
[Gave, 1999]	95,9	-
[DeLuchi, 1993]	97,3	Data based on recovery in United States only
[Arthur D Little, 1996]	95,7	Estimate of year 2000 efficiencies; data based on recovery in US only
[Verbeek, 1997]	96,0	This number includes transportation to the refinery. If efficiency for transportation is assumed to be 99,1 %, efficiency for recovery is 96,9%.
[Johansson, 1992]	97,0	-
[GM, 2001]	98,0	Estimate of year 2005 efficiencies; data based on recovery in US only
This study	95,8	Average of [Gave,1999] and [Arthur D Little,1996]

Table 6.6.1: efficiencies in the extraction of crude oil

Division of process energies (%)	[Gave, 1999]	[DeLuchi, 1993]	This study
Crude oil	11,7	14,5	13,1
Diesel	8,9	11,0	10,0
Gasoline	3,6	4,5	4,0
Heavy fuel oil	0,7	0,0	0,3
Natural gas	58,4	49,2	53,8
Electricity	16,7	20,8	18,8
Other		0,0	
Total	100,0	100,0	100,0

Table 6.6.2: distribution of process energies in the extraction of crude oil

Energy use per MJ of crude oil extracted	
Crude oil	1,006
Diesel	0,004
Gasoline	0,002
Heavy fuel oil	0,000
Natural gas	0,024
Electricity	0,008
Total	1,044

Table 6.6.3: energy flows in the extraction of crude oil

Origin	Energy use by mode of transportation	Amount of product transported	Distance from origin to Netherlands	Process energy use
	$J_{process}/MJ_{product}$-km	$MJ_{product}$	km	$MJ_{process}$
Netherlands	1,436	8,597E+10	100	1,235E+07
United Kingdom	1,436	8,384E+11	520	6,261E+08
Denmark	3,015	8,349E+10	1.340	3,373E+08
Norway	3,015	9,553E+11	1.860	5,357E+09
Russia	3,015	6,835E+11	14.000	2,885E+10
Kazakhstan	3,015	1,759E+10	10.600	5,622E+08
Algeria	3,015	1,919E+11	3.400	1,967E+09
Nigeria	3,015	4,096E+10	10.000	1,235E+09
Angola	3,015	1,688E+10	15.600	7,939E+08
Venezuela	3,015	1,654E+10	15.600	7,779E+08
Syria	3,015	8,772E+10	6.600	1,746E+09
Iraq	3,015	1,771E+11	7.400	3,951E+09
Iran	3,015	1,875E+11	9.000	5,088E+09
Saudi-Arabia	3,015	6,828E+11	9.400	1,935E+10
Kuwait	3,015	2,040E+11	8.800	5,413E+09
Total		4,270E+12		7,607E+10
Mean				*0,018*

Table 6.6.4: transportation of crude oil

Extraction of crude oil

The first step in the fuel chain is the recovery of crude oil. Crude oil is usually pumped up from wells. The fluid that is pumped up consists not only of crude oil, but also contains natural gas and water. These components are separated at the extraction spot. In the past, natural gas was often flared or vented. Nowadays more and more countries have legislation that prohibits venting and flaring. Instead, the natural gas and water are pumped back into the earth. Other operations that take place to prepare the crude for shipping are the removal of salt and sulpher and stabilization of the crude. Desalting and desulpherisation are necessary to prevent corrosion problems, while stabilization is performed to reduce volatility and thus restrain emissions. Finally, the crude is stored some time before it is shipped [Abdel-Aal, 2003].

Data found in literature on the efficiency of extraction of crude oil are summarized in table 6.1. The table shows efficiencies ranging from 95,9% to 98,0%. Data from Verbeek are left beyond consideration because they contain a high level of uncertainty. It appears that older data show efficiencies of about 97%, (Johansson, DeLuchi) while newer data show efficiencies of almost 96% (Gave, Arthur D. Little). This is in concurrence with the increased use of enhanced recovery techniques that require more energy. Because it is likely that the use of enhanced recovery techniques will be maintained or increased in the coming years, this study takes into consideration the newest data from Gave and Arthur D. Little. Their average is used, which equals 95,8%.

If the efficiency is assumed to be 95,8%, it takes 1/0,958=1,044 MJ of energy input to obtain 1 MJ of crude that is ready to be shipped. 1 MJ of this number consists of crude. The other 0,044 MJ consist of process energies and losses of crude and process energies. The energy content from the vented and flared associated gas is also contained in this number. Data on the distribution of energy use are provided by Gave and DeLuchi [Gave, 1999]; [DeLuchi, 1993]. DeLuchi provides data on two years, 1982 and 1987. Both data sets are quite different. Because the 1987-data are most recent, these will be used. All data, both from Gave and DeLuchi, are recalculated from HHVs to LHVs. The recalculations were performed with the fuel specifications from appendix D. The recalculated data sets can be found in table 6.2. Because it is not known whether one data set is more reliable than the other, this study uses their average, with some small adjustments to the rounding up in order to obtain a total of 100,0%. By combining the division of fuel use from table 6.2 with the total amount of process fuels and spills (=0,44 MJ) and adding the amount of direct crude input (=1 MJ), the energy flow of each fuel through the step can be calculated. The results of this calculation are shown in table 6.3.

Transportation of crude oil

The next step in the fuel chain is transportation of the crude from the point of origin to the refinery. Most crude is brought to the Netherlands by tanker ship, although some is transported by pipeline. This is especially the case with crude from the North Sea and the United Kingdom. The point of destination is in all cases assumed to be the port of Rotterdam, where all Dutch refineries are situated.

From Gave we learn the energy use by transportation mode per kilometer per MJ of product transported both for transportation by pipeline and for transportation by tanker ship [Gave, 1999]. For transportation by pipeline, this number equals 1,436 J per MJ of product per km and for transportation by tanker ship it is 3,015 J per MJ of product per km. The quantities of crude imported in the Netherlands are found in Statline, a database from Statistics Netherlands [CBS, 2003]. The internet provides data on the distances from the point of origin to the port of Rotterdam [How far is it?, 2003]. For transportation by pipeline, the one-way distance is used. For transportation by tanker ship, the two-way distances should be used because the tanker ship has to return, too. All data are shown in table 6.4. The distances

Energy use per MJ of crude oil transported	
Crude oil	1,000
Heavy fuel oil	0,018
Electricity	0,000
Total	1,018

Table 6.5: energy flows in the transportation of crude oil

Reference	Efficiency	Comments
[Gave, 1999]	94,9	-
[DeLuchi, 1993]	94,2	Data based on production in United States only
[Arthur D Little, 1996]	96,9	Estimate of year 2000 efficiencies; data based on production in US only
[Verbeek, 1997]	95,0	Based on other sources from literature
[Johansson, 1992]	95,2	Average process energy in refinery equals 8% of refinery output. Middle distillates, which include diesel, use 25% of all process energy and make up 40% of refinery output. This leads to an efficiency for diesel of 95,2%.
[GM, 2001]	87,0	Estimate of year 2005 efficiencies; data based on recovery in US only
This study	95,2	Data from [Johansson, 1992] are used because they are best specified

Table 6.6: efficiencies in the production of diesel

shown for transportation by tanker ship are two way distances. With this information, the average amount of energy needed to transport 1 MJ of crude can be calculated, which turns out to be 0,018 MJ per MJ of crude.

According to Gave the only relevant process fuel for transportation by tanker is heavy fuel oil. Some electricity is used to pump the crude into and out of the tanker, but the quantity used on the whole tanker is so small that the amount per MJ of crude can be neglected [Gave, 1999]. For transportation by pipeline Gave mentions electricity as only relevant process fuel. We can deduct from table 6.4 that 1,7% of the crude used in the Netherlands is brought here by pipeline and that the remainder 98,3% comes here by ship. Therefore we know the division of process fuels. With this division and the total amount of process fuel used, it can be calculated how much of each process fuel is needed to transport an average MJ of crude. The results are shown in table 6.5.

Refining from crude oil to diesel

The third step in the fuel cycle is the production step in which the conversion from primary feedstock to transportation fuel takes place. In the refinery, crude oil is distilled under atmospheric pressure. This process results in three fractions of products: heavy distillates, middle distillates and light distillates. Light distillates have short carbon chains, middle distillates have carbon chains of medium length and heavy distillates have long carbon chains. Heavy distillates are products like tar or asphalt. After distillation they need little processing. Examples of middle distillate products are diesel, heavy fuel oil, and jet fuel. After distillation, middle products are cracked and desulpherised. In the cracking process, all carbon chains are cut into pieces so that they all have the same length. Desulpherisation, also known as sweetening, is a process in which sulpher is removed. This is done to prevent corrosion problems and because of environmental legislation. Light distillates, like gasoline and LPG, require most processing. Like the middle distillates, light distillates are cracked and desulpherised. However, light distillates and especially the gasoline fraction require also isomerisation and polymerisation. By these processes, all molecules obtain similar carbon structures and similar burning behaviour [Johansson, 1993];[GM Europe, 2002]. The ratio between heavy distillate output, medium distillate output and light distillate output can be varied to some extent. There are borders to the variation, however. For example, it is not possible to adjust the refinery in such a way that only light and medium distillates are produced.

Because diesel, gasoline and LPG are all products of the same production step, the fuel chains are in reality connected to each other. In literature, however, they are treated as separate fuel chains, each with its own efficiency. The efficiency is calculated by allocating a weighted part of the refinery's energy use and emissions to each output. The weighting is usually based on the amount of processing a fuel needs and the ratio of energy contents. For example, the energy used in distillation is allocated partly to heavy distillates, partly to medium distillates and partly to light distillates because all fractions require distillation. The energy used in cracking is divided over the medium distillate fraction and the light distillate fraction because these are the only fractions that use the products from the cracking process, whereas the energy used in the isomerisation process is allocated completely to light distillates. Because heavy distillates require least processing, only a small part of the refinery's energy use and emissions are allocated to heavy distillates and the efficiency is high. Light distillates require the most processing of all fractions and therefore their production is least efficient.

Data found in literature on the processing of diesel are summarized in table 6.6. As the table shows, most sources mention efficiencies of about 95%. Only GM mentions a number that is considerably lower. Because GM gives no clear explanation for this, their number is left beyond consideration. Data from Johansson are best specified and are in concurrence with

Division of process energies (%)	[Gave, 1999]	[DeLuchi, 1993]	This study
Crude oil	96,2	97,7	97,0
Diesel	0,0	0,0	0,0
LPG	0,0	0,0	0,0
Heavy fuel oil	0,3	0,0	0,1
Natural gas	1,4	0,1	0,8
Electricity	0,1	0,2	0,2
Refinery gas	1,1	1,7	1,4
Petroleum coke	0,7	0,3	0,5
Total	100,0	100,0	100,0

Table 6.7: distribution of process energies in the production of diesel

Energy use per MJ of diesel produced	
Crude oil	1,019
Diesel	0,000
LPG	0,000
Heavy fuel oil	0,001
Natural gas	0,008
Electricity	0,002
Refinery gas	0,015
Petroleum coke	0,005
Total	1,050

Table 6.8: energy flows in the production of diesel

Energy use (MJ) per ton of product per km	
[Gave, 1999]	1,20
[DeLuchi, 1993]	1,20
[De Jager, 1998]	0,5 to 2,9
[Marano, 2001]	1,25
This study	1,22

Table 6.9: energy use of a diesel truck

	Primary input in the WTT chain MJ/MJ_{diesel}	Energy use in the TTW chain MJ_{diesel}/km	Primary input in the WTW chain MJ/km
Crude oil	1,08		2,72
Natural gas	0,05		0,12
Coal	0,01		0,03
Diesel		2,51	
Total	1,14	2,51	2,87

Table 6.10: WTT, TTW and WTW energies in the diesel fuel chain

the efficiencies of the other sources. Therefore the number provided by Johansson, 95,2%, is used in this study.

With an efficiency of 95,2%, it takes 1,050 MJ to produce 1 MJ of diesel. Data on the composition of this energy flow are provided by Gave and DeLuchi [Gave,1999]; [DeLuchi, 1993]. Gave distinguishes the refinery of diesel, gasoline and LPG separately. In this fuel chain the data on refining crude oil to diesel are used. DeLuchi provides data for a European refinery and a refinery in the United States. Although the data for the United States refinery contain a diesel part and a gasoline part while the data for the European refinery do not, this study prefers the data for the European refinery. These data are thought to represent best the Dutch situation. All data have been recalculated from HHVs to LHVs with the fuel specifications from appendix D. Data from DeLuchi have also been recalculated to include crude oil input, which was originally not included in the energy flow. The final data set used in this study is the average of Gave and DeLuchi, with little adjustments in order to reach a sum of exactly 1,000. Both data sets and the final set used in this study are shown in table 6.7.

By combining the overall process efficiency provided by Johansson and the division of process energies as given by Gave and Deluchi, the amounts of direct energy input and of process fuel input per process fuel can be calculated. These are shown in table 6.8.

Distribution of diesel

The final step in the fuel chain is the transportation of diesel from the refinery to the refueling station and fuelling vehicles with the diesel. The transportation of diesel from the refinery to the refueling station is taken care off by diesel trucks. Data on the energy use of such a truck per kilometer per ton of product are provided by several sources, presented in table 6.9. In this study, an energy consumption of 1,22 MJ per ton per kilometer is assumed. The average distance from the refinery to a refueling station in the Netherlands is assumed to be 80 kilometers [Gave, 1999]. Because the truck also needs to drive back to the refinery, all calculations are performed with the two-way distance that equals 160 kilometers. With the energy content of a ton of diesel fuel, which we know from the fuel specifications in appendix D, the information needed to calculate process energy use per MJ of fuel is complete. The only process fuel that has to be included in the calculations is diesel. Some electricity is used to pump the diesel into and out of the truck and to fuel a car at the refueling station but this amount is so small it is negligible on a MJ basis. Process energy use comes down to 0,005 MJ per MJ of fuel, all of which is diesel fuel.

WTT results

By combining all energy flows in the separate steps in the way described by formula (8) and (12) in section 4.3, the total energy input of the direct primary feedstock and of the process fuels can be calculated. The direct primary feedstock in the diesel fuel chain equals 1,047 MJ. The total amount of process fuel used in the fuel chain equals 0,074 MJ. This amount consists of diesel, gasoline, heavy fuel oil, natural gas and electricity. By applying formula (14) of chapter 4, whereby information from all fuel chains included in the model is used, the primary energy needed to create the process fuels is included in the calculations. We find that the total diesel fuel system uses three primary feedstocks: crude oil, raw natural gas and coal. The exact quantities of each feedstock are shown in table 6.10. Because neither the diesel fuel chain itself nor the fuel chains of the process fuels produce byproducts, there are no direct or indirect byproducts that have to be accounted for.

The Tank to Wheel and Well to Wheel chain

In the Tank to Wheel part of the fuel chain, diesel is used in a compression ignition engine. By measuring fuel economy in the way explained in section 4.5, the fuel economy of a diesel car is 2,51 MJ/km [TNO, 2003]. By multiplying the fuel economy with the amounts of primary energy from table 6.10 the primary energy use per kilometer can be calculated, as shown in table 6.10.

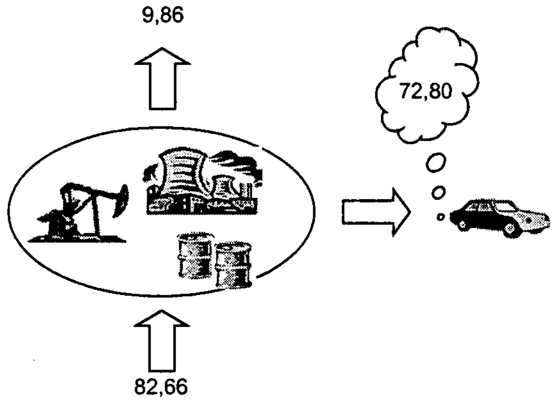

Figure 6.1: carbon balance of the diesel fuel chain (values in gCO_2/MJ_{diesel})

CH_4 (10^{-3} g/MJ)	[Johansson, 1992]	[Arthur D Little, 1996]	[De Jager, 1998]	This study
Extraction	26,0	6,8	13,8	16,4
Transportation	<<1	0,1	0,2	0,1
Production	0,00	0,3	0,1	0,15
Distribution	<<1	0,0	0,0	0,0
WTT emissions				27,2
TTW emissions				1,6
WTW emissions				28,8
WTW emissions (mg/km)				*72,5*

Table 6.11: methane emissions in the diesel fuel chain

N_2O (10^{-3} g/MJ)	[Johansson, 1992]	This study
Extraction	<<1	0,0
Transportation	<<1	0,0
Production	1,5	1,5
Distribution	<<1	0,0
WTT emissions		1,6
TTW emissions		2,7
WTW emissions		4,2
WTW emissions (mg/km)		*10,6*

Table 6.12: nitrous oxide emissions in the diesel fuel chain

Emissions

Carbon dioxide

As explained in chapter 4, carbon dioxide emissions are estimated by means of a carbon balance. The carbon balance for the diesel fuel chain is shown in figure 6.1. The oval figure represents the production of the fuel and the process fuels in the WTT chain. The car with the smoke coming from the tail pipe represents the TTW part of the fuel chain. The total carbon dioxide input in the fuel chain, summed over all primary feedstocks, equals 82,66 gCO_2 per MJ of diesel fuel and is completely of fossil origin. 72,80 gram of this quantity gets contained in the diesel fuel and is released as emissions during the TTW part of the fuel cycle. The other 9,86 g is lost during the WTT fuel chain. Total WTW carbon dioxide emissions equal 82,66 gCO_2 per MJ of diesel. With the fuel economy of a diesel engine of 2,51 MJ/km this equals 207,8 gCO_2 per kilometer.

Methane

Data on methane emissions are collected from Johansson, Arthur D. Little and De Jager [Johansson, 1992]; [Arthur D. Little, 11996]; [De Jager, 1998]. The emissions per step are recorded in table 6.11. As the table shows, the data contain considerable differences. Also, all three authors remark in their studies that their data contain a high level of uncertainty. To reflect uncertainty of this kind, many studies use confidence intervals. However, for the presentation of the final results, all emissions are multiplied with their GWP and summed. As we will see later on, methane emissions contribute only a minor proportion of the total CO_2-equivalent greenhouse gas emissions. The confidence interval, which is only a fraction of the methane emissions, becomes so small that it is negligible. This is discussed more elaborately in chapter 11. In stead of calculating confidence intervals, this study determines for each step an educated estimate. By summing the values of the individual steps and including the emissions from the production of the process fuels, the WTT emissions are found. These equal 27,2 mg/MJ. The Tank to Wheel emissions have been determined from measurements on vehicles in the way described in section 4.5. These emissions equal 1,6 mg/MJ. By summing WTT and TTW data the WTW emissions in mg/MJ can be determined. Multiplying this value with the fuel economy of a diesel engine gives the WTW data in mg/km. The value for the first number equals 28,8 mg/MJ; for the second it is 72,5 mg/km. These numbers confirm that methane emissions are only a fraction of carbon dioxide emissions.

Nitrous oxide

In section 5.5 we have seen that emissions of nitrous oxide are preliminary the result of agriculture. Because the diesel fuel chain is completely based on fossil fuels and makes no use of any crop whatsoever, emissions of nitrous oxide play only a minor role. Because of this they are very poorly mapped. In this study, data from Johansson are used [Johansson, 1992]. The data are shown in table 6.12. As we see, Johansson estimates nitrous oxide emissions in the recovery step, transportation step and distribution step to be negligible, which leaves only the production step as source of emissions. The emissions in this step equal 1,5 mg N_2O per MJ of diesel. Including the emissions from the production of the process fuels in the calculation leads to a slightly higher result of 1,6 mg. The TTW emissions have been measured in the way described in section 4.5 and equal 2,7 mg/MJ. This brings the total WTW result at 4,2 mg/MJ. Expressed in mg per kilometer the outcome is 10,6 mg/MJ, which is considerably lower than methane emissions.

Emissions in CO_2-equivalents

In section 5.5 we have seen that all emissions have a Global Warming Potential (GWP) by which they can be expressed in CO_2-equivalent emissions. The use of CO_2-equivalent emissions makes it possible to sum the emissions. The CO_2-equivalent emissions can be calculated by multiplying each emission with its GWP. The GWPs for carbon dioxide, methane and nitrous oxide can be found in appendix C. For the diesel fuel chain, the total CO_2-equivalents emissions equal 212,6 CO_2-eq/km.

Reference	Efficiency	Comments
[Gave, 1999]	87,8	-
[DeLuchi, 1993]	85,5	Data based on recovery in United States only.
[Arthur D Little, 1996]	89,7	Estimate of year 2000 efficiencies; data based on production in US only.
[Verbeek, 1997]	86,0	This number is based on other sources from literature.
[Johansson, 1992]	86,5	Average process energy in refinery equals 8% of refinery output. Light distillates, which include gasoline, use 68% of all process energy and make up 40% of refinery output. This leads to an efficiency for diesel of 86,5%.
[GM, 2001]	85,5	Estimate of year 2005 efficiencies; data based on United States only.
This study	86,5	Data from [Johansson, 1992] are used because they are best specified

Table 6.13: efficiencies in the production of gasoline

Division of process energies (%)	[Gave, 1999]	[DeLuchi, 1993]	This study
Crude oil	86,9	92,3	89,6
Diesel	0,1	0,0	0,1
LPG	0,1	0,1	0,1
Heavy fuel oil	1,0	0,0	0,5
Natural gas	4,6	0,4	2,5
Electricity	0,4	0,7	0,5
Petroleum coke	3,2	1,0	2,1
Refinery gas	3,7	5,5	4,6
Total	100,0	100,0	100,0

Table 6.14: distribution of process energies in the production of gasoline

Energy use per MJ of gasoline produced	
Crude oil	1,036
Diesel	0,001
LPG	0,001
Heavy fuel oil	0,006
Natural gas	0,029
Electricity	0,006
Petroleum coke	0,024
Refinery gas	0,053
Total	1,156

Table 6.15: energy flows in the production of gasoline

6.3 *The gasoline fuel chain*

This section describes the gasoline fuel chain. The section starts by modeling the energy flows in the WTT chain, followed by the energy flows in the TTW chain and the combination of the WTT and TTW part. Finally the emissions are modelled.

The Well to Tank chain

The gasoline fuel chain consists of four steps: recovery of crude oil, transportation of crude oil to the refinery, production of gasoline and distribution of gasoline. The first two steps in the gasoline fuel chain are identical to the first two steps in the diesel fuel chain. Because these steps are already described in the diesel fuel chain, they are not repeated here. The reader is referred to section 6.2.

Refining from crude oil to gasoline

The third step in the gasoline fuel chain is the production step. In this step, crude oil is refined to gasoline. We have seen in section 6.2 that although diesel, gasoline and LPG are in reality different outputs of the same process, they are treated as separate processes in literature. Of all refinery outputs, gasoline requires most processing and therefore the efficiency of the production of gasoline is lower than that of diesel. Data found in literature are presented in table 6.13. The table shows efficiencies ranging from 85,5% to 89,7%. Data from Johansson are best specified and are well within the range mentioned by other sources. Therefore this study uses the efficiency mentioned by Johansson which equals 86,5%.

With an efficiency of 86,5%, it takes 1,156 MJ to produce 1 MJ of gasoline. Data on the composition of this flow are given by Gave and DeLuchi [Gave, 1999]; [DeLuchi, 1993]. Gave provides separate data for the production of diesel, gasoline and LPG. Therefore the dataset for gasoline is used. DeLuchi provides data for a European refinery and an American refinery. Although the data set from the American refinery treats diesel and gasoline separately while the data set from the European refinery does not, this study prefers the data set from the European refinery. The geographical scope of this study is the Netherlands so the data set for the European refinery is thought to resemble the truth best. Both data sets from Gave and DeLuchi have been recalculated from HHVs to LHVs with the fuel specifications from appendix D. Also, in DeLuchi the flow of crude oil has been included, which was not the case in the original data set. The results of these calculations are shown in table 6.14. As it is not known whether one data set is more reliable than the other, this study takes the average of the two for further calculations. With the distribution of the energy flow through the step and the total energy flow through the step, the contribution of each fuel can be calculated, as is shown in table 6.15.

Distribution of gasoline

The final step in the fuel chain is the distribution of gasoline. Gasoline is transported by diesel truck from the refinery to refueling stations all over the Netherlands. At the refueling stations, the gasoline is fuelled into the tank of a vehicle.

In table 6.9, we have seen that a diesel truck uses 1,22 MJ to transport 1 ton of products over a distance of 1 kilometer. With an assumed average distribution distance of 160 kilometers two-way and the energy content of gasoline from appendix D, the average energy used to transport 1 MJ of gasoline can be calculated. This turns out to be 0,004 MJ per MJ of gasoline. Besides diesel to transport the gasoline from the refinery to the refueling station, some electricity is used to pump the gasoline into and out of the diesel truck and at the refueling station, to pump the gasoline into a vehicle. However, this amount is this small that it can be neglected on a MJ basis. Therefore diesel is the only relevant process fuel of which 0,004 MJ is used per MJ of gasoline.

	Primary input in the WTT chain MJ/MJ$_{gasoline}$	Energy use in the TTW chain MJ$_{gasoline}$/km	Primary input in the WTW chain MJ/km
Crude oil	1,17		3,42
Natural gas	0,08		0,23
Coal	0,01		0,04
Gasoline		2,93	
Total	1,26	2,93	3,69

Table 6.16: WTT, TTW and WTW energies in the gasoline fuel chain

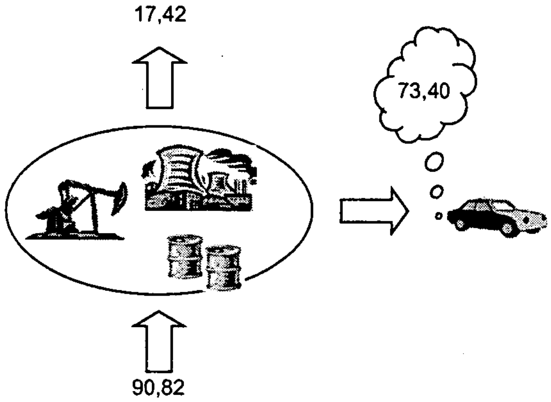

Figure 6.2: carbon balance of the gasoline fuel chain (values in $gCO_2/MJ_{gasoline}$)

CH_4 (10^{-3} g/MJ)	[Johansson, 1992]	[Arthur D Little, 1996]	[De Jager, 1998]	This study
Extraction	26,0	6,8	13,8	16,4
Transportation	<<1	0,1	0,2	0,1
Production	0,0	0,5	0,2	0,25
Distribution	<<1	0,05	0,00	0,0
WTT emissions				33,3
TTW emissions				3,0
WTW emissions				36,3
WTW emissions (mg/km)				*106,5*

Table 6.17: methane emissions in the gasoline fuel chain

WTT results

At this point the sizes of all energy flows directly entering the fuel chain are known. In figure 4.1, these are the blue and red lines entering the black boxes. The direct crude oil input, represented by a blue line in figure 4.1, equals 1,120 MJ. The sum of all process energies entering the fuel chain, represented by the red arrows in figure 4.1, equals 0,110 MJ. Process fuels used are diesel, gasoline, LPG, heavy fuel oil, natural gas and electricity. In order to correctly model all energy flows through the fuel chain, the production of the process fuels has to be included. This can be done by applying equation (14) from chapter 4. One must keep in mind though, that all fuel chains must be completely modelled before this calculation can be performed. After applying the equation, it turns out that the gasoline fuel chain uses three primary feedstocks: crude oil, natural gas and coal. The total energy use equals 1,259 MJ per MJ of gasoline. The contribution of each individual feedstock is presented in table 6.16. Because neither the gasoline fuel chain itself nor the fuel chains of the process fuels produce byproducts, there are no direct or indirect byproducts that have to be accounted for.

The Tank to Wheel and Well to Wheel chain

Gasoline is used in a spark ignition engine. The fuel economy of gasoline vehicle is determined in the way described in section 4.5 and equals 2,93 MJ per kilometer [TNO, 2003]. This means that a gasoline-fuelled vehicle is a little less efficient than a diesel fuelled vehicle. By multiplying the fuel economy with the WTT primary feedstock use, the WTW primary feedstock use can be calculated. The results are shown in table 6.16.

Emissions

Carbon dioxide

Like the carbon dioxide in the diesel fuel chain, carbon dioxide emissions in the gasoline fuel chain are calculated by means of a carbon balance. The carbon balance for the gasoline fuel chain is shown in figure 6.2. The oval in the figure represents the WTT part of the fuel chain while the car with the smoke coming from the tail pipe represents the TTW part of the fuel chain. As we see in the figure, the total carbon dioxide content of all primary feedstocks entering the fuel chain equals 90,82 gCO_2/MJ. The emissions from the TTW part are with 73,40 g/MJ almost identical to those from the diesel chain (72,80 g/MJ). Due to the fact that the production of gasoline consumes more energy than the production of diesel does, the emissions are somewhat higher: 17,42 g/MJ for gasoline versus 9,86 g/MJ for diesel. All primary energy used in the fuel chain comes from fossil sources, and therefore the WTW carbon dioxide emissions are identical to the carbon dioxide content of the primary feedstock, namely 90,82 gCO_2 per MJ of gasoline, which is 207,8 g/km.

Methane

Data on methane emissions are collected from three sources: Johansson, Arthur D Little and De Jager [Johansson, 1992]; [Arthur D. Little, 1996]; [De Jager, 1998]. As discussed in section 2 of this chapter, methane emissions are poorly mapped and contain a certain degree of uncertainty. However, this study does not apply confidence intervals but tries to determine an educated value for the emissions. The values mentioned by literature and value that is used in this study are depicted in table 6.17. By summing the emissions from the individual steps and including emissions from the production of the process fuels, the WTT emissions are found. These equal 33,3 mg per MJ of gasoline. The TTW emissions have been measured in the real world driving cycle described in section 4.5. With a value of 3,2 mg/MJ they are considerably higher than the methane emissions from a diesel engine. Together the WTT and TTW emissions constitute the WTW emissions. By multiplying the emissions with the fuel economy of a gasoline-fuelled vehicle, the emissions can be expressed in mg per kilometer. In doing so, we find values of 36,3 mg/MJ and 106,5 mg/km.

N_2O (10^{-3} g/MJ)	[Johansson, 1992]	This study
Extraction	<<1	0,0
Transportation	<<1	0,0
Production	2,0	2,0
Distribution	<<1	0,0
WTT emissions		2,1
TTW emissions		1,2
WTW emissions		3,2
WTW emissions (mg/km)		*9,4*

Table 6.18: nitrous oxide emissions in the gasoline fuel chain

Reference	Efficiency	Comments
[Gave, 1999]	95,4	-
[DeLuchi, 1993]	94,6	Data based on production in United States only.
[Arthur D Little, 1996]	95,3	Estimate of year 2000 efficiencies; data based on production in United States only.
[Verbeek, 1997]	93,0	Based on other sources from literature.
[Johansson, 1992]	90,0	Refinery of LPG is assumed to require less processing energy than gasoline.
[GM, 2001]	-	GM provides no separate data on the production and distribution of LPG.
This study	95,1	The average from Gave, DeLuchi and Arthur D Little is used.

Table 6.19: efficiencies in the production of LPG

Nitrous oxide

The gasoline fuel chain is a fuel chain that uses only fossil feedstocks. Nitrous oxide emissions are especially important when agriculture is involved, and because this is not the case in the gasoline fuel chain, nitrous oxide emissions only play a minor role. Unfortunately this minor role has apparently led researchers to overlook them. Very little data are available and data that are available contain large degrees of uncertainty.

In this study, data from Johansson are used [Johansson, 1992]. They are depicted in table 6.18. We see that the only relevant step for nitrous oxide emissions is the production step, as was the case in the diesel fuel chain. In this step, 2 mg N_2O is produced per MJ of gasoline. Summing the steps and adding the production processes of the process fuels brings us to the WTT emissions. These equal 2 mg N_2O per MJ of gasoline. The TTW emissions are determined by the driving cycle explained in section 4.5. TTW emissions equal 1,2 mg per MJ, which is considerably lower than nitrous oxide emissions from a diesel fuelled vehicle. By summing the WTT and TTW emissions and multiplying them with the fuel economy of a gasoline fuelled vehicle, the WTW emissions per MJ can be calculated. These turn out to be respectively 3,2 mg/MJ and 9,4 mg/km.

Emissions in CO_2-equivalents

By multiplying each emission with its GWP, the emissions can be expressed in CO_2-equivalents and summed. Performing this calculation with the data from the gasoline fuel chain results in a value for the WTW emissions of 271,3 gCO_2-eq/km.

6.4 The LPG fuel chain

The last fuel chain that is based on crude oil and included in this study, is Liquefied Petroleum Gas, LPG. In most refineries, it is not a main product but merely a byproduct that is upgraded to a transportation fuel. LPG consists of a mixture of two gases, namely propane and butane. The ratio between these two components varies over time of the year and over country. In the Benelux the following rule of thumb is a good first estimate: 40% propane with 60 % butane in summer and 60% propane with 40% butane in winter [VITO, 1999].

The Well to Tank chain

As said above, the LPG fuel chain uses crude oil as primary feedstock. The fuel chain consists of four steps: extraction of crude oil, transportation of crude oil to the refinery, production of LPG and finally distribution of LPG. The first two steps are identical to the first two steps in the diesel fuel chain and the gasoline fuel chain. Because these steps have been discussed in detail before in the description of the diesel fuel chain, they are not repeated here.

Refining from crude oil to LPG

LPG is a light distillate. It has the shortest carbon chains of all fuels made from crude oil. In general, light distillates require more processing than medium or heavy distillates. The most important light distillate, gasoline, requires a lot of processing in order to obtain synchronised molecular structures and burning behaviour. However, the carbon chains of propane and butane are smaller and simpler than the carbon chains in gasoline. It is easier to shape them and thus less energy is required. The efficiency of the refining process is determined from literature. An overview of data found in literature is provided in table 6.19. As the table shows, the values for the efficiency vary between 90,0 and 95,4%, which is, as expected, more efficient than the refining of crude oil to gasoline but less efficient than the refining of crude oil to diesel. The very low value of 90% is provided by Johansson. Although this author is very accurate on data for gasoline and diesel, he provides no clear reason why production of LPG would have such low efficiency. Therefore his data are disregarded. Data from Gave, DeLuchi

Division of process energies (%)	[Gave, 1999]	This study
Crude oil	86,8	86,8
Diesel	0,1	0,1
LPG	0,1	0,1
Heavy fuel oil	1,0	1,0
Natural gas	4,6	4,6
Electricity	0,4	0,4
Petroleum coke	3,2	3,2
Refinery gas	3,7	3,7
Total	100,0	100,0

Table 6.20: distribution of process energies in the production of LPG

Energy use per MJ of LPG produced	
Crude oil	1,045
Diesel	0,000
LPG	0,000
Heavy fuel oil	0,001
Natural gas	0,002
Electricity	0,000
Petroleum coke	0,002
Refinery gas	0,002
Total	1,052

Table 6.21: energy flows in the production of LPG

	Primary input in the WTT chain MJ/MJ_{LPG}	Energy use in the TTW chain MJ_{LPG}/km	Primary input in the WTW chain MJ/km
Crude oil	1,09		3,19
Natural gas	0,04		0,12
Coal	0,01		0,03
LPG		2,93	
Total	1,14	2,93	3,34

Table 6.22: WTT, TTW and WTW energies in the LPG fuel chain

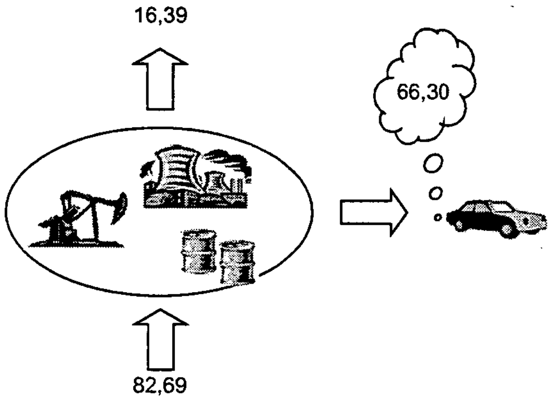

Figure 6.3: carbon balance of the LPG fuel chain (values in gCO_2/MJ_{LPG})

and Arthur D Little are considered most trustworthy and therefore their average is taken. This equals 95,1%.

With an efficiency of 95,1%, it takes 1,052 MJ to create 1 MJ of LPG. Data on the composition of this energy flow are provided by Gave [Gave, 1999]. Gave provides separate data for the refining of crude oil to diesel, to gasoline and to LPG. In this fuel chain, the LPG data set is used. The data have been converted from HHVs to LHVs with the fuel specifications from appendix D. The recalculated data set is depicted in table 6.20. With the composition of the energy flow and the total amount of energy used in the production step, the contribution of each fuel can be calculated. The results of this calculation are shown in table 6.21.

Distribution of LPG

LPG is distributed by diesel trucks. Under normal conditions, LPG is gaseous and thus has a low energy content per cubic meter. To increase the energy content, the LPG is distributed under pressure, in liquefied form. The tanks in which LPG is distributed need to be able to endure the force exerted by the pressure. They need to be strong but as a result they are heavy, which makes the transport less efficient. Therefore the distribution of LPG requires 0,007 MJ of process energy per MJ of fuel transported. At the refueling station, some electricity is used to dispense the LPG into a vehicles fuel tank, but this amount is so small it can be neglected. Diesel is the only relevant process fuel.

WTT results

All energy that enters the LPG fuel chain directly is now known and consists of 1,054 MJ of primary feedstock and 0,069 MJ of process fuels. The process fuels used in the LPG fuel chain are diesel, gasoline, LPG, heavy fuel oil, natural gas and electricity. If the energy use in the fuel chains of the process fuels is included in the calculations, the total primary energy input in the LPG fuel chain system equals 1,142 MJ per MJ of LPG. The division of this number over crude oil, natural gas and coal is provided by table 6.22. Because there are no byproducts produced in the fuel chains of the process fuels, there are no direct or indirect byproducts that have to be accounted for.

The Tank to Wheel and Well to Wheel chain

In the TTW part of the fuel cycle, LPG is burned in a spark ignition engine, like gasoline. The fuel economy of a LPG fuelled car is identical to that of a gasoline fuelled car: 2,93 MJ/km for both [TNO, 2003]. These data have been measured in the way described in section 4.5. With the WTT energy use and the TTW energy use, the WTW energy use can be determined. The results per primary input are shown in table 6.22.

Emissions

Carbon dioxide

Carbon dioxide emissions are calculated by means of a carbon balance. The carbon balance for the LPG fuel chain is depicted in figure 6.3. The oval figure represents the WTT part of the fuel chain while the TTW part is visualised by the car with the smoke coming from the tailpipe. As the figure shows, the total carbon dioxide content of all primary inputs entering the fuel chain system, equals 82,69 gCO_2 per MJ of LPG. 66,30 g of this quantity is first contained in the fuel and later emitted in the TTW part of the fuel chain. The remainder is emitted in the WTT part of the fuel chain. Because the LPG fuel chain uses only fossil primary inputs, the total WTW carbon dioxide emissions equal the carbon dioxide content of the primary feedstock, 82,69 gCO_2/MJ. Based on the fuel economy mentioned before, this equals 222,5 gCO_2 per kilometer.

CH_4 (10^{-3} g/MJ)	[Johansson, 1992]	[Arthur D Little, 1996]	[De Jager, 1998]	This study
Extraction	26,0	6,8	13,8	16,4
Transportation	<<1	0,1	0,2	0,1
Production	0	0,4	1,6	0,8
Distribution	<<1	0,1	0,0	0,0
WTT emissions				26,5
TTW emissions				2,4
WTW emissions				28,9
WTW emissions (mg/km)				*84,6*

Table 6.23: methane emissions in the LPG fuel chain

N_2O (10^{-3} g/MJ)	[Johansson, 1992]	This study
Extraction	<<1	0,0
Transportation	<<1	0,0
Production	0,3	0,3
Distribution	<<1	0,0
WTT emissions		0,4
TTW emissions		0,9
WTW emissions		1,3
WTW emissions (mg/km)		*3,7*

Table 6.24: nitrous oxide emissions in the LPG fuel chain

Fuel chain	WTT primary energy (MJ_{prim}/MJ_{output})	TTW energy (MJ_{output}/ km)	WTW primary energy (MJ_{prim}/km)	WTW CO_2 emissions (gCO_2/km)	WTW CH_4 emissions (gCH_4/km)	WTW N_2O emissions (gN_2O/km)	Total WTW emissions (g CO_2-eq./km)
Diesel	1,14	2,51	2,87	207,8	0,07	0,01	212,6
Gasoline	1,26	2,93	3,69	266,0	0,11	0,01	271,3
LPG	1,14	2,93	3,34	242,0	0,08	0,00	245,0

Table 6.25: summary of results for the diesel fuel chain, gasoline fuel chain and LPG fuel chain

Methane

A second source of greenhouse gas emissions is methane. Data on methane emissions are not very accurately mapped so one should be cautious with interpreting them. In this study, a value is assigned to each step in the fuel chain based on an educated consideration of the available information. The available data are shown in table 6.23. By summing the data on the separate steps and including emissions from the production of the process fuels in the way described in section 4.4, the WTT methane emissions are calculated. Their value equals 26,5 mg CH_4/MJ. The TTW data are measured in the way described in section 4.5 and equal 2,4 mg/MJ. By summing the WTT number and the TTW number, the WTW emissions are obtained. With a value of 28,9 mg CH_4 per MJ LPG they are almost identical to the WTW emissions from diesel. Due to the higher fuel consumption of LPG as compared to diesel, the WTW emissions expressed in mg/km are higher for LPG: 84,6 mg/km for LPG versus 72,5 mg/km for diesel.

Nitrous oxide

The LPG fuel chain is a fossil fuel based fuel chain. Nitrous oxide emissions are especially of interest when the cultivation of crops is involved. Because this is not the case in the LPG fuel chain, nitrous oxide emissions are limited. Data on the size of the emissions are taken from Johansson [Johansson, 1992]. The emissions per step are shown in table 6.24. The total WTT emissions, calculated by summing the emissions of the separate steps and including the emissions from the production of the process fuels, equal 0,4 mg/MJ of LPG. With TTW emissions of 0,9 mg/MJ the WTW emissions equal 1,3 mg/MJ. With the fuel consumption of a LPG fuelled vehicle this becomes 3,7 mg/km.

Emissions in CO_2-equivalents

In order to be able to sum emissions, emissions are expressed in CO_2-equivalents. The CO_2-equivalent of an emission is obtained by multiplying the value of the emission with its global warming potential. Doing so for the emissions in the LPG fuel chain results in WTW emissions of 245,0 CO_2-eq/km. The global warming potentials that have been used in the calculation can be found in appendix D.

6.5 Summary of results

The most important results of the diesel fuel chain, gasoline fuel chain and LPG fuel chain are summarized in table 6.25.

7 Natural gas based fuel chains: CNG and FT diesel from natural gas

7.1 *Introduction*

This chapter is the second in a series of four in which fuel chains are modelled. In this chapter, fuel chains based on natural gas are discussed. The model contains two such fuel chains: compressed natural gas (CNG) and Fischer-Tropsch diesel (FT diesel). Both fuel chains start with the extraction of natural gas. At, or very near to, the spot of extraction the natural gas is processed. Impurities and water are removed and the natural gas is put under pressure. The third step in the fuel chain is transportation. Natural gas can be transported by pipeline or in liquefied form by tanker. In this study, all transportation is assumed to take place by pipeline. For the CNG fuel chain, the natural gas is transported to the refueling station, where it is compressed and ready to be sold. For the FT diesel fuel chain, it is assumed that the natural gas is transported to a central plant in the Randstad area. Here the gas is converted to FT diesel, after which the FT diesel is distributed by truck to refueling stations and sold. The CNG fuel chain is discussed more elaborate in section 2; the FT diesel chain in section 3.

Unlike crude oil, which is divided into a number of clearly defined categories according to viscosity and specific gravity, there is no clear division for natural gas. Sometimes a distinction is made between high calorific natural gas and low calorific natural gas, but the border between these two is vague. The composition of natural gas varies widely between different fields though, as is shown in table 7.1. The table shows that the main component in all fields is methane and that the gas contains smaller fractions of other alkanes up to 5 carbon atoms. Natural gas from most gas fields also contains impurities such as hydrogen sulfide, carbon dioxide and nitrogen. In the Netherlands, all natural gas is sold with Groningen specifications. This means that the gas contains about 15-vol.% nitrogen. Even natural gas from smaller fields that doesn't contain such a high nitrogen level, is mixed with nitrogen until it has the properties of Groningen gas. Because Groningen quality is standard in the Netherlands, this study uses low calorific Groningen gas in its base case. In the sensitivity analysis of chapter 11, other gases including high calorific gas are used.

7.2 *The CNG fuel chain*

In this section the CNG fuel chain is modelled. The structure of this section is identical to the structure used in chapter 6: first the energy flows in the WTT part of the fuel chain are modelled, then the energy flows in the TTW part of the fuel chain are modelled and subsequently the two parts are combined. Finally the emissions are modelled.

The Well to Tank chain

The WTT fuel chain consists of four steps that are discussed one by one. The analysis is completed by including the energy use in the production of the process fuels.

Recovery of natural gas

Natural gas is recovered from natural gas fields. The natural gas is locked in these fields under high pressure and high temperature, so once a borehole is drilled, the gas flows out spontaneously. During years and years of recovery the pressure in the gas field slowly falls. Spontaneous recovery can only be sustained until the natural gas in the field is in equilibrium

Composition (%)	Groningen (Netherlands)	Frigg (Norway)	Urengoy (Former Sovjet Union)	Hassi R'Mel (Algeria)
Methane	81,3	95,7	85,3	83,7
Ethane	2,9	3,6	5,8	6,8
Propane	0,4	-	5,3	2,1
Butanes	0,1	-	2,1	0,8
C_{5+}	0,1	-	0,2	0,4
Nitrogen	14,3	0,4	0,9	5,8
H_2S	-	-	-	-
CO_2	0,9	0,3	0,4	0,2

Table 7.1: composition of natural gases from a number of gas fields
Source: [Rojey, 1997]

Reference	Efficiency	Comments
[Gave, 1999]	95,0	-
[DeLuchi, 1993]	97,3	Data based on recovery in United States only.
[Arthur D Little, 1996]	97,3	Estimate of year 2000 efficiencies; data based on recovery in United States only.
[Verbeek, 1997]	97,0	Based on other sources from literature.
[Johansson, 1992]	97,0	-
[GM, 2001]	97,5	Estimate of year 2005 efficiencies; data based on recovery in United States only.
This study	97,3	Gave is left beyond consideration. Of all other sources the average is taken.

Table 7.2: efficiencies in the recovery of raw natural gas

Division of process energies (%)	[Gave, 1999]	[DeLuchi, 1993]	This study
Natural gas	91,3	92,0	91,7
Diesel	4,3	4,0	4,2
Gasoline	1,5	1,3	1,4
Heavy fuel oil	0,4	0,3	0,3
Crude oil	0,8	0,8	0,8
Electricity	1,6	1,5	1,6
Total	100,0	100,0	100,0

Table 7.3: distribution of process energies in the extraction of natural gas

Energy use per MJ of natural gas extracted	
Natural gas	1,025
Diesel	0,001
Gasoline	0,000
Heavy fuel oil	0,000
Crude oil	0,000
Electricity	0,000
Total	1,028

Table 7.4: energy flows in the extraction of natural gas

Reference	Efficiency	Comments
[Gave, 1999]	97,4	-
[DeLuchi, 1993]	97,6	Data based on processing in United States only.
[Arthur D Little, 1996]	95,0	Processing to pipeline quality. No specifications of what pipeline quality means.
[Verbeek, 1997]	98,0	Based on other sources from literature.
[Johansson, 1992]	98,0	Data based on Swedish situation.
[GM, 2001]	97,5	Data based on processing in United States only.
This study	97,7	[Gave,1999] and [Johansson,1992] are closest to current Dutch situation. Therefore their average is used.

Table 7.5: efficiencies in the processing of raw natural gas

with the natural gas in the pipelines at the recovery station. At equilibrium there is still quite some natural gas left in the field, which can be recovered using compressors. These compressors are fed with a fraction of the natural gas they pump up [NAM, 2003]. From the borehole, the natural gas is led to an installation that reduces temperature and pressure. Water vapour and condensates that are dispersed in the gas become fluid and can be separated from the gas. Water is returned into the gas field whereas the condensate is transported to refineries. The natural gas itself is now ready for further processing [NAM b, 2003].

The efficiencies for the recovery of natural gas are shown in table 7.2. Except for Gave, all studies indicate efficiencies between 97,0 and 97,5%. The estimate from Gave is exceptionally low and will therefore be disregarded. None of the studies mention the production of condensates as a byproduct. Apparently the data on recovery are already corrected for the condensates. In this study the average of all sources except Gave is used, which equals 97,3%.

With an efficiency of 97,3%, it takes 1,028 MJ to recover 1 MJ of natural gas. 1 MJ of this number comes from the energy content of the natural gas that is ready to serve as input for the next step, which leaves 0,028 MJ for process energies and losses of natural gas and process energies. A distribution of this energy flow is given by Gave and DeLuchi. With the fuel specifications from appendix D, their data have been recalculated into LHVs. The result is shown in table 7.3. Both data sets are almost identical and therefore this study uses the average of the two. As can be seen in the table, the main process energy is natural gas. This is partly due to recovery by compressors which use natural gas as energy source and partly due to spills and leakages. With the distribution from table 7.3 and the total amount of process energy, the contribution of each process fuel can be calculated, which is shown in table 7.4.

Processing of natural gas

In the processing step the natural gas is cleared of impurities and adjusted to prescribed specifications. These specifications can be transport specifications or conditions of use. Transport conditions are usually aimed at preserving the quality of the pipeline by preventing the formation of a liquid phase, preventing clogging of the line by hydrates and preventing excessive corrosion. Conditions of use include a range for the heating value and the removal of toxic components. All these conditions require the total or partial removal of hydrogen sulfide (H_2S), carbon dioxide (CO_2), mercury, water and heavy hydrocarbons [Rojey, 1997]. In many countries nitrogen is also removed. In the Netherlands however, natural gas with Groningen specifications is used which contains 15-vol.% nitrogen. Natural gas that does not have such a high nitrogen content, such as gas from smaller fields or imported gas, is mixed with nitrogen until Groningen specifications are reached.

Table 7.5 provides an overview of the efficiencies in the processing step as mentioned by a number of sources. All efficiencies range from 95% to 98%. Unfortunately, very little extra information is provided with these efficiencies and therefore it is very unclear what exactly is included in the numbers. Natural gas from the North Sea, which is an important source for the Netherlands, is almost free of sulpher. Consequently, it needs less processing than average. Therefore sources from literature that focus entirely upon non-North Sea natural gas are disregarded. Johansson and Gave, which have respectively Sweden and the Netherlands as geographical scope, are considered most trustworthy for this process step. This study uses the average of efficiencies stated by them, which is 97,7%. With this efficiency, 1,024 MJ of energy is needed to obtain 1 MJ of natural gas ready to be transported. After subtracting the energy content of the natural gas from this value, there is 0,024 MJ of energy left for process energies. A distribution of process energies is given by Gave and DeLuchi. Both data sets have been converted to LHVs using the fuel specifications from appendix D. The recalculated data sets are shown is table 7.6. Like the data on the recovery step, the data sets are almost

Division of process energies (%)	[Gave, 1999]	[DeLuchi, 1993]	This study
Natural gas	97,3	98,6	98,0
Gasoline	0,1	0,0	0,0
Electricity	2,6	1,4	2,0
Total	100,0	100,0	100,0

Table 7.6: distribution of process energies in the processing of natural gas

Energy use per MJ natural gas processed	
Natural gas	1,003
Gasoline	0,000
Electricity	0,020
Total	1,024

Table 7.7: energy flows in the processing of natural gas

Reference	Efficiency	Comments
[Gave, 1999]	94,5	-
[DeLuchi, 1993]	95,0	Data based on United States only.
[Arthur D Little, 1996]	93,8	-
[Verbeek, 1997]	91,0	Includes transportation. When transportation is assumed to have an efficiency of 99,8%, this leaves 91,2% for compression.
[Johansson, 1992]	93,0	-
[GM, 2001]	97,0	Natural gas compressor.
This study	94,0	The average from all sources except Verbeek is taken

Table 7.8: efficiencies in the compression of natural gas

	Primary input in the WTT chain MJ/MJ_{CNG}	Energy use in the TTW chain MJ_{CNG}/km	Primary input in the WTW chain MJ/km
Crude oil	0,02		0,06
Natural gas	1,13		3,50
Coal	0,07		0,23
CNG		3,10	
Total	1,23	3,10	3,79

Table 7.9: WTT, TTW and WTW energies in the CNG fuel chain

equal end therefore their average is used in this study, with some rounding up in order to obtain a sum of exactly 100,0%. The main process fuels are natural gas and electricity. The use of gasoline is so small that it doesn't show if numbers are rounded up to three digits behind the comma. By combining the efficiency from table 7.5 and the division of process fuels from table 7.6, the energy flows through the production step can be calculated. These are shown in table 7.7.

Transportation of natural gas

The processed natural gas is now delivered to the distribution company. The most common form of transportation is by pipeline. If the natural gas is distributed to consumers, it is subsequently distributed through a high pressure network, a medium pressure network and a low pressure network. Refuelling stations though will probably be connected to the high or medium pressure network. It is assumed that distribution through the high pressure network is the only relevant way of distribution. In the Netherlands, all distribution through the high pressure network is taken care of by Gasunie Trade & Supply. If the transportation distance is long the gas is recompressed during transport, to countereffect pressure drop due to friction [Gasunie, 2003].

Because all distribution of natural gas is taken care of by Gasunie Trade & Supply, data on the use of process energies in the distribution step are obtained directly from Gasunie Trade & Supply, instead of collected from other sources of literature. In 2002 Gasunie Trade & Supply transported $2,98 \cdot 10^{12}$ MJ of natural gas and used $4,64 \cdot 10^{9}$ MJ of process energy. This comes down to 0,002 MJ of process energy per MJ of transported natural gas. 83,8% of process energies consists of natural gas, which is used for recompression during transportation. The remainder of the process energy consists of electricity [Gasunie, 2003].

Compression of natural gas

The final stage in the CNG fuel chain is compression. At the refueling station, the natural gas is compressed in order to increase the energy content by volume and thereby increase the range of a vehicle between refueling.

Table 7.8 provides an overview of the efficiencies in compression. They range from 91,0 to 97,0%. The Verbeek estimate is very low while the GM estimate is very high. When they are left beyond consideration, 94,0% efficiency seems reasonable. Which process fuels are used is commented on by Gave and DeLuchi. According to Gave, compression takes place mainly by compressors that are fed with natural gas. On the other hand, DeLuchi reports compression to take place entirely by electricity. In the Netherlands it is common practice that small compressors, like the ones that will be placed at refueling stations, are fed by electricity. Therefore this study assumes all compression in the distribution step to take place by electricity. With this assumption and the total amount of process energies, it can be calculated how much electricity is needed. This is 0,064 MJ per MJ of compressed natural gas.

WTT results

All direct energy flows in the individual steps are known. They can be combined according to the method described in section 4.2. By doing so, we find that the total CNG fuel chain uses 1,030 MJ of natural gas input and 0,087 MJ of process fuel. This number consists of diesel, gasoline, heavy fuel oil and electricity. The process fuels have been produced in fuel chains themselves. In order to correctly model all energy flows in the CNG fuel chain system, these production processes have to be taken into account. This can be done by applying formula (12) of chapter 4, after all fuel chains have been modelled. It turns out that the CNG fuel chain uses three primary feedstocks: crude oil, natural gas and coal. The total primary energy input equals 1,22 MJ. The exact quantities of each feedstock are shown in table 7.9. Because there are no byproducts produced in the diesel fuel chain or any of the fuel chains of the process fuels, there are no direct or indirect byproducts that have to be accounted for.

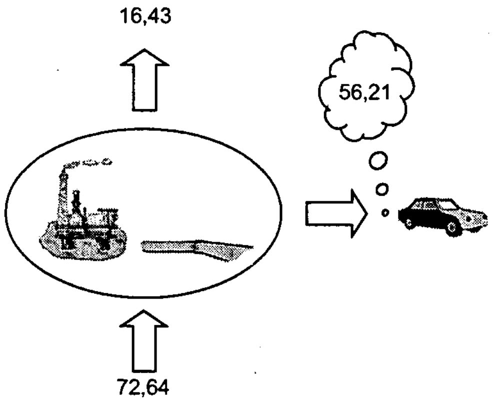

Figure 7.1: carbon balance of the CNG fuel chain (values in gCO_2/MJ_{CNG})

CH_4 (10^{-3} g/MJ)	[Johansson, 1992]	[Arthur D Little, 1996]	[Gasunie, 2003]	This study
Recovery	64,0	32,4		48,2
Processing	62,0	27,4		44,7
Transportation			0,9	0,9
Compression	0,0	1,8		0,9
WTT emissions				137,7
TTW emissions				24,0
WTW emissions				161,7
WTW emissions (mg/km)				*500,6*

Table 7.10: methane emissions in the CNG fuel chain

N_2O (10^{-3} g/MJ)	[Johansson, 1992]	This study
Recovery	<<1	0,0
Processing	<<1	0,0
Transportation	<<1	0,0
Compression	<<1	0,0
WTT emissions		0,0
TTW emissions		0,2
WTW emissions		0,2
WTW emissions (mg/km)		*0,6*

Table 7.11: nitrous oxide emissions in the CNG fuel chain

The Tank to Wheel and Well to Wheel fuel chain

Like LPG and gasoline, CNG is burned in a spark ignition engine. The fuel economy has been measured in the way described in section 4.5 and is significantly higher than that of LPG and gasoline: 3,10 MJ/km [TNO, 2003]. The WTW energy use can now be calculated from the TTW energy use and the WTT energy use, as shown in formula (34) of chapter 4. The results of this calculation are shown in table 7.9.

Emissions

Carbon dioxide

Emissions of carbon dioxide are estimated by means of a carbon balance. The carbon balance for the CNG fuel chain is shown in figure 7.1. The oval figure represents the production of the fuel and the process fuels, or the WTT chain. The car with the smoke coming from the tail pipe represents the TTW part of the fuel chain. The total carbon dioxide input in the fuel chain, summed over all primary feedstocks, equals 73,09 gCO_2 per MJ of diesel fuel and is completely of fossil origin. 56,21 gram gets contained in the CNG and is released as emissions during the TTW part of the fuel cycle. The other 16,88 g of this quantity is lost during the WTT fuel chain. Because all primary feedstocks are of fossil origin the WTW emissions equal the carbon dioxide content of the primary feedstocks, which is 73,09 gCO_2 per MJ of CNG. With the fuel economy of a CNG fuelled vehicle of 3,10 MJ/km this equals 224,9 gCO_2 per kilometer.

Methane

Data on methane emissions are collected from literature. For the transportation step, data from Gasunie are used. The emissions in the other steps are determined from several sources. As can be seen in table 7.10, where all data are shown, the data contain quite some differences. Because it is not known whether one data source is more reliable than the other, this study uses their average. With the data on the separate steps and data on the emissions in the production of the process fuels, the WTT emissions can be calculated. These equal 137,7 mg/MJ. The TTW emissions are determined from the TNO-study [TNO, 2003]. These equal 24,0 $mgCH_4$ per MJ of CNG. This value is considerably higher than methane emissions from crude oil based fuels. The reason is that a small part of the methane leaves the vehicles engine unburned. By summing WTT and TTW emissions and multiplying the sum with the fuel economy of CNG fuelled car, the WTW emissions can be determined. These equal 500,6 mg/km.

Nitrous oxide

Data on nitrous oxide emissions are depicted in table 7.11. As the table shows, the emissions are almost negligible. Only in the TTW part of the fuel cycle some nitrous oxide is emitted, but this amount is very small. On a WTW basis the nitrous oxide emissions are 0,6 mg/km, which is 32 times as little as WTW emissions in the diesel fuel chain.

Emissions in CO_2-equivalents

In section 5.5 we have seen that all emissions have a Global Warming Potential (GWP) by which they can be expressed in CO_2-equivalent emissions. The use of CO_2-equivalent emissions makes it possible to sum the emissions. By summing each emission with its GWP the CO_2-equivalent emissions can be calculated. The GWPs for carbon dioxide, methane and nitrous oxide can be found in appendix D. For the CNG fuel chain, the total CO_2-equivalents emissions equal 236,5 gCO_2-eq/km.

7.3 *The Fischer-Tropsch diesel from natural gas fuel chain*

In this section, the Fischer-Tropsch (FT) diesel from natural gas fuel chain is discussed. Fischer-Tropsch diesel is named after two German scientists, Franz Fischer and Hans

	Input (MJ)		Ouput (MJ)
Natural gas	2,279	FT diesel	1,000
Catalysts & chemicals	0,000	FT gasoline	0,584
		FT LPG	0,043
		Electricity	0,014
Total	2,279	Total	1,641

Table 7.12: energy flows in the production of FT diesel from natural gas

Tropsch, who developed in 1928 a process to make synthetic diesel from syngas. Their original goal was to convert coal to liquid fuels. After they had accomplished this goal, it turned out that the process can be applied to other inputs, too. Nowadays a lot of research is done to produce FT fuels, especially diesel, from natural gas, coal, residual waste and biomass. In this study, two of these feedstocks are studied in detail: FT diesel from natural gas in this section, and FT diesel from cellulosic biomass in section 8.2.

The Well to Tank chain

The fuel chain under consideration here uses Dutch natural gas as input. Natural gas is recovered in the usual fields where Dutch natural gas is recovered from. It is processed to pipeline quality and transported to a central plant in the Randstad area. There the gas is converted to FT diesel after which the diesel is distributed throughout the country. This short description of the fuel chain shows that the first three steps of the fuel chain are identical to the first three steps in the CNG fuel chain. These have been discussed in detail in the previous section and will not be repeated here.

Production of Fischer-Tropsch diesel

After the third step in the fuel chain, transportation, the natural gas has arrived at the production facility. The conversion from natural gas to FT diesel can be divided into three stages: production of syngas, synthesis of distillates and upgrading of products [Wang, 2002]. In the first stage, natural gas is converted to syngas, a mixture of hydrogen and carbon monoxide. Natural gas can react with steam, oxygen or a mixture of both. When the feedstock consists of natural gas, the reaction with oxygen is very favourable. In the next stage of the production step, carbon monoxide and hydrogen react to FT products. This reaction requires a catalyst to run properly. Two metals often serve as catalysts: iron and cobalt. Iron catalysts have the ability to change the carbon monoxide/hydrogen ratio in the syngas. This means that the iron catalysts can handle syngases with varying compositions. On the other hand, iron catalysts produce products with varying properties. A lot of processing is needed to give these products the desired characteristics. The other metal that is often used as catalyst is cobalt. Cobalt lacks the ability to change the composition of the syngas, but has the great advantage that the products that are produced require much less processing. In the fuel chain discussed here, the feedstock in the production step is natural gas of pipeline quality. This has a very constant composition. Consequently, the syngas that is produced from the natural gas, is also of constant composition. There is no need for a catalyst that can handle syngas of varying compositions, and thus cobalt is the catalyst of choice. The FT reaction results in molecules with carbon chains of different lengths. By adjusting the process for temperature and pressure, the process can be optimalised for a specific chain length. If the process is optimalised for the chain length of diesel molecules, not only diesel is formed but also some LPG, gasoline and waxes. The latter are molecules with carbon chains longer than those of diesel. In the final stage of the production step, upgrading of products, the waxes are cracked to diesel molecules. This increases the diesel yield in the production step. The upgrading stage also includes isomerisation in order to give all molecules similar characteristics. The final output of the production stage consists of diesel, gasoline, LPG and electricity. The latter has been generated with excess heat from the FT reaction. A more detailed description of the FT process can be found in appendix E.

Marano provides data on a FT plant that is optimalised for maximum diesel production [Marano, 2001]. Data on the input requirements are provided in table 7.12. We see that the plant uses 2,279 MJ of natural gas to produce 1 MJ of FT diesel and a range of byproducts. Also some catalysts and chemicals are used. This amount is so small, however, that it is negligible on a MJ basis. The byproducts consist of FT LPG, FT gasoline and electricity. The total amount of byproducts that is produced per MJ of FT diesel equals 0,641 MJ. An overview of the inputs and outputs is presented in table 7.12.

	Primary input in the WTT chain $MJ/MJ_{FT\text{-}diesel}$	Energy use in the TTW chain $MJ_{FT\text{-}diesel}/km$	Primary input in the WTW chain MJ/km
Crude oil	0,02		0,05
Natural gas	2,41		6,23
Coal	0,04		0,11
FT-diesel		2,59	
Total	2,47	2,59	6,39

Table 7.13: WTT, TTW and WTW energies in the FT-diesel from natural gas fuel chain, before accounting for byproducts

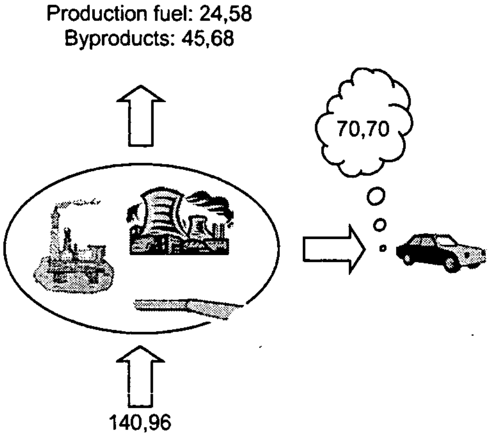

Figure 7.2: carbon balance of the FT diesel from natural gas fuel chain (values in $gCO_2/MJ_{FT\text{-}diesel}$)

Distribution of Fischer-Tropsch diesel

The final step in the fuel chain is the distribution of FT diesel. FT diesel is transported by diesel truck from the FT plant to refueling stations all over the Netherlands. At the refueling stations, the diesel is fuelled into the tank of a vehicle.

With the data from table 7.9 the average energy needed to transport 1 ton of product over a distance of 1 km has been estimated to be 1,22 MJ. With an assumed average distribution distance of 160 kilometers two-way and the energy content of FT diesel from appendix D, the average energy for transportation form the FT plant to refueling stations is calculated. It equals 0,005 MJ per MJ of FT diesel. At the refueling station, some electricity is used to pump the FT diesel into and out of the diesel truck and to pump the FT diesel into a vehicle. However, this amount is so small that it can be neglected on a MJ basis. Therefore diesel is the only relevant process fuel of which 0,005 MJ is used per MJ of FT diesel.

WTT results

We now have data on the energy flows in the separate steps. In order to obtain results for the whole fuel chain, the steps have to be combined. This is done according to the methodology described in section 4.2. We find that the FT diesel from natural gas fuel chain uses 2,347 MJ of natural gas and 0,057 MJ of process fuels per MJ of FT diesel. The amount of process fuels consists of diesel, gasoline, heavy fuel oil and electricity. In order to map all energy used to produce FT diesel, the energy needed to produce the process fuels has to be included. This can be done by applying the methodology from chapter 4, after all individual fuel chains have been modelled. We find a total primary feedstock use of 2,467 MJ per MJ of FT diesel. The contribution of a number of primary feedstocks is shown in table 7.13. The amount of byproducts produced directly in the fuel chain equals 0,641 MJ per MJ of FT diesel produced. There are no byproducts produced in the production of the process fuel and therefore the total amount of byproduct stays at 0,641 MJ. The division over the different byproducts is the same as in table 7.12. The total output from the fuel chain equals 1,641 MJ, divided over four outputs. The other fuel chains that have been modelled so far only had one output. It is impossible to make an equal comparison between fuel chains with different outputs. Therefore some additional calculations have to be made to account for byproducts. The background of these calculations has been described in section 4.7. The calculations themselves are performed in chapter 10, where the results from all fuel chains are presented and compared.

The Tank to Wheel and Well to Wheel fuel chain

In the TTW part of the fuel cycle, FT diesel is burned in a compression ignition engine. It is assumed that the CO_2 emission per kilometer from a compression ignition engine is equal for diesel from crude oil and for FT diesel. For diesel from crude oil, the carbon dioxide emissions equal 183 g/km [TNO, 2003]. This means that the carbon dioxide emissions for FT diesel are also 183 g/km. With the carbon content of the fuel as specified in appendix D, the fuel economy can be calculated. The fuel consumption comes down to 2,59 MJ per kilometer. Multiplying the WTT energy with the TTW energy results in the WTW energy. The results per primary input are shown in table 7.13.

Emissions

Carbon dioxide

Carbon dioxide emissions are calculated by a carbon balance. For FT diesel from natural gas, the balance is depicted in figure 7.2. The oval figure represents the production of the fuel and the process fuels in the WTT part of the fuel chain. The car with the smoke coming from the tailpipe represents the TTW part of the fuel chain. As we see in the figure, FT diesel has a carbon dioxide content of 70,70 gram per MJ, which is a little less than diesel that is made from crude oil. The emissions that emerge in the course of the fuel chain equal 24,58 g/MJ.

CH_4 (10^{-3} g/MJ)	[Johansson, 1992]	[Arthur D Little, 1996]	[De Jager, 1998]	[Marano, 2001]	[Gasunie, 2003]	This study
Recovery	64,0	32,4				48,2
Processing	62,0	27,4				44,7
Transportation	0,0	0,0			0,9	0,9
Production				2,6		2,6
Distribution	0,0	0,0	0,0			0,0
WTT emissions						242,1
TTW emissions						1,6
WTW emissions						243,6
WTW emissions (mg/km)						*630,7*

Table 7.14: methane emissions in the FT diesel from natural gas fuel chain

N_2O (10^{-3} g/MJ)	[Johansson, 1992]	[Marano, 2001]	This study
Recovery	<<1		0,0
Processing	<<1		0,0
Transportation	<<1		0,0
Production		0,5	0,5
Distribution	0,0		0,0
WTT emissions			0,5
TTW emissions			2,6
WTW emissions			3,1
WTW emissions (mg/km)			*8,0*

Table 7.15: nitrous oxide emissions in the FT diesel from natural gas fuel chain

Fuel chain	WTT primary energy (MJ_{prim} / MJ_{output})	WTT byproducts ($MJ_{bypr.}$ / MJ_{output})	TTW energy (MJ_{output} / km)	WTW primary energy (MJ_{prim} / km)	WTW CO_2 emissions (gCO_2/km)	WTW CH_4 emissions (gCH_4/km)	WTW N_2O emissions (gN_2O/km)	Total WTW emissions* (g CO_2-eq./km)
CNG	1,23		3,10	3,79	224,9	0,50	0,00	236,5
FT diesel	2,47	0,64	2,59	6,39	364,9	0,63	0,01	381,8

Table 7.16: summary of results for the CNG fuel chain and the FT diesel from natural gas fuel chain

*: not corrected for byproducts

All byproducts together have a carbon dioxide content of 45,68 g/MJ$_{FT\text{-}diesel}$. For now, this content is included in the WTT emissions. The carbon dioxide content of the byproducts is accounted for in chapter 10. This means that at this point, WTT emissions consists of the sum of the emissions from the production of the fuel and the carbon dioxide content of the byproducts, which equals 70,26 g/MJ. The total amount of carbon dioxide entering the fuel chain equals 140,96 g/MJ.

Methane

In the first three steps of the fuel chain, the methane emissions are identical to the emissions in the CNG fuel chain. For the fourth step in the fuel chain, production, a number provided by Marano is used [Marano, 2001]. In the final step, literature suggests that the emissions are negligible. The WTT emissions are calculated by summing the emissions in the individual steps and adding the emissions from the production of the process fuels. The calculation results in a value for the WTT emissions of 242,1 mg/MJ. Compared to other fuel chains, this is a very high value. This is partly due to leakages and spills of methane and partly because this fuel chain is less efficient than the fuel chains we have seen so far. More energy loss implies higher upstream emissions per unit output. The TTW emissions are assumed to be identical to TTW methane emissions from diesel that is based on crude oil, which is 1,6 mg/MJ. By summing the WTT number and the TTW number, the WTW emissions in mg/MJ are obtained. Multiplication with the energy consumption of a diesel engine results in the WTW emissions in mg/km. The first number equals 243,6 mg/MJ, the latter 630,7 mg/km. All data can be found in table 7.14.

Nitrous oxide

The FT diesel from natural gas fuel chain is a fossil fuel based fuel chain. Nitrous oxide emissions are especially of interest when the cultivation of crops is involved. Because this is not the case in this fuel chain, nitrous oxide emissions are limited. Data on the size of the emissions are taken from Johansson and Marano, although it must be remarked that these data contain a level of uncertainty. The emissions per step are shown in table 7.15. The production step is the only step in the fuel chain with relevant emissions. The WTT emissions, calculated by summing the emissions of the separate steps and including the emissions from the production of the process fuels, equal 0,5 mg/MJ of FT diesel. With TTW emissions of 2,8 mg/MJ the WTW emissions can be calculated. These equal 3,3 mg/MJ. With the fuel economy of a FT diesel fuelled vehicle this becomes 7,9 mg/km.

Emissions in CO_2-equivalents

In order to be able to sum emissions, emissions are expressed in CO_2-equivalents. The CO_2-equivalent of an emission is obtained by multiplying the value of the emission with its global warming potential. Doing so for the emissions in the FT diesel from natural gas fuel chain results in WTW emissions of 381,8 CO_2-eq/km. The global warming potentials that have been used in the calculation can be found in appendix D.

7.4 Summary of results

The results of the CNG fuel chain and the FT diesel from natural gas fuel chain are depicted in table 7.16.

8 Biomass based fuel chains: FT diesel from cellulosic biomass, ethanol from cellulosic biomass and ethanol from sugary biomass

8.1 Introduction

This is the third in a series of four chapters that describe the fuel chains that are modelled in this study. In this chapter, fuel chains with biomass as primary feedstock are discussed. There are three such feedstocks in the model: FT diesel from cellulosic biomass, ethanol from cellulosic biomass and ethanol from sugary biomass. In the fuel chains, two kinds of biomass are used: cellulosic biomass and sugary biomass. Cellulosic biomass is wood-like biomass or herbaceous biomass. Some examples are poplar, willow, and miscanthus. Sugary biomass consists of crop-like plants, such as corn, wheat, sugar beet or rapeseed. There are a couple of differences between cellulosic biomass and sugary biomass: first of all, the way in which they are grown. Cellulosic biomass is grown in a forestry-like manner. Only a part of the trees is harvested at a time, according to a rotating schedule. Sugary biomass is grown in a farming process. All plants are harvested at once, after which all new plants are grown. Second, the two kinds of biomass have different characteristics and thus require different processing in order to convert them to transportation fuels.

All fuel chains discussed in this chapter start with a growing step in which the biomass is grown. In the next step, the harvested biomass is transported to a central plant that is assumed to be located in the Randstad area. Once it has arrived there, the biomass is converted to the transportation fuel. For cellulosic biomass there are two possibilities: conversion to FT diesel or conversion to ethanol. Sugary biomass is only converted to ethanol. Finally, the FT diesel or the ethanol is distributed to refueling stations all over the country and sold to customers. In the TTW parts of the fuel chains, the ethanol and FT diesel are burned. The Fischer-Tropsch diesel from cellulosic biomass fuel chain is discussed in section 2. Section 3 deals with ethanol from cellulosic biomass and section 4 with ethanol from sugary biomass. The results from all three fuel chains are summarized in section 5.

8.2 The FT diesel from cellulosic biomass fuel chain

In this section, the FT diesel from cellulosic biomass fuel chain is discussed. The section starts with the modeling of the individual steps, after which the steps are combined. With the inclusion of indirect process fuels and byproducts, the WTT part of the fuel chain is completed. Next, the TTW part is modelled and the two parts are combined into the WTW fuel chain. Finally, the emissions are modelled.

The Well to Tank chain

The Well to Tank chain consists of four steps: growing of cellulosic biomass, which includes harvesting and chipping the wood in pieces, transportation of the biomass to a central plant in the Randstad area, production of Fischer-Tropsch diesel and finally distribution of Fischer-Tropsch diesel.

Reference	Efficiency	Comments
[Gave, 1999]	93,6	Poplar
[DeLuchi, 1993]	91,3	Unknown which trees are used
[Arthur D Little, 1996]	94,7	Unknown which trees are used
[Johansson, 1992]	93,5	Willow
[De Jager, 1998]	94,3	Poplar
This study	94,3	De Jager is best reasoned (see table 8.2)

Table 8.1: efficiencies in the growing of cellulosic biomass

Energy source	MJ/ha-year
Biomass yield	179.700
Fertilizer	
N - Nitrogen	2.280
P - Phosphor	99
K - Potassium	258
Pesticides	21
Diesel	8.300
Total process energy	10.958
Process energy ($MJ_{process}/MJ_{yield}$)	0,061

Table 8.2: energy use in the growing of cellulosic biomass
Source: [De Jager, 1998]

Division of process energies (%)	[Gave, 1999]	[DeLuchi, 1993]	This study
Coal	5,4	0,0	0,0
Diesel	29,6	84,8	84,8
Gasoline	14,7	5,0	5,0
LPG	5,2	0,0	0,0
Natural gas	34,1	4,8	4,8
Electricity	11,0	5,4	5,4
Total	100,0	100,0	100,0

Table 8.3: distribution of process energies in the growing of cellulosic biomass

Energy use per MJ of biomass grown	
Coal	1,000
Diesel	0,051
Gasoline	0,003
LPG	0,000
Natural gas	0,003
Electricity	0,003
Total	1,060

Table 8.4: energy flows in the growing of cellulosic biomass

Growing of cellulosic biomass

The first step in the fuel chain is the growing of cellulosic biomass. The step includes growing trees on plantations, harvesting the wood and chipping it. The growing stage is referred to as Short Rotation Intensive Cultivation (SRIC) or Short Rotation Intensive Forestry (SRIF). During this period, some use is made of herbicides, pesticides and insecticides, although this is limited compared to the amount that is used on sugary biomass. Many activities in this stage require the use of machinery. Examples of such activities are the planting of the trees, applying herbicides, pesticides and insecticides, harvesting and chipping. Virtually all fuel use consists of diesel [Marano, 2001].

The efficiency of the step is obtained from various sources from literature, depicted in table 8.1. De Jager provides very detailed information about how he obtains his number for the efficiency. Also, the efficiency mentioned by De Jager lies within the range provided by other sources in literature. For these two reasons, this study follows the efficiency from De Jager that equals 94,3%.

With the efficiency mentioned above, one needs 1,060 MJ of energy to obtain 1 MJ of harvested and chipped biomass. This number comprises 0,060 MJ of process fuels. Data on distribution of this energy flow are found in Gave, DeLuchi and De Jager. De Jager shows an overview of fossil fuel use, use of fertilizer, herbicides and insecticides. This overview provides clear insight in the process of the growing step. Unfortunately, De Jager does not provide information about the amounts of primary feedstock that are needed to produce fertilizer, herbicides and insecticides. Therefore his data do not fit in the methodology of this study. The other two sources, Gave and DeLuchi, don't provide a detailed overview of all products that are used during the growing step. However, they do provide an overview of process energies in terms of fuels that are modelled in this study. Although it is not clear how they have obtained their data, their data fit best into the framework of this study. Therefore the data from De Jager will be presented here only for the purpose of creating insight in the process, while the data from Gave and DeLuchi will be used to calculate with. Data from De Jager are depicted in table 8.2; those from Gave and DeLuchi in table 8.3. Their data have been recalculated form HHVs to LHVs with the fuel specifications from appendix D. As table 8.3 shows, their data sets contain considerable differences. From De Jager we know that diesel is an important process fuel. This seems to fit best with the data form DeLuchi, where diesel makes up almost 85% of total process fuel use. For this reason, the data set from DeLuchi is preferred in this study over that from Gave.

With the overall efficiency of the step and the division of process energies that was deducted from DeLuchi, the energy flows of each process fuel can be calculated. This calculation is shown in table 8.4.

Transportation of cellulosic biomass

In the growing step, the biomass has been harvested and cut into chips. In this step, these chips are transported from all over the Netherlands to a central plant in the Randstad area. From table 6.9, we know it takes 1,22 MJ to transport 1 ton of product over a distance of 1 km. With the heating value of cellulosic biomass from appendix D, the energy content of 1 ton of product is known. It is assumed that the distance equals 120 kilometers one-way, which makes 240 kilometers two-way. The average distance between biomass growing areas and the Randstad area is assumed to be longer than the average distance between refuelling stations and the Randstad area because the main agricultural areas in the Netherlands are located near the borders of the country, quite far away from the Randstad area. Now all information is complete to calculate the amount of process energy needed to transport 1 MJ of cellullosic biomass can be calculated. This equals 0,016 MJ per MJ of cellulosic biomass. Because transportation takes place by truck, it is assumed that diesel is the only relevant process fuel.

Production of Fischer-Tropsch diesel

The third step in the fuel chain is the production of Fischer-Tropsch diesel. The conversion from feedstock to Fischer-Tropsch products can be divided into three stages: production of syngas, synthesis of distillates and upgrading of products [Wang, 2002]; [Oukaci, 2002]. In the first stage, cellulosic biomass is converted to syngas, a mixture of hydrogen and carbon monoxide. The biomass can react with steam, oxygen or a mixture of both. Cellulosic biomass, which is a solid, has a high carbon-hydrogen ratio. This means that it contains much carbon and little hydrogen. To obtain a syngas with a good hydrogen-carbon monoxide ratio for the FT reaction, additional hydrogen is needed. This can be accomplished by using steam or a mixture of steam and oxygen in the production of the syngas. Biomass often contains some contaminations of sulpher or nitrogen that damage the catalysts that are used in the next stage of the production step. Also, some carbon is converted to ashes in stead of carbon monoxide. This, too, diminishes the working of the catalyst. Therefore the syngas needs to be cleaned before it can move on to the next stage.

The next stage is the FT reaction. This reaction requires a catalyst. The two catalysts that are used most are iron (Fe) and cobalt (Co). Iron catalysts have the ability to change the hydrogen/carbon monoxide ratio in the syngas. This is very useful when the composition of the syngas is suspect to changes, as is the case with biomass. On the other hand, iron catalysts produce products with varying compositions. A lot of processing is needed to give these products the desired characteristics. Cobalt catalysts lack the ability to change the composition of the syngas. On the other hand they produce products that require much less processing than the products of iron catalysts. However, with biomass as feedstock one can generally say that the ability of the catalyst to change the composition of the syngas is more valuable than the production of products that require little processing. Therefore iron catalysts are most suited for syngas that is made from biomass. The FT reaction results in products with a range of chain lengths. Besides the desired diesel fraction, also LPG, gasoline and waxes are produced.

In the third stage of the production step, the products are upgraded. To all fractions isomerisation is applied in order to give all molecules similar properties. Also, the waxes are cracked in a hydrocracker. In the hydrocracker, each long carbon chain is cut into several smaller pieces. This increases the diesel yield. The production step is now finished. We have seen that it consists of several subprocesses. Most of these processes produce heat, and some consume heat. On an overall basis, more heat is produced than consumed. The excess heat is generally used to generate electricity. A detailed description of all process stages can be found in appendix E.

Very little reliable data exist for the production of FT diesel from biomass. Marano provides data for a small-scale plant that is optimalised for power rather than the production of FT-fuels [Marano, 2001]. Consequently, electricity is the main output. This case is not deemed representative for the fuel chain of interest in this study and therefore the data from Marano will be disregarded. Another study on FT diesel from biomass has been performed by Sde [Sde, 2002]. This study provides detailed information on the yield for different fuels like diesel, gasoline and LPG, but gives no data on the production of electricity and is therefore also disregarded. From the description of the production of FT diesel in section 7.3, this section and appendix E, we know that the production of FT diesel from natural gas and FT diesel from biomass is very similar. The largest differences exist in the production of the syngas. Therefore it seems appropriate to use the data from the production of FT diesel from natural gas, with some adjustments to account for the different way in which the syngas is made. In Weiss and Ecotraffic we find that the production of FT diesel from biomass is 5% less efficient than the production of FT diesel from natural gas due to syngas production [Weiss, 2000]; [Ecotraffic, 2001]. From section 7.3, where the production of FT diesel from natural gas is discussed, we know that it takes 2,279 MJ of direct input to produce 1 MJ of FT diesel and

	Input (MJ)		Ouput (MJ)
Cellulosic		FT diesel	1,000
biomass	2,449	FT gasoline	0,584
Catalysts &		FT LPG	0,043
chemicals	0,000	Electricity	0,014
Total	2,449	Total	1,641

Table 8.5: energy flows in the production of FT diesel from cellulosic biomass

	Primary input in the WTT chain $MJ/MJ_{FT\text{-}diesel}$	Energy use in the TTW chain $MJ_{FT\text{-}diesel}/km$	Primary input in the WTW chain MJ/km
Crude oil	0,19		0,50
Natural gas	0,03		0,07
Coal	0,01		0,02
Biomass	2,45		6,34
FT-diesel		2,59	
Total	2,68	2,59	6,93

Table 8.6: WTT, TTW and WTW energies in the FT diesel from cellulosic biomass fuel chain

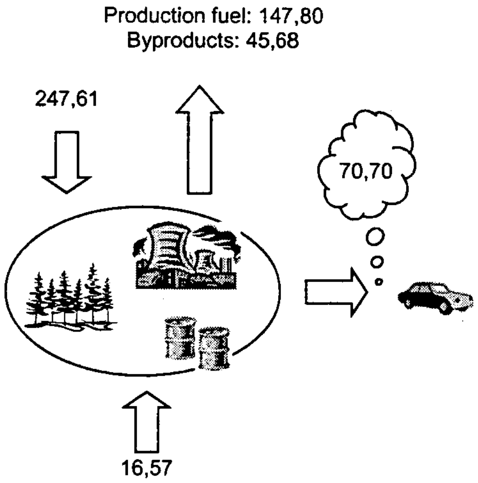

Figure 8.1: carbon balance of the FT diesel from cellulosic biomass fuel chain (values in $gCO_2/MJ_{FT\ diesel}$)

0,641 MJ of byproducts. If the efficiency is calculated as the total output divided by the input, the efficiency equals 72%. This means that the efficiency with cellulosic biomass as primary feedstock equals 67%. With an output of 1,641 MJ, the input equals 2,449 MJ. The division of inputs and outputs for FT diesel from cellulosic biomass is shown in table 8.5.

Distribution of Fischer-Tropsch diesel

In the last step of the fuel chain, FT diesel is distributed by diesel truck. This step is identical to the distribution step in the Fischer-Tropsch diesel from natural gas fuel chain, which tells us that it takes 0,005 MJ to transport 1 MJ of FT diesel with diesel as only relevant process fuel.

WTT results

All steps in the fuel chain have now been modelled. The way in which separate steps can be combined into a fuel chain, is described in section 4.2. By applying formula (7), (10) and (11), the direct fuel input and process fuel input can be calculated. However, one must keep in mind that all fuel chains included in this study must be modelled before the correct results can be calculated. By applying the formulas in the correct way, we find that the biomass input equals 2,449 MJ per MJ of FT diesel and the process fuel input equals 0,193 MJ per MJ of FT diesel. The process fuels used are diesel, gasoline, natural gas and electricity. In order to give a complete overview of all energy use in the fuel chain system, the energy needed to produce the process fuels has to be included in the calculation. This can be done by applying formula (12) from chapter 4. It turns out that the FT diesel from cellulosic biomass fuel chain uses 2,677 MJ per MJ of FT diesel. The division of this amount of energy over different primary feedstocks is provided in table 8.6.

The FT diesel from cellulosic biomass fuel chain produces not only diesel but also byproducts. The amount of byproducts produced directly in the fuel chain equals 0,641 MJ per MJ of diesel. There are no byproducts produced in the fuel chains of the process fuels and therefore the total amount of byproducts produced in the entire fuel chain system equals 0,641 MJ. The contribution of the individual byproducts to the total amount is the same as that provided by table 8.5. In order to make an equal comparison between all fuel chains, the comparison must be based on comparable outputs. In this study, the output that is used for the comparison of the fuel chains is 1 MJ of a transportation fuel. For this chain, the transportation fuel of interest is FT diesel. This means that all other outputs have to be accounted for in some way. Three ways of accounting for byproducts have been described theoretically in section 4.7. The application of these methods to the results of all fuel chains takes place in chapter 10.

The Tank to Wheel and Well to Wheel chain

The FT diesel from cellulosic biomass fuel chain results in the same product as the FT diesel from natural gas fuel chain. To the final product of both fuel chains it does not matter from which primary feedstock the diesel comes from. Therefore the results in the TTW chain are identical for both primary feedstocks, namely a fuel economy of 2,59 MJ per kilometer. The WTW results can be calculated by multiplying the WTT and TTW results. Both the TTW and WTW results are shown in table 8.6.

Emissions

Carbon dioxide

Carbon dioxide emissions are measured by means of a carbon balance. For FT diesel from cellulosic biomass the carbon balance is shown in figure 8.1. The oval figure represents the production of the fuel while the car with the smoke coming from the tailpipe represents the TTW part of the fuel chain. The total amount of carbon dioxide flow through the fuel chain equals 264,19 gram per MJ of FT diesel. On the input side, 16,57 gram carbon dioxide comes from fossil fuels. The remainder, 247,61 gram, comes from biomass. On the output side,

CH_4 (10^{-3} g/MJ)	[Johansson, 1992]	[Arthur D Little, 1996]	[Marano, 2001]	[De Jager, 1998]	This study
Growing		0,3	0,5		0,4
Transportation		0,1	0,2		0,1
Production			3,4		3,4
Distribution	0,0	0,0		0,0	0,0
WTT emissions					14,3
TTW emissions					1,6
WTW emissions					15,9
WTW emissions (mg/km)					*41,2*

Table 8.7: methane emissions in the FT-diesel from cellulosic biomass fuel chain

N_2O (10^{-3} g/MJ)	[Johansson, 1992]	[Marano, 2001]	This study
Growing		0,9	0,9
Transportation	<<1	0,2	0,2
Production		4,3	4,3
Distribution	<<1		0,0
WTT emissions			7,3
TTW emissions			2,6
WTW emissions			9,9
WTW emissions (mg/km)			*25,5*

Table 8.8: nitrous oxide emissions in the FT-diesel from cellulosic biomass fuel chain

70,70 gram ends up in the fuel and 45,68 gram in the byproducts. This leaves 147,80 gram of carbon dioxide that is lost during production of the fuel and the process fuels. However, the carbon dioxide content of the biomass is carbon dioxide that has been taken up from the air to grow the biomass. Therefore this amount may be subtracted from the emissions during production, which brings the emissions at –99,81 gram/MJ. For now, the carbon content of the byproducts is included in the WTT emissions, which brings WTT emissions at –54,13 g/MJ. In chapter 10, the carbon content of the byproducts will be accounted for.

Methane

As all fuel chains, this fuel chains lacks reliable, exact data on methane emissions. To reflect this uncertainty, many studies depict methane emissions within a confidence interval. This study does not. In the presentation of the final results, all emissions are multiplied with their Global Warming Potential and summed. The contribution of methane to the total greenhouse gas emissions in CO_2-equivalents is small. The confidence in the emissions is even smaller. Therefore the added value from such a confidence interval is small. If one is careful in interpreting the results, the confidence interval may just as well be left out.

The data that have been found in literature are depicted in table 8.7. For the growing step and the transportation step, this study uses the average of the numbers mentioned by Arthur D. Little and Marano [Arthur D. Little, 2001]; [De Jager, 1998]. For the production step, the number from Marano is followed while the emissions in the distribution step are assumed to be negligible [Marano, 2001]. By summing the data on the individual steps and including the emissions from the production of the process fuels, the WTT emissions can be calculated. These equal 14,3 mg/MJ. In the TTW part, methane emissions are identical to those in the FT diesel from natural gas fuel chain, which is 1,7 mg/MJ. By summing the WTT and TTW emissions the WTW emissions per MJ can be calculated. Multiplying this value with the fuel economy of FT diesel gives the WTW emissions in mg/km. The first value equals 15,9 mg/MJ, the latter 41,2 mg/km.

Nitrous oxide

Data on nitrous oxide emissions are even scarcer than data on methane emissions. For the emissions in most steps, only one number was found. The data that have been found in literature are shown in table 8.8. By summing the data on the individual steps and including the emissions from the production of the process fuels, the WTT emissions can be calculated. These equal 7,8 mg/MJ. By adding the TTW emissions to the WTT emissions, the WTW emissions in mg/MJ can be calculated. This number multiplied with the fuel economy results in the WTW emissions in mg/km. For FT diesel from cellulosic biomass this number equals 25,5 m/MJ, which is quite high. This is mainly due to the use of fertilizer.

Emissions in CO_2-equivalents

In section 5.5 we have seen that all emissions have a Global Warming Potential (GWP) by which they can be expressed in CO_2-equivalent emissions and which makes it possible to sum the emissions. The CO_2-equivalent of an emission can be calculated by multiplying the emission with its GWP. Information on the GWPs for carbon dioxide, methane and nitrous oxide can be found in appendix D. For the FT diesel from cellulosic biomass fuel chain, the total CO_2-equivalents emissions equal 51,4 gCO_2-eq/km.

8.3 The ethanol from cellulosic biomass fuel chain

The ethanol from cellulosic biomass fuel chain consists of four steps: growing of cellulosic biomass, transportation of cellulosic biomass, production of ethanol and finally distribution of ethanol. First the energy flows in the individual steps are described after which the energy use in the production of the process fuels in included to obtain WTT result. The TTW fuel chain is modelled and the two parts are combined into the WTW chain. The section ends by modeling the emissions.

Reference	Efficiency*	$MJ_{el.}/MJ_{ethanol}$
[Gave, 1999]	49,0	0,082
[Wang,1999]	38,6	0,070
[De Jager, 1998]	44,5	0,037
[Johansson, 1992]	36,1	0,137
This study	42,5	0,075

Table 8.9: efficiencies and production of byproducts in the conversion of cellulosic biomass to ethanol

*: efficiency has been calculated as ethanol output per total input. The production of electricity is not yet credited for.

The Well to Tank chain

The first two steps in the WTT chain, growing of cellulosic biomass and transportation of cellulosic biomass, are identical to the first two steps in the FT diesel from cellulosic biomass fuel chain. These steps have been discussed in detail in the previous section and are therefore not repeated here. For information on these steps the reader is referred to section 8.2.

Production of ethanol

After being transported to a central plant in the Randstad area, the biomass is converted to ethanol. The conversion takes place in three stages: pretreatment of biomass, conversion to ethanol and upgrading of products. The pretreatment stage is very important for the yield of the conversion later on. Cellulosic biomass consists of cellulose, hemicellulose and lignin. Cellulose is the main component but the molecules are connected by very strong hydrogen bonds. The pretreatment serves to weaken these bonds. Without pretreatment, the yield of the conversion step is less than 20% [Hamelinck, 2003]. During pretreatment, the hemicellulose is converted into sugars. In the next production stage, the cellulose is converted into sugars. The lignin is now separated from the sugar-lignin mixture and burned to generate heat, steam and electricity. The sugars are fermented to by bacteria or yeast to ethanol. However, the concentration of ethanol in the fermentation products is not yet high enough and therefore the ethanol is purified and distilled. The final product contains over 99,9 vol.% pure ethanol. The lignin that was separated from the mixture produces more electricity than is needed in the ethanol plant and so a small amount of excess electricity can be sold as byproduct. A more elaborate description of the production process can be found in appendix F.

Data on the efficiency of the production process of ethanol are provided by several sources. An overview of the efficiencies is provided in table 8.9. It goes for all data in table 8.9 that the efficiency excludes the production of electricity as a byproduct. As we see in the table, the differences between the numbers are quite high. At this time, there is little experience with ethanol plants. This makes it hard to tell whether one estimate is better than the others are. Therefore this study assumes more or less the average of the numbers found in literature, which is 42,5%. With this efficiency, it takes 2,353 MJ of cellulosic biomass to obtain 1 MJ of ethanol. According to Gave and DeLuchi, an ethanol plant of this kind is completely self-sufficient [Gave, 1999]; [DeLuchi, 1993]. Cellulosic biomass is the only input. Data on the amount of green electricity that is produced are found in the same sources as the data on the efficiency of the process step and are also shown in table 8.9. As the table shows, the amount of electricity produced per MJ of ethanol is not very large. In this study, a value of 0,075 MJ per $MJ_{ethanol}$ is assumed.

Distribution of ethanol

The final stage in the WTT chain is distribution. From table 6.9 we know that it takes 1,22 MJ to transport 1 ton of products over a distance of 1 km. With the fuel specifications from appendix D and an assumed distance between the central production plant and the refueling station of 160 kilometers 2-way, the process energy is calculated to be 0,008 MJ per MJ of ethanol. Distribution takes place by diesel truck. It is assumed that diesel is the only relevant process fuel.

WTT results

All steps in the fuel chain have now been modelled separately. The steps are now combined into a fuel chain in the way explained in chapter 4. The direct fuel input in the ethanol from cellulosic biomass fuel chain turns out to be 2,353 MJ of biomass and 0,188 MJ of process fuel. The process fuels that are used in the fuel chain are diesel, gasoline, natural gas and electricity. In order to correctly model all energy flows in the fuel chains, the production of the process fuels has to be taken into account. Again the theoretical model from chapter 4 is

	Primary input in the WTT chain MJ/$MJ_{Ethanol}$	Energy use in the TTW chain $MJ_{Ethanol}$/km	Primary input in the WTW chain MJ/km
Crude oil	0,19		0,57
Natural gas	0,03		0,08
Coal	0,01		0,03
Biomass	2,35		7,02
Ethanol		2,98	
Total	2,58	2,98	7,69

Table 8.10: WTT, TTW and WTW primary energies in the ethanol from cellulosic biomass fuel chain

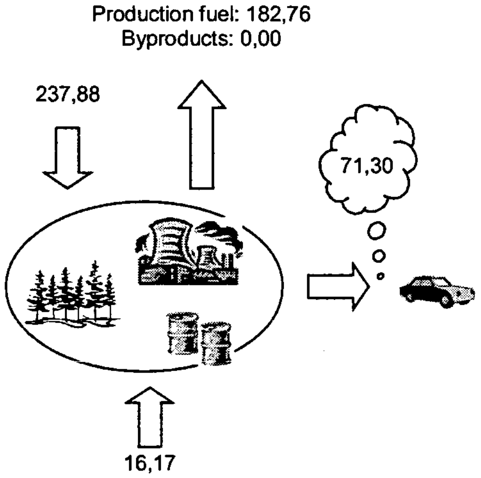

Figure 8.2: carbon balance of the ethanol from cellulosic biomass fuel chain (values in $gCO_2/MJ_{ethanol}$)

CH_4 (10^{-3} g/MJ)	[Johansson, 1992]	[Arthur D Little, 1996]	[Marano, 2001]	This study
Growing		0,3	0,5	0,4
Transportation		0,1	0,2	0,1
Production		3,5		3,5
Distribution	<<1	0,2		0,2
WTT emissions				14,4
TTW emissions				2,7
WTW emissions				17,0
WTW emissions (mg/km)				*50,9*

Table 8.11: methane emissions in the ethanol from cellulosic biomass fuel chain

applied. With this model, the total fuel use in the WTT chain is calculated to equal 2,575 MJ. The exact distribution over various primary feedstocks is shown in table 8.10.

Besides ethanol, the fuel chain also leads to the production of 0,075 MJ of green electricity. Because there are no byproducts produced in the production of the process fuels, the total amount of byproducts in the entire fuel chain system equals 0,075 MJ. In order to make a fair comparison between all fuels in the model, the outputs of all fuel chains must be equal. This means that the byproducts have to be accounted for in some way. How this is done, is shown in chapter 10.

The Tank to Wheel and Well to Wheel chain

In the Tank to Wheel part of the fuel cycle, ethanol is burned in a spark ignition engine. Ethanol fuelled cars were not included in the measurements on vehicle economy performed by TNO and therefore no direct data are available [TNO, 2003]. To have some estimate of the fuel economy, the average fuel economy from other cars with spark ignition engines is used. There are three such cars included in the framework: gasoline fuelled vehicles, LPG fuelled vehicles and CNG fuelled vehicles. The average of the fuel economy of these three cars equals 2,98 MJ per kilometer. By multiplying the WTT results with the TTW results, the WTW results can be calculated. These are shown in table 8.10.

Emissions

Carbon dioxide

Emissions of carbon dioxide are assessed by means of a carbon balance. The carbon balance for the ethanol from cellulosic biomass fuel chain is depicted in figure 8.2. The oval figure represents the production of the fuel whereas the car represents the TTW part of the fuel chain. The fuel chain uses two sources of carbon dioxide input: fossil and renewable. The fossil input equals 16,17 g/MJ; the renewable input 237,88 g/MJ. This brings the total flow of carbon dioxide through the fuel chain at 254,06 $g/MJ_{ethanol}$. A part of this flow, namely 71,30 gram, gets contained in the fuel. The remainder is lost during the production of the fuel. There is no carbon contained in the byproducts. Electricity is the only byproduct produced in this fuel chain and that has no carbon content. This brings the carbon dioxide releases during production at 182,76 g/MJ. However, the growing of the cellulosic biomass took up carbon dioxide from the air. This amount, which equals the biomass input of 237,88 g, should be subtracted from the WTT emissions. The net WTT emissions now become –55,13 g/MJ.

Methane

Data on methane emissions, as far as reliable data exist, are shown in table 8.11. The data on the separate steps are combined in the way described in chapter 4 and the emissions from the production of the process fuels have been included. This results in the WTT emissions, which have a value of 14,4 mg/MJ. This value is of the same order of magnitude as the WTT emissions in the FT diesel from cellulosic biomass fuel chain. The TTW emissions have been determined by taking the average of TTW emissions from a gasoline fuelled vehicle and a LPG fuelled vehicle. The CNG fuelled vehicle has been left beyond consideration. The number that was needed was the emissions of methane from a spark ignition engine. With methane as a fuel, leakages of fuel and unburned fuel are included in the methane emissions from the engine. This was not considered representative. The value calculated for the TTW emissions equals 2,7 mg/MJ. By summing the WTT and TTW emissions, the WTW emissions are calculated in mg/MJ. This number multiplied with the fuel economy of an ethanol fuelled vehicle gives the WTW emissions in mg/km. The latter number equals 50,9 mg/km. Both values are a little higher than those for FT diesel from cellulosic biomass are. This is mainly due to the higher methane emissions in the TTW part of the fuel chain.

N_2O (10^{-3} g/MJ)	[Johansson, 1992]	[Marano, 2001]	This study
Growing		0,9	0,9
Transportation	<<1	0,2	0,2
Production			0,0
Distribution	<<1		0,0
WTT emissions			2,9
TTW emissions			0,7
WTW emissions			3,6
WTW emissions (mg/km)			*10,7*

Table 8.12: nitrous oxide emissions in the ethanol from cellulosic biomass fuel chain

Reference	Efficiency	Comments
[Gave, 1999]	87,5	Reference year 1995.
[DeLuchi, 1993]	83,8	Includes energy for fertilizers and machinery.
[Arthur D Little, 1996]	86,5	Includes energy for fertilizers, herbicides, pesticides, seeds and machinery on the farm. Includes the energy required to separate corn kernels from cobs and stalks.
[De Jager, 1998]	85,9	Includes machinery, herbicides, pesticides and fertilizers.
[Johansson, 1992]	83,0	Includes energy for fertilizers, herbicides, pesticides, seeds and machinery on the farm.
[S&t, 2003]	91,6	Includes energy for fertilizers, herbicides, pesticides, seeds and machinery on the farm.
[Babfo, 2000]	92,3	Includes energy for fertilizers, herbicides, pesticides, seeds and machinery on the farm.
[Concawe, 2002]	89,2	Includes energy for fertilizers, herbicides, pesticides, seeds and machinery on the farm.
[Elsayed, 2003]	95,3	Includes energy for fertilizers, herbicides, pesticides, seeds and machinery on the farm.
This study	91,2	Based on the newest sources (year 2000 and beyond)

Table 8.13: efficiencies in the farming of sugar containing biomass

Nitrous oxide

Data on nitrous oxide emissions are depicted in table 8.12. The ethanol from cellulosic biomass fuel chain uses inputs from agriculture. Due to the nitrogen that is contained in fertilizers, the nitrous oxide emissions are higher than in fuel chains that use only fossil inputs. The use of fertilizer is moderate with cellulosic biomass in comparison with sugary biomass and thus the emissions of nitrous oxide are moderate. In the WTT fuel chain, the emissions equal 2,9 mg/MJ. However, due to lack of data on the emissions during production, this number contains an underestimation. The TTW emissions are calculated by taking the average of TTW emissions of gasoline, LPG and CNG fuelled vehicles. This equals 0,7 mg/MJ. The WTT emissions expressed as mg/MJ are calculated by summing the WTT and TTW emissions. Multiplying this number with the fuel economy of an ethanol fuelled vehicle results in the WTW emissions expresses in mg/km. These equal 10,7 mg/km.

Emissions in CO_2-equivalents

In section 5.5 we have seen that all emissions have a Global Warming Potential (GWP) by which they can be expressed in CO_2-equivalent emissions. The use of CO_2-equivalent emissions makes it possible to sum the emissions. By summing each emission with its GWP the CO_2-equivalent emissions can be calculated. The GWPs for carbon dioxide, methane and nitrous oxide can be found in appendix D. For the ethanol from cellulosic biomass fuel chain, the total CO_2-equivalents emissions equal 52,6 gCO_2-eq/km.

8.4 The ethanol from sugary biomass fuel chain

The third fuel chain discussed in this chapter is the ethanol from sugary biomass fuel chain. This fuel chain consists of four steps: farming of sugary biomass, transportation from the farm to a central plant in the Randstad area, conversion from sugary biomass to ethanol and finally distribution of ethanol. The structure of this section is the same as that from the previous sections in this chapter.

The Well to Tank chain

Farming of sugary biomass

The ethanol from sugary biomass fuel chain starts with growing and harvesting the biomass. This step includes sowing and growing the biomass. During growing, a lot of herbicides, pesticides and insecticides are applied. This phase also involves the use of machinery. When the crops are fully grown, they are harvested.

Data on the efficiency of growing sugary biomass can be found in many sources in literature. Some of these are recorded in table 8.13. As we see in the figure, the older sources mention in general lower efficiencies than newer sources. In this study, we use the newest results. Based on efficiencies from sources in literature from the year 2000 onwards, this study assumes an efficiency of 91,2%. Like in the case of growing cellulosic biomass, there are two kinds of studies: those that provide a detailed overview of herbicide, pesticide and insecticide use but don't tell from what primary feedstocks herbicides, pesticides and insecticides are made, and those that don't tell anything about herbicides, pesticides and insecticides but do provide data on process fuel use and primary feedstock use. Although sources of literature of the first kind tell us what happens in the step, they don't fit very well into the model that is developed in this study. Sources of literature of the second kind provide the kind of information that fits well into the methodology of this study and therefore these sources are preferred over the other ones. To provide insight in the step, some data from De Jager, Babfo and Elsayed are provided in table 8.14. The table shows that values mentioned in De Jager, an older study, are clearly higher than those from Babfo and Elsayed, two newer studies. Data on process fuel use in terms of process fuels included in this study are presented in table 8.15. These data are from Gave and DeLuchi. Both data sets have been converted from

Energy source	[De Jager, 1998] MJ/ha-year	[Babfo, 2000] MJ/ha-year	[Elsayed, 2003] MJ/ha-year
Biomass yield	119.000	152.320	136.117
Fertilizer:			
N - Nitrogen	7.720	7.410	1.396
P - Phosphor	0	210	948
K - Potassium	0	0	0
Pesticides	258	0	0
Diesel	11.600	4.640	3.800
Total process energy	19.580	12.700	6.700
Process energy ($MJ_{process}/MJ_{yield}$)	0,165	0,083	0,049

Table 8.14: energy use in the growing of sugary biomass

Process energy	[Gave, 1999]	[DeLuchi, 1993]	This study
Diesel	19,9	46,6	33,0
Gasoline	9,9	19,8	14,0
LPG	3,5	0,0	2,0
Natural gas	53,3	11,8	33,0
Electricity	9,7	15,0	12,0
Coal	3,7	6,7	6,0
Total	100,0	100,0	100,0

Table 8.15: distribution of process energies in the farming of sugary biomass

Energy use per MJ of biomass grown	
Diesel	0,032
Gasoline	0,013
LPG	0,002
Natural gas	0,032
Electricity	0,012
Coal	0,006
Total	0,096

Table 8.16: energy flows in the growing of sugary biomass

Reference	Efficiency*	$MJ_{an. feed.}$/ $MJ_{ethanol}$
[$(S\&T)^2$, 2003]	46,6	0,516
[Arthur D Little, 1996]	46,2	
[De Jager, 1998]	54,0	
[Johansson, 1992]	53,5	
[Babfo, 2000]	59,4	
[Elsayed, 2003]	48,9	0,758
This study	48,9	0,758

Table 8.17: efficiencies and production of animal feed in the conversion of sugary biomass to ethanol

*: efficiency has been calculated as ethanol output per total input. The production of animal feed is not yet credited for.

HHVs to LHVs using the fuel specifications from appendix D. Because there are no clues that the data from one study are better or worse than those from the other, this study uses their average with some small adjustments in order to reach a sum of exactly 100,0%. The total amount of process fuel use in this step can be deducted from the efficiency and equals 0,096 MJ per MJ of biomass. With the division of the process fuels from table 8.15, the contribution of each process fuel can be calculated. The results of this calculation are shown in table 8.16.

Transportation of sugary biomass

Sugary biomass is transported by diesel truck from all over the Netherlands to a central plant in the Randstad area. We know from table 6.9 that it takes 1,22 MJ to transport 1 ton of products over a distance of 1 km. The energy content of 1 ton of product is taken from the fuel specifications in appendix D. For the average transportation distance, the same arguments apply as for the transportation of cellulosic biomass. Therefore the distance is assumed to be 120 kilometers one-way, which is 240 kilometers two-way. A detailed description of the arguments can be found in section 2 of this chapter. With the fuel specifications and the distance, the amount of process energy can be calculated. This equals 0,017 MJ per MJ of sugary biomass transported. Diesel is the only relevant process fuel.

Production of ethanol

In the third step of the fuel chain, the conversion from biomass to ethanol takes place. The conversion from sugary biomass to ethanol is easier to accomplish than the conversion from cellulosic biomass to ethanol because sugary biomass doesn't contain cellulose. Like the conversion from cellulosic biomass to ethanol, the conversion from sugary biomass to ethanol consists of three stages: pretreatment, saccharification and fermentation, and upgrading of products. In the pretreatment stage, the sugary biomass is milled and cooked with enzymes. The milling serves to enlarge the surface of the biomass. This facilitates processing in the saccharification and fermentation stage. By cooking with enzymes the cell partitions are broken down. This too facilitates processing later on in the production step. The next stage of the production process starts with saccharification. Enzymes that are added to the cooked biomass hydrolyse the biomass and convert it into a mixture of sugars. This mixture is fermented with yeast or bacteria into ethanol. The fermentation product is upgraded in the third stage of the production step. After fermentation, the concentration of ethanol in the product is still low. By means of purification and distillation the ethanol is concentrated, untill is has an ethanol content of at least 99,9 vol.% pure ethanol. The cell partitions and other non-converted material are dried and sold as animal feed. Sugary biomass contains no lignin and therefore there is no green electricity produced. A more detailed description of the production step can be found in appendix F.

Data on the efficiency of the conversion step that have been found in literature are summarized in table 8.17. Most sources record efficiencies between 45 and 55%. The number from Elsayed is best reasoned. It also lies well within the range indicated by other sources. Therefore this study uses the number from Elsayed which is 48,9%. Data on the distribution of process energies are summarized in table 8.18. If the ethanol plant is fed with cellulosic biomass, it is self-sufficient. The lignin that is a part of the cellulosic biomass can not be converted to ethanol. Instead, it is burned to produce all the heat, steam and electricity that the plant needs. Sugary biomass does not contain lignin. Therefore heat, steam and electricity are needed as external inputs. In two out of three sources biomass accounts for more than 90 % of total input in the ethanol plant. Data from Elsayed are best reasonned and therefore this study uses the division of process energies provided by Elsayed. With an efficiency of 48,9% it takes 2,045 MJ of input to obtain 1 MJ of ethanol. With the division of direct input and process energies from table 8.18, it can be calculated how much of each fuel is needed to create 1 MJ of ethanol. The results of this calculation are shown in table 8.19.

Division of process energies (%)	[(S&T)^2, 2003]	[De Jager, 1998]	[Elsayed, 2003]	This study
Sugary biomass	75,5	91,9	93,9	93,9
Diesel			1,3	1,3
Natural gas	24,0		4,3	4,3
Electricity	0,5	1,6	0,5	0,5
Total	100,0	00,0	100,0	100,0

Table 8.18: division of process energies in the production of ethanol from sugary biomass

Energy use per MJ of ethanol produced	
Sugary biomass	1,920
Diesel	0,027
Natural gas	0,088
Electricity	0,010
Total	2,045

Table 8.19: energy flows in the production of ethanol from sugary biomass

	Primary input in the WTT chain $MJ/MJ_{Ethanol}$	Energy use in the TTW chain $MJ_{Ethanol}/km$	Primary input in the WTW chain MJ/km
Crude oil	0,18		0,53
Natural gas	0,20		0,61
Coal	0,04		0,13
Biomass	1,92		5,73
Ethanol		2,98	
Total	2,35	2,98	7,00

Table 8.20: WTT, TTW and WTW primary energies in the ethanol from sugary biomass fuel chain

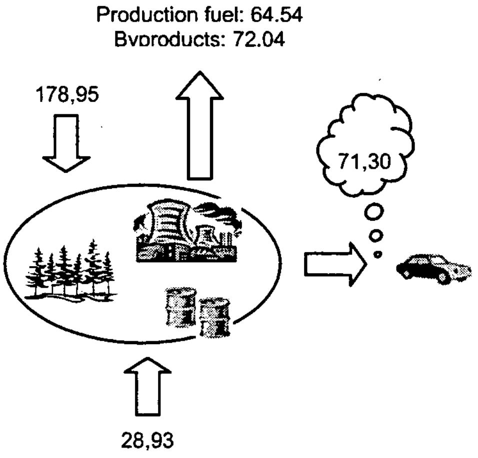

Figure 8.3: carbon balance of the ethanol from sugary biomass fuel chain (values in $gCO_2/MJ_{ethanol}$)

Besides ethanol, the fuel chain also produces animal feed as a byproduct. Unfortunately, only a few sources give detailed information about the amount of byproduct produced, as can be seen in table 8.17. In this study, it is assumed that there is 0,758 MJ of animal feed produced per MJ of ethanol.

Distribution of ethanol

Finally, the ethanol is distributed. The distribution step is identical to the distribution step in the ethanol from cellulosic biomass fuel chain. In this step, process fuel use equals 0,005 MJ per MJ of ethanol, all of which is assumed to be diesel.

WTT results

All individual steps in the ethanol from sugary biomass fuel chain have now been modelled. In order to obtain WTT results, the steps are combined in the way described in section 4.2. The direct input of primary feedstock in the fuel chain equals 1,920 MJ. Besides primary feedstock, the fuel chain uses 0,348 MJ of process fuels. This amount consists of diesel, gasoline, LPG, natural gas, electricity and coal. The total amount of primary energy needed to create the process fuels together with the direct primary energy input equals 2,346 MJ. The contribution of the feedstocks crude oil, natural gas, coal and sugary biomass is shown in table 8.20.

However, ethanol is not the only output leaving the fuel chain. In the production step, 0,758 MJ of animal feed is produced. Because there are no byproducts produced in the fuel chains of the process fuels, this amount equals the total byproduct output of the fuel chain system. In order to be able to compare fuel chains in which byproducts are produced with fuel chains in which only the transportation fuel is produced, the byproducts have to be accounted for. This is done in chapter 10.

The Tank to Wheel and Well to Wheel chain

In the TTW fuel chain, it does not matter whether the ethanol is made from cellulosic biomass or sugary biomass. Therefore the TTW energy is equal in both fuel chains, which is 2,98 MJ/km. Multiplying the fuel economy with the amount of primary energy used in the WTT part of the fuel chain results in the WTW primary energy use. The WTW values of all primary feedstocks are shown in table 8.20.

Emissions

Carbon dioxide

Carbon dioxide emissions are assessed by a carbon balance. The carbon balance for ethanol from sugary biomass is depicted in figure 8.3. The oval figure represents the production of the fuel and the process fuels in the WTT part of the fuel chain. The car with the smoke coming from the tailpipe represents the TTW part of the fuel chain. The total carbon dioxide equivalent input in the fuel chain equals 207,88 $gCO_2/MJ_{ethanol}$/. The main part of this, 178,95 gCO_2/MJ, comes from sugary biomass. The remainder, 28,93 gCO_2/MJ, is of fossil origin. Out of the total carbon dioxide equivalent input in the fuel chain, 71,30 g gets contained in the fuel and 72,04 g gets contained in animal feed. The remainder, 64,54 $gCO_2/MJ_{ethanol}$, is lost during production of the fuel and the process fuels. However, this number does not equal the WTT emissions. The fuel chain involves biomass. The biomass has taken up carbon dioxide from the air to grow. This amount, which equals the sugary biomass carbon dioxide equivalent input of 178,95 g, may be subtracted from the emissions that emerge from production. This brings the WTT emissions at –114,41 gCO_2/MJ. In this number the byproducts are not included. Because byproducts are only accounted for in chapter 10, the byproducts have to be included in the WTT emissions, which results in a value of –42,37 gCO_2/MJ.

CH_4 (10^{-3} g/MJ)	[Elsayed, 2003]	[Johansson, 1992]	[Arthur D Little, 1996]	[Marano, 2001]	This study
Growing	1,9	<<1	0,9		1,4
Transportation	0,0	<<1	0,1	0,2	0,1
Production	28,2		0,6		13,8
Distribution		<<1	0,0		0,0
WTT emissions					58,4
TTW emissions					2,7
WTW emissions					61,1
WTW emissions (mg/km)					*182,3*

Table 8.21: methane emissions in the ethanol from sugary biomass fuel chain

N_2O (10^{-3} g/MJ)	[Babfo, 2000]	[Elsayed, 2003]	[Johansson, 1992]	[Marano, 2001]	This study
Growing	54,5	13,6	1,8		26,3
Transportation		0,0	<<1	0,2	0,2
Production		0,0			0,0
Distribution		0,0	<<1		0,0
WTT emissions					51,2
TTW emissions					0,7
WTW emissions					51,9
WTW emissions (mg/km)					*154,8*

Table 8.22: nitrous oxide emissions in the ethanol from sugary biomass fuel chain

Fuel chain	WTT primary energy (MJ_{prim} / MJ_{output})	WTT byproducts ($MJ_{bypr.}$ / MJ_{output})	TTW energy (MJ_{output} / km)	WTW primary energy (MJ_{prim} / km)	WTW CO_2 emissions (gCO_2/km)	WTW CH_4 emissions (gCH_4/km)	WTW N_2O emissions (gN_2O/km)	Total WTW emissions* (g CO_2-eq./km)
FT diesel (w. bio)	2,68	0,64	2,59	6,93	42,9	0,04	0,03	51,4
Ethanol (w. bio)	2,58	0,08	2,98	7,69	48,3	0,05	0,01	52,6
Ethanol (s. bio)	2,35	0,76	2,98	7,00	86,3	0,18	0,15	136,3

Table 8.23: summary of results for the FT diesel from cellulosic biomass fuel chain, the ethanol from cellulosic biomass fuel chain and the ethanol from sugary biomass fuel chain

*: not corrected for byproducts

Methane

Data on methane emissions are depicted in table 8.21. As the table shows, there are many blank spaces of missing and incomplete data. From the data that are available we can tell that the emissions in the growing step, transportation step and distribution step are very small. Data on the production step are contradictory. According to Arthur D. Little, the emissions are as small as in the other steps. Elsayed on the other hand claims that the production of ethanol from sugary biomass results in high methane emissions. This study calculates with an intermediary value of 13,8 mg/MJ$_{ethanol}$. By summing the data on the individual steps and including the emissions from the production of the process fuels in the way described in section 4.3, the WTT methane emissions can be calculated. These equal 58,4 mg/MJ. By including the TTW emissions of 2,7 mg/MJ, the WTW emissions based on energy content can be calculated. Multiplying this value with the fuel economy of an ethanol fuelled vehicle results in the WTW emissions based on traveled distance. This value equals 182,3 mg/km, which is quite high.

Nitrous oxide

The growing of sugary biomass requires the use of fertilizer that contains nitrogen. Some of this nitrogen is converted to nitrous oxide and released as emissions. Therefore the nitrous oxide emissions in this fuel chain are high in comparison with the other fuel chains in the model. As we see in table 8.22, there are hardly any nitrous oxide emissions other than those in the growing step. Summing the emissions of the separate steps and including the emissions form the production of the process fuels results in the WTT emissions. These equal 51,2 mg/MJ, which is more than 7 times as much as in any other fuel chain in the model. Including the TTW emissions and multiplying with the fuel economy of an ethanol fuelled vehicle results in the WTW emissions per traveled kilometer. This value equals 154,8 mg/km.

Emissions in CO_2-equivalents

In order to be able to sum emissions, emissions are expressed in CO_2-equivalents. The CO_2-equivalent of an emission is obtained by multiplying the value of the emission with its global warming potential. Doing so for the emissions in the ethanol from sugary biomass fuel chain results in WTW emissions of 136,3 CO_2-eq/km. The global warming potentials that have been used in the calculation can be found in appendix D.

8.5 Summary of results

A summary of the most important results of the three fuel chains discussed in this chapter is provided in table 8.23.

9 Process fuels

9.1 *Introduction*

This is the last chapter in a series of four in which fuel chains are modelled. In this chapter, the process fuels are modelled which are used in the fuel chains described in the previous chapters. Process fuels are defined in this study as those fuels that are used as process energy in one or more fuel chains but which are not used as transportation fuel in this study. Therefore the fuel chains of process fuels consist only of a well to tank part and don't have a tank to wheel part. Even the term well to tank is actually a misnomer because the production process of these fuels does not end in a transportation fuel and therefore these fuels will not be found in the tank of a vehicle. However, the term well to tank is applied here to indicate the whole process of making a fuel and transporting it to its point of use, thereby taking into account all energies, byproducts and emissions that are used in, or emerge from, the production process of this fuel. The second difference between this chapter and the other chapters from the series is that in each of the other chapters all the fuels that are described in one chapter have their primary feedstock in common. In chapter 6 this is crude oil, in chapter 7 it is natural gas and in chapter 8 it is biomass. In this chapter however, the reader will find all kinds of primary feedstocks.

This chapter starts in section 2 with the fuel chain of heavy fuel oil. Heavy fuel oil is a product of refineries. It is a heavy distillate, whose carbon chains are longer than those of diesel are. Heavy fuel oil is based on the primary feedstock crude oil. In section 3, the fuel chain of natural gas is described. This fuel chain consists of the first three steps of the CNG fuel chain, and is based on the primary feedstock natural gas. Section 4 is dedicated to coal. Coal is mined, transported to the Netherlands, and used here to produce electricity or heat. The primary feedstock is raw coal. Section 5 discusses the production of electricity. In the Netherlands, electricity is mainly produced from natural gas and coal. The fuel chain consists of two steps: production and distribution. Section 6 is devoted to petroleum coke and refinery gas, two fuels that are used in refineries. Finally, a short overview of the results of all process fuels is provided in section 7.

9.2 *Heavy fuel oil*

In this section, the fuel chain of heavy fuel oil is modelled. The energy flows in the fuel chain are modelled first, followed by the emissions.

Energy flows

Heavy fuel oil is made from crude oil. The first two steps in the fuel chain, extraction of crude oil and transportation of crude oil from the point of origin to the port in Rotterdam, are identical to the first two steps in other fuel chains that are based on crude oil. These steps have been described in detail in section 6.2 and are not repeated here. A summary of the results is provided in table 9.1 though.

Production

The third step in the fuel chain is production. In a refinery, crude oil is distilled into three fractions: light distillates, medium distillates and heavy distillates. Heavy fuel oil is a heavy distillate. There are very little data available on the efficiency of heavy distillate production. Because heavy distillates require little processing, just like middle distillates, it is assumed

Energy use per MJ output of the process step	Extraction	Transportation
Crude oil	1,006	1,000
Diesel	0,004	
Gasoline	0,002	
Heavy fuel oil	0,000	0,018
Natural gas	0,024	
Electricity	0,008	0,000
Total	1,044	1,018

Table 9.1: overview of energy flows in the first two steps in the heavy fuel oil fuel chain

Division of process energies (%)	[DeLuchi, 1993]	This study
Crude oil	97,2	97,2
Diesel	0,0	0,0
LPG	0,0	0,0
Heavy fuel oil	0,3	0,3
Natural gas	1,0	1,0
Electricity	0,2	0,2
Petroleum coke	0,3	0,3
Refinery gas	1,0	1,0
Total	100,0	100,0

Table 9.2: distribution of process energies in the production of heavy fuel oil

Energy use per MJ of heavy fuel oil produced	
Crude oil	1,023
Diesel	0,000
LPG	0,000
Heavy fuel oil	0,003
Natural gas	0,011
Electricity	0,002
Petroleum coke	0,003
Refinery gas	0,011
Total	1,053

Table 9.3: energy flows in the production of heavy fuel oil

	Primary input in the WTT chain $MJ/MJ_{\text{heavy fuel oil}}$
Crude oil	1,075
Natural gas	0,051
Coal	0,010
Total	1,137

Table 9.4: WTT primary energies in the heavy fuel oil chain

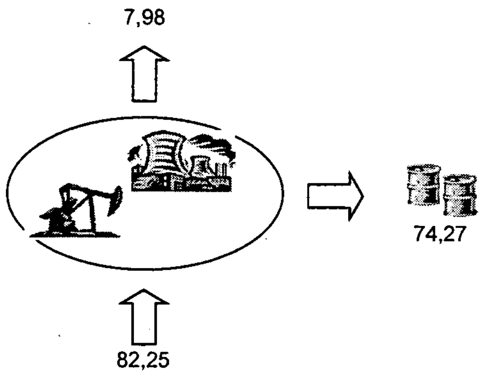

Figure 9.1: carbon balance of the heavy fuel oil fuel chain (values in $gCO_2/MJ_{\text{heavy fuel oil}}$)

here that the efficiency of the refining step of the diesel fuel chain is applicable to the refining step of the heavy fuel oil fuel chain. This efficiency is 95%. With this efficiency, it takes 1,053 MJ of energy to produce 1 MJ of heavy fuel oil. Data on the distribution of crude and process energies in this flow are found in DeLuchi and are depicted in table 9.2. The data have been recalculated from HHVs to LHVs using the fuel specifications from appendix D. The recalculated data set is used by this study. With these data and the overall efficiency of the step, it can be calculated how much of each process fuel is used in the step in order to obtain 1 MJ of heavy fuel oil output. The results of this calculation are shown in table 9.3.

Distribution

Heavy fuel oil is a so-called half-product. It is not sold to individual consumers, but used by other companies in order to obtain heat or to operate large machinery. It is also used as ship fuel. Because most large manufacturing sites are positioned in or near Rotterdam, it is likely that heavy fuel oil will only be distributed over very small distances. Because it is used only by companies, one may assume it is sold and distributed in bulk quantities. The energy needed to transport bulk quantities is very small per MJ of transported product. Because of the small transportation distances and the efficient way of transporting heavy fuel oil, it is assumed that the process energy in the distribution step in negligible.

WTT results

We know now all energy flows in the individual steps of the fuel chain. By combining these in the way described by equation (7) and (10) of chapter 4, all energy flows can be related to the energy flow leaving the fuel chain. Equation (10) can only be applied correctly though, after all fuel chains that are included in the study are modelled. If this condition is met, it turns out that the heavy fuel oil fuel chain uses 1,053 MJ of primary input and 0,074 MJ of process fuels to create 1 MJ of heavy fuel oil. The process fuels used are diesel, gasoline, heavy fuel oil, natural gas and electricity. If the energy needed to produce these fuels is taken into account in the way described by formula (12) of chapter 4, the total primary energy use in the heavy fuel oil fuel chain can be calculated. This equals 1,137 MJ per MJ of heavy fuel oil and consists of crude oil, natural gas and coal. The contribution of the individual primary feedstocks to the total amount of energy is shown in table 9.4.

Emissions

Carbon dioxide

Emissions of carbon dioxide are assessed by means of a carbon balance. The carbon balance of the heavy fuel oil fuel chain is depicted in figure 9.1. The oval figure represents the production process of the heavy fuel oil, whereas the two barrels on the right of the oval figure represent the carbon dioxide content of the fuel itself. As we see in the figure, the carbon content of heavy fuel oil is 74,27 gCO_2 per MJ of heavy fuel oil. During production, 7,98 g/MJ is emitted. Because the heavy fuel oil fuel chain uses only fossil inputs, the total emissions are equal to the carbon content all primary feedstocks that have been used, which is 82,25 g/MJ.

Methane

In this study, methane emissions are calculated from literature. As we have seen in chapter 6, 7 and 8, only a few sources mention numbers for methane emissions. Because heavy fuel oil is only a process fuel and no transportation fuel, data are even scarcer. The first two steps are identical to the first two steps of any fuel that is based on crude oil and therefore the emissions are known. For the production step, no data are available. To have some estimate, data are used from the fuel chain that resembles best the fuel chain of heavy fuel oil. This fuel chain is diesel. This leaves only one step that has to be accounted for, namely the distribution step. The distribution step was assumed to have a perfect efficiency, which means there are no losses in this step and consequently no emissions. With these assumptions and the emissions emerging from the production of the process fuels, a value

CH_4 (10^{-3} g/MJ)	[Johansson, 1992]	[Arthur D Little, 1996]	[De Jager, 1998]	This study
Extraction	26,0	6,8	13,8	16,4
Transportation	<<1	0,1	0,2	0,1
Production	<<1	0,3	0,1	0,2
Distribution				0,0
WTT emissions				27,3

Table 9.5: methane emissions in the heavy fuel oil chain

N_2O (10^{-3} g/MJ)	[Johansson, 1992]	This study
Extraction	<<1	0,0
Transportation	<<1	0,0
Production	1,5	1,5
Distribution		0,0
WTT emissions		1,6

Table 9.6: nitrous oxide emissions in the heavy fuel oil chain

Energy use per MJ output of the process step	Extraction	Processing	Transportation
Natural gas	1,025	1,003	1,002
Diesel	0,001		
Gasoline	0,000		
Heavy fuel oil	0,000		
Electricity	0,000	0,020	0,000
Total	1,028	1,024	1,002

Table 9.7: summary of energy flows in the natural gas fuel chain

	Primary input in the WTT chain $MJ/MJ_{natural\ gas}$
Crude oil	0,006
Natural gas	1,056
Coal	0,019
Total	1,080

Table 9.8: WTT primary energies in the natural gas fuel chain

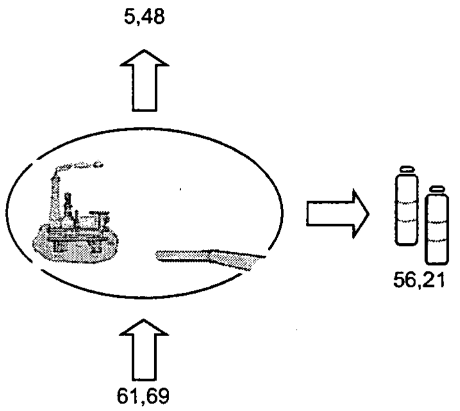

Figure 9.2: carbon balance of the natural gas fuel chain (values in $gCO_2/MJ_{natural\ gas}$)

for the WTT emissions can be calculated. This value equals 27,0 mg per MJ of heavy fuel oil. All data on the individual steps and the total WTT emissions are depicted in table 9.5.

Nitrous oxide

Like data on methane emissions, data on emissions of nitrous oxide in the heavy fuel oil fuel chain are very scarce. Fortunately we do know that the heavy fuel oil fuel chain uses only fossil inputs so that nitrous oxide emissions play only a minor role. The emissions are only a fraction of carbon dioxide emissions. For the extraction step and the transportation step, the emissions are equal to the emissions in all other fuel chains that are based upon crude oil. For the production step, data from the diesel fuel chain are used. Finally, in the distribution step the emissions are assumed to be zero due to the perfect efficiency in that step. By summing the emissions in the individual steps and including the emissions from the production of the process fuels, the WTT emissions can be calculated. These equal 1,6 mg per MJ of heavy fuel oil. A summary of the results can be found in table 9.6.

9.3 Natural gas

The second process fuel discussed here is natural gas. Natural gas is a process fuel that is often used for heating purposes, either by companies or by consumers. The fuel chain consists of three steps: first recovery of natural gas from a gas field, then processing to remove impurities and water and finally transportation. If the natural gas is sold to consumers, an odorant is added for safety reasons [NAM, 2003]. The natural gas fuel chain is identical to the first three steps of the CNG fuel chain. Because this fuel chain has already been described in detail in chapter 7, this chapter only gives a summary of the results. For a detailed description the reader is referred to section 7.2.

Energy flows

The energy flows per step have been summarized in table 9.7. If the steps are linked to each other according to the method described in section 4.3, the direct natural gas input in the fuel chain and the total amount of process energy can be calculated. The natural gas input in the fuel chain equals 1,030 MJ per MJ of natural gas; the amount of process fuels equals 0,023 MJ per MJ of natural gas. Process fuels used in the natural gas fuel chain are diesel, gasoline, heavy fuel oil and electricity. If the production of the process fuels is taken into account, total primary energy use comes down to 1,080 MJ per MJ of natural gas. The division over the primary feedstocks crude oil, natural gas and coal is given in table 9.8.

Emissions

Carbon dioxide

Carbon dioxide emissions are measured by means of a carbon balance. The balance for natural gas is shown in figure 9.2. The oval figure represents the production of the natural gas whereas the two cilinders represent the final product. Natural gas has a favourable carbon balance. The emissions from production equal only 5,48 g/MJ, which is very little. Also, because methane has a favourable carbon-hydrogen ratio, the amount of carbon dioxide contained in the fuel is relatively low: 56,21 g/MJ. Therefore the total WTT emissions equal only 61,69 gCO_2 per MJ of natural gas.

Methane and nitrous oxide

The methane and nitrous oxide emissions for the individual steps have been discussed in section 7.2. The emissions of each step are related to the output of the fuel chain in the way described in chapter 4 and summed. To this number the emissions from the production of the process fuels are added in order to obtain WTT results. For methane this equals 105,0 mg per MJ of natural gas. Nitrous oxide emissions are virtually zero. The emissions in each step

CH_4 (10^{-3} g/MJ)	[Johansson, 1992]	[Arthur D Little, 1996]	[Gasunie, 2003]	This study
Recovery	64,0	32,4		48,2
Processing	62,0	27,4		44,7
Transportation			0,9	0,9
WTT emissions				105,0

Table 9.9: methane emissions in the natural gas fuel chain

N_2O (10^{-3} g/MJ)	[Johansson, 1992]	This study
Recovery	<<1	0,0
Processing	<<1	0,0
Transportation	<<1	0,0
WTT emissions		0,0

Table 9.10: nitrous oxide emissions in the natural gas fuel chain

Reference	Efficiency	Comments
[DeLuchi, 1993]	99,2	-
[Arthur D Little, 1996]	99,1	-
This study	99,1	-

Table 9.11: efficiencies in the extraction of coal

Division of process energies (%)	DeLuchi & Arthur D Little	This study
Diesel	60,2	60,2
Gasoline	4,2	4,2
Heavy fuel oil	6,2	6,2
Natural gas	1,1	1,1
Electricity	21,4	21,4
Coal	6,9	6,9
Total	100,0	100,0

Table 9.12: distribution of process energies in the extraction of coal

Energy use per MJ of coal extracted	
Diesel	0,005
Gasoline	0,000
Heavy fuel oil	0,001
Natural gas	0,000
Electricity	0,002
Coal	1,001
Total	1,009

Table 9.13: energy flows in the extraction of coal

	Primary input in the WTT chain MJ/MJ_{coal}
Crude oil	0,015
Natural gas	0,003
Coal	1,002
Total	1,021

Table 9.14: WTT primary energies in the coal fuel chain

and the total WTT emissions are shown in table 9.9 and 9.10 for methane and nitrous oxide respectively.

9.4 Coal

Coal is used to produce electricity and therefore its fuel chain is added to the model. The fuel chain from coal is quite short in comparison to other fuel chains. The first step in the fuel chain is mining. Because coal is a solid any corrosive or toxic contaminants that it contains are trapped in the coal. They can not escape and therefore no processing is needed. The next step, which is also the last step in the fuel chain, is transportation to the Netherlands. This is done by ship.

Energy flows

Mining

The fuel chain starts with mining of the coal. If the coal is found close to the surface of the earth, the coal is dug up in a process called open pit mining. If the coal is found deeper in the earths crust, underground mining is applied to retrieve the coal. After recovery, the coal needs virtually no processing. Any contaminants that it contains are only released when the coal is burned. They are at that time taken care off in aftertreatment processess.

Data on the efficiency of the mining step are provided by Arthur D. Little and DeLuchi and are shown in table 9.11. This study uses the average of both sources, which equals 99,1%. With this efficiency, one needs 1,009 MJ to mine 1 MJ of coal. 1 MJ of this number consists of coal that will be shipped. The remainder 0,009 MJ consists of spills of coal and of process energies. A distribution of the composition of this energy flow is provided by Arthur D. Little and DeLuchi but turns out to be identical. This distribution is shown in table 9.12 and copied by this study. With this distribution and the overall efficiency, it can be calculated how much of each process fuel is used in order to obtain 1 MJ of coal. The result of this calculation is shown in table 9.13.

Transportation

The second and last step of the coal fuel chain is transportation from abroad to the Netherlands. Unfortunately, there are no data publicly available on the origin of coal imported in the Netherlands and on the transportation distances. Therefore it is impossible to make the kind of calculation that was made for crude oil. Instead, input from literature is used. Both Arthur D Little and DeLuchi mention an efficiency for transportation of 99,3%. Both numbers are based on data for the United States. Therefore it is likely that they contain transportation by train or barge, while coal that is transported to the Netherlands is only transported by ship. However, these data are the best available and therefore they are used. Under these assumptions, it takes 0,007 MJ of process energy to transport 1 MJ of coal. Because all transportation is done by ship, it is assumed that heavy fuel oil is the only relevant process fuel.

WTT results

The direct primary input in the coal fuel chain equals 1,001 MJ per MJ of coal. Also, 0,016 MJ of process fuel is used. The process fuels used are diesel, gasoline, heavy fuel oil, natural gas and electricity. If the production of these process fuels is taken into account, the fuel chain system of coal consumes 1,020 MJ of primary energy to produce 1 MJ of coal. The division over the primary feedstocks is provided in table 9.14.

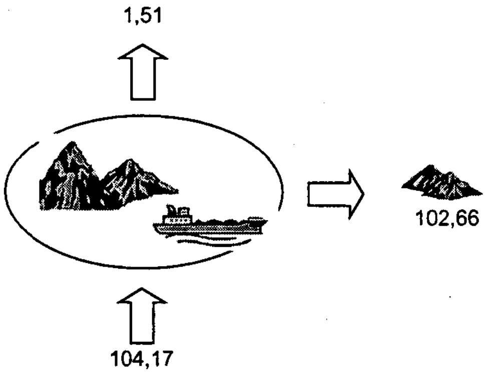

Figure 9.3: carbon balance of the coal fuel chain (values in gCO_2/MJ_{coal})

CH_4 (10^{-3} g/MJ)	[Arthur D Little, 1996]	[DeLuchi, 1993]	This study
Mining	507	399	453
Transportation			0,0
WTT emissions			454,4

Table 9.15: methane emissions in the coal fuel chain

Energy use per MJ of electricity produced	
Heavy fuel oil	0,151
Natural gas	1,081
Processed coal	0,823
Total	2,055

Table 9.16: energy flows in the production of electricity

Emissions

Carbon dioxide

Carbon dioxide emissions are calculated by means of a carbon balance. The carbon balance for coal is shown in figure 9.3. The oval figure represents the production of the coal whereas the two piles represent coal that has arrived in the Netherlands and is ready to be used as process fuel. As we see in the figure, coal has the highest carbon content of all fossil fuels, 102,66 gCO_2 per MJ of coal. The production process is very carbon efficient: the production of 1 MJ of coal only produces 1,51 g carbon dioxide. This brings the total carbon dioxide emissions emerging from the use of 1 MJ of coal to 104,17 gCO_2.

Methane and nitrous oxide

The mining of coal is a large source of methane emissions. Coalbed methane, a mixture of gases of which methane is the main component, is released from the coal during mining thereby causing emissions. Some countries are running projects to capture the coalbed methane and to use it as fuel, but in most mines the methane escapes through the ventilation system [WEA, 2002]. Data on the emissions of the mining step are provided by Arthur D Little and DeLuchi. The first estimates emissions to be 507 mg/MJ; the latter estimates 399 mg/MJ. It is not known if one estimate is more reliable than the other is. Therefore the average from both data is used in this study. No data have been found on emissions during transportation. However, methane emissions from the engines of ships are very low. For comparison: the emissions from the transportation of crude oil are only 0,1 mg/MJ_{crude}. This number shows that the error that comes forth from neglecting methane emissions from transportation of coal is negligible. Including the emissions from the production of the process fuels in the calculation results in a value for the WTT emissions of 454,4 mg/MJ. All values are presented in table 9.15.

Data on nitrous oxide emissions have not been found. However, the fuel chain uses only fuels that are based on fossil feedstocks. For these feedstocks, emissions of nitrous oxide are generally low. Furthermore, the production process of coal uses only a very small amount of energy, which is a second clue that emissions will be low. Therefore this study assumes emissions of nitrous oxide to be negligible.

9.5 *Electricity*

Energy flows

The electricity fuel chain consists of two steps: production of electricity and distribution. Both steps are described here.

Production

The main part of the electricity that is used in the Netherlands is produced in the country itself. Most of it is generated in central plants, although a growing part comes from decentral generating facilities, for example cogeneration or combined heat & power. In this study, the data on production of electricity from the grid are based on data from 27 central electricity plants in the Netherlands. The inputs from all 27 plants are summed and divided by the output summed over all plants, to obtain data on the production of an average MJ. The data from the individual plants are obtained from annual environmental reports[4]. Import of electricity and decentrally generated electricity are not included in the calculation due to lack of data. Nevertheless it is assumed that the outcome of the calculation is representative for all electricity used in the Netherlands. The complete calculation with data from all the electricity plants can be viewed in appendix G. In table 9.16, a summary of the results is shown. As can be seen in the table, it takes 2,055 MJ of process energies to produce 1 MJ of electricity. This

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[4] In Dutch: milieujaarverslag. In the Netherlands, companies that use a lot of resources are obliged by the government to register their energy use and emissions.

	Primary input in the WTT chain $MJ/MJ_{electricity}$
Crude oil	0,188
Natural gas	1,198
Coal	0,881
Total	2,268

Table 9.17: WTT primary energies in the electricity fuel chain

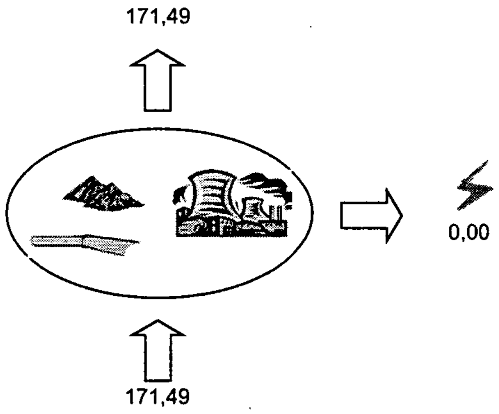

Figure 9.4: carbon balance of electricity production (all values in $gCO_2/MJ_{electricity}$)

Fuel chain	WTT primary energy (MJ_{prim}/MJ_{output})	WTT CO_2 emissions (gCO_2/km)	WTT CH_4 emissions (gCH_4/km)	WTT N_2O emissions (gN_2O/km)	Total WTT emissions (g CO_2-eq./km)
Heavy fuel oil	1,14	8,0	0,03	0,00	9,1
Natural gas	1,08	5,5	0,11	0,00	7,9
Processed coal	1,02	1,5	0,45	0,00	12,0
Electricity	2,27	171,5	0,51	0,00	183,3

Table 9.18: summary of results for heavy fuel oil, natural gas, coal and electricity

amount consists of natural gas, coal, and “other inputs”. The term “other inputs” includes half-products, byproducts from industrial processes and (upgraded) waste materials. It is assumed that the energy chains of these products can be represented by that of heavy fuel oil.

Distribution

After production, electricity is distributed. Statistics Netherlands provides data on the total amount of electricity produced and on the distribution losses in 2002 [CBS, 2003]. From these data we can deduce that 3,9% of the electricity produced is lost in distribution. This means 1,041 MJ of electricity has to be generated in order to get 1 MJ of electricity to the customer.

WTT results

By combining the distribution step with the production step we find that it takes 2,138 MJ of fuel input to deliver 1 MJ of electricity at the customer. This amount consists of heavy fuel oil, natural gas and processed coal. By including the fuel chains from these process fuels in the calculation, the total amount of primary feedstock used in the fuel chain can be calculated. This equals 2,266 MJ. The distribution of this amount over different primary feedstocks can be found in table 9.17.

Emissions

Carbon dioxide

The carbon dioxide emissions are calculated by means of a carbon balance. Figure 9.4 shows the carbon balance for the production of electricity. The oval figure represents the production process while the shaft of lightning represents the endproduct, the electricity. Electricity has no mass and consequently no carbon content. Therefore all the carbon dioxide that enters the fuel chain is released during production. From the figure we see that this amount equals 171,49 $g/MJ_{electricity}$. In literature, a value of 167 $g/MJ_{electricity}$ has been found, which indicates that the value calculated here is reliable [ECN, 2001].

Methane and nitrous oxide

Data on emissions of methane and nitrous oxide are only reported in annual environmental reports if the size of the emissions exceeds a limit imposed by the government. For most plants, this was not the case and therefore no data are recorded. As a result, there are not enough data available to deduct a reliable number for direct methane emissions. Only the emissions from the production of the process fuels can be calculated. In this way methane emissions become 511,4 mg/MJ. Nitrous oxide emissions equal 0,3 mg/MJ.

9.6 Petroleum coke and refinery gas

The last two fuels in the model are petroleum coke and refinery gas. Petroleum coke is based on crude oil. It is a heavy distillate that is formed at two places in the refinery: as product from distillation and as product from cracking. There are only a few small markets for petroleum coke. For most of it there is no market and therefore it is used as fuel in the refinery [IUPAC, 1997]. Refinery gas is a mixture of alkanes and other gases that are stripped from crude oil. Because the composition of the crude oil varies, the composition of refinery gas varies, too. There are little markets for refinery gas so this product too is burned in the refinery for heating purposes [Joeco, 2003]. Neither for petroleum coke nor for refinery gas data could be found to make the kind of analysis that is used in this study. However, they enter the refinery as crude oil and are consumed in the refinery. This makes them comparable to excess crude oil. In all calculations, they are added to the flow of crude oil through the refinery.

9.7 Summary of results

Data on the fuel chains of heavy fuel oil, natural gas, coal and electricity are summarized in table 9.18.

10 Presentation of results

10.1 Introduction

In the previous chapters, 8 fuel chains of transportation fuels have been modelled. In this chapter, the results for all 8 fuel chains are presented. Some of the fuel chains produce byproducts that have to be accounted for in some way before an equal comparison can be made. In section 4.7, four methods have been presented of accounting for byproducts, namely Avoided Primary Energy and Emissions, Multiple Vehicle Kilometers and the first and second Ratio of Energy Contents method. All methods will be applied in this chapter. In all cases, the way of accounting for byproducts influences only the WTT results. The TTW energies and emissions are equal in all presentations.

First the results for all fuel chains are presented without any accounting for byproducts at all. This is done is section 2. In section 3, the results according to the Avoided Primary Energy and Emissions method will be discussed and section 4 is dedicated to the Multiple Vehicle Kilometers method. The first and second Ratio of Energy Contents method are described in respectively section 5 and 6. Finally, some conclusions about the results from the different methods are drawn in section 7.

10.2 Results without accounting for byproducts

This section shows the results for all fuel chains in the case that byproducts are given no credit at all. This means that the total energy use in the fuel chain is attributed to the transportation fuel and that the same goes for the emissions. Figure 10.1 shows the division over WTT and TTW results. As we see in the figure, the TTW energy use in compression ignition engines is in all cases lower than that in spark ignition engines. As for the WTT energy use, the Fischer-Tropsch process and the production of ethanol require significantly more energy than the production processes of the other fuels. The most efficient production processes are those of diesel and LPG: both require 1,14 MJ of primary energy input to produce 1 MJ of transport fuel. The second best is the production process of CNG, closely followed by gasoline. The production of ethanol is least efficient of all, irrespective of the type of biomass that is used as input.

In figure 10.2, the results for all fuel chains are shown by primary feedstock use. We see that the diesel fuel chain, gasoline fuel chain and LPG fuel chain use primarily crude oil, as was to be expected. Besides crude oil, natural gas and coal are used in these fuel chains, although the use of coal is this small that is doesn't show in the figure. In the fuel chains based on natural gas, natural gas is the main feedstock. In comparison with the other fuel chains, the use of coal is quite high. This is because the CNG fuel chain and the FT diesel fuel chain use more electricity than the other fuel chains and because the electricity has been generated partly from coal. In the case of the biomass-based fuel chains, we see that the chains that use woody biomass require less fossil energy than the fuel chain that uses sugary biomass. The explanation is that woody biomass contains lignin, which can not be converted but is burned to generate heat, electricity and steam. Sugary biomass does not contain lignin and therefore the heat, steam and electricity that are needed in the fuel chain have to be obtained by burning fossil inputs.

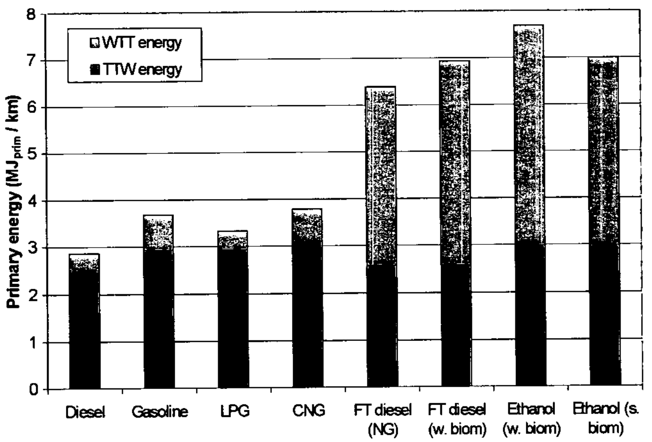

Figure 10.1: WTT and TTW energy use, without accounting for byproducts

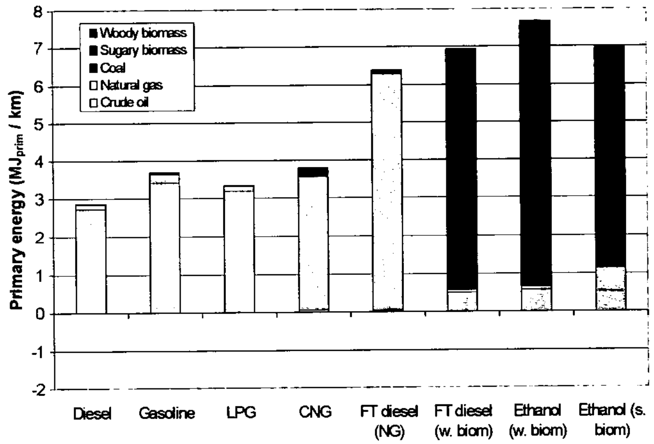

Figure 10.2: WTW energy use by primary feedstock, without accounting for byproducts

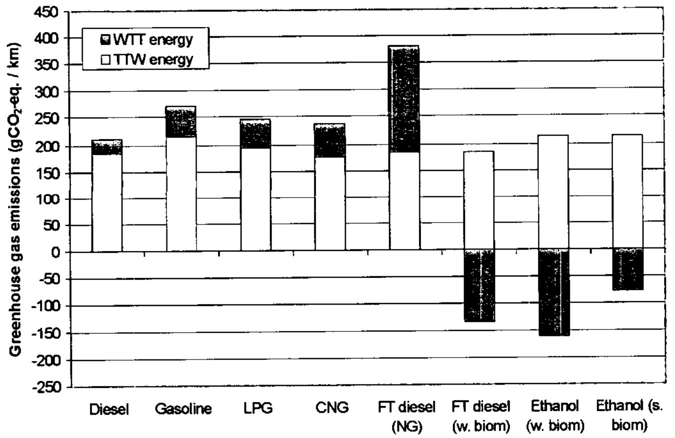

Figure 10.3: WTT and TTW emissions, without accounting for byproducts

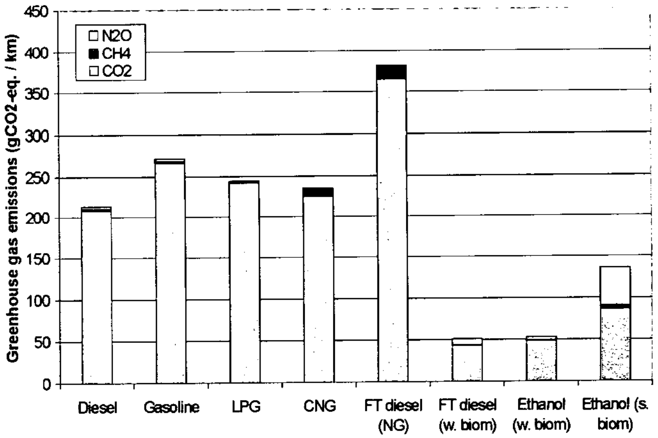

Figure 10.4: WTW emissions by source, without accounting for byproducts

Figure 10.3 shows the emissions in all fuel chains, divided into WTT and TTW emissions. For the crude oil and natural gas based fuel chains, the amount of emissions correlates roughly with the amount of energy used: the more energy is used in the fuel chain, the higher the emissions are. For the biomass based fuels the WTT emissions are negative. This is due to the fact that biomass takes up carbon dioxide from the air to grow. The TTW emissions are comparable in size to TTW emissions from other fuel chains. This brings the WTW emissions to a value larger than zero but substantially smaller than WTW emissions from fossil fuel based fuel chains. The absolute height from the WTW emissions in the biomass based fuel chains can be obtained from figure 10.4.

Finally, figure 10.4 shows the emissions divided over the three substances modelled in this study: carbon dioxide, methane and nitrous oxide. In all fuel chains, carbon dioxide is the main source of emissions. Methane emissions are only worth mentioning in the natural gas fuel chains. Nitrous oxide emissions are especially relevant in the biomass based fuel chains, especially the fuel chain based on sugary biomass.

10.3 Results according to the Avoided Primary Energy and Emissions method

One way of accounting for byproducts, is the Avoided Primary Energy and Emissions method (APEE). The mathematics behind this method have been described in section 4.7. In the APEE method, byproducts are credited with the amount of primary energy that would have been used, would they have been produced in a dedicated production process. The idea behind this method is that, had the transportation fuel not been made, the byproducts would have been made anyway. By producing the transportation fuel, the production of the byproducts in the common way is avoided. What is actually done in this method, is that the system borders are extended. The production of byproducts in their usual way is included in the study in a reference case. Next, a case of interest is determined in which transportation fuels are produced in whose fuel chains byproducts are produced. The production of the byproducts in the case of interest replaces the usual production of byproducts. Calculations over the entire system for both the reference case and the case of interest show the difference, which equals the avoided primary energy and emissions.

This way of crediting for byproducts is much applied in system calculations. If the usual production methods of the byproducts are clearly defined, this way of crediting works very well. However, if this way of accounting for byproducts is applied in WTW calculations, this method has some drawbacks. In WTW calculations, there are no usual production methods defined for the byproducts. Therefore, it is not automatically clear what energies and emissions are avoided by producing byproducts. By assuming very inefficient, high-emitting production processes for the regular production of the byproducts, the energies and emissions that are avoided can be calculated as being very high. Due to the fact that the results for the transportation fuel are calculated as the difference between the total energy use and emissions and the avoided energy and emissions, the results for the transportation fuel can be easily flattered.

A second point of attention is the so-called “double counting”. In the Netherlands, green electricity is sold with a green certificate. Such a certificate ensures the buyer that the electricity was generated using renewable sources and thus that emissions have been avoided. If the emissions and energy use of the production of the transportation fuel have been calculated using the APEE method, the fuel has been credited with the avoided emissions. However, if the electricity that has been generated as a byproduct from the fuel is sold as green electricity, the electricity is credited with avoided emissions, too. The avoided energy and emissions are calculated twice, but in reality they are avoided only once of course. This kind of “double counting” can be avoided by careful bookkeeping, but the more renewable transportation fuels are used, the higher the chances are that double counting occurs.

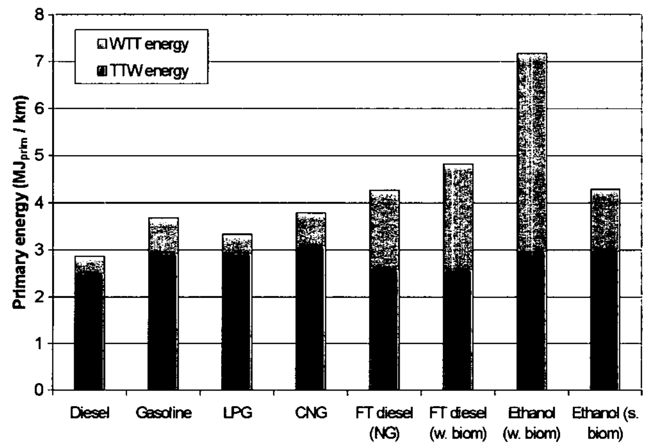

Figure 10.5: WTT and TTW energy use, with accounting for byproducts according to APEE

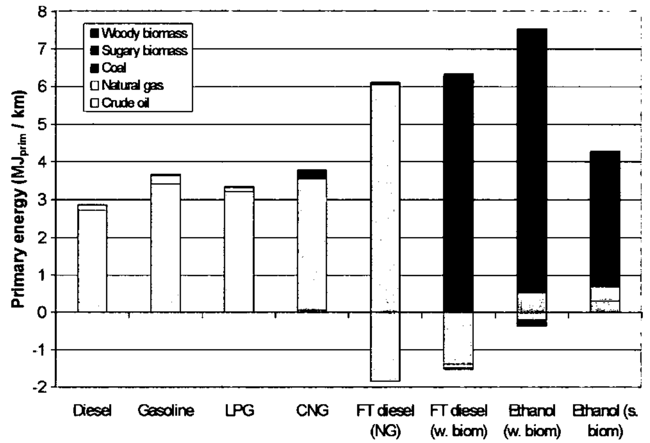

Figure 10.6: WTW energy use by primary feedstock, with accounting for byproducts according to APEE

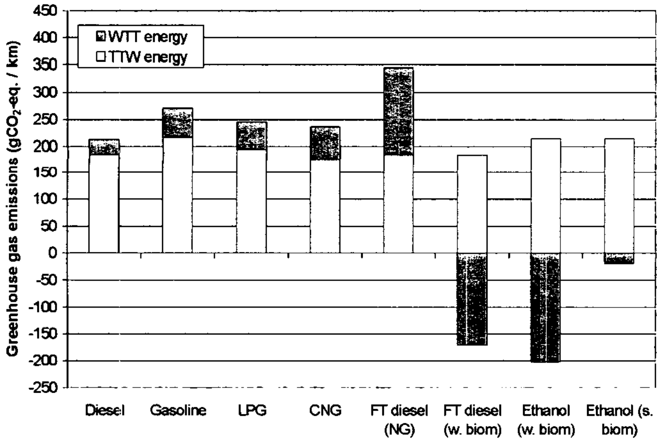

Figure 10.7: WTT and TTW emissions, with accounting for byproducts according to APEE

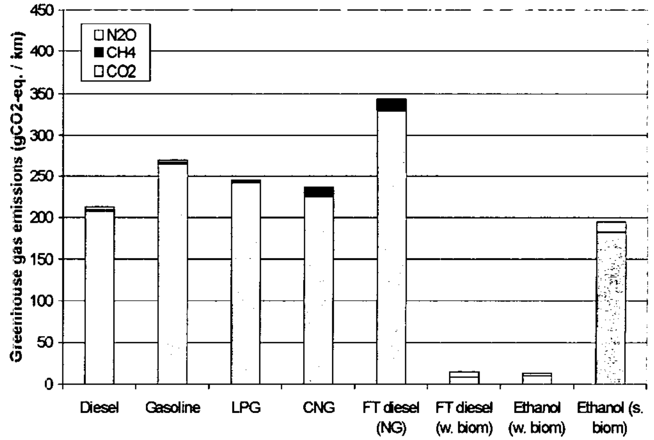

Figure 10.8: WTW emissions by source, with accounting for byproducts according to APEE

Nonetheless the APEE method is quite popular in WTW calculations and therefore it has been included in this study, among other ways of accounting for byproducts. For the byproduct electricity, the avoided primary energy and emissions are calculated with WTT data on the production of electricity from the grid. For the avoided primary energy and emissions of gasoline and LPG, data from respectively the WTT part of the gasoline fuel chain and the WTT part of the LPG fuel chain are used. In the case of animal feed, it was assumed that the WTT avoided primary energy and emissions equal 1,20 MJ per MJ of animal feed. This number is based on the growing step and the transportation step of sugary biomass, which together consume 1,10 MJ per MJ of biomass, plus an additional 0,10 MJ for processing of biomass to animal feed and for distribution.

In figure 10.5, the WTT and TTW energy use according to APEE are depicted. In the fuel chains of diesel, gasoline, LPG and CNG as they have been modelled in this study, no byproducts are produced. Therefore the results for these fuel chains are identical to the results depicted in figure 10.1. In the other fuel chains, we see that especially the fuel chain of ethanol made from sugary biomass benefits from this way of accounting for byproducts. According to APEE, the production of ethanol from sugary biomass is the most efficient of all biomass-based fuel chains. If ethanol is made from cellulosic biomass on the other hand, the WTT efficiency is the lowest of all fuel chains included in this study.

Figure 10.6 shows the amount of energy that is used per primary feedstock. We see immediately that there is something unusual going on: there are three fuel chains in which some primary energies are negative. The Fischer-Tropsch diesel from natural gas fuel chain shows a negative amount of crude oil use. This is due to the fact that this fuel chain produces gasoline and LPG as byproducts, which are both based on crude oil. Hardly any crude oil is used in the fuel chain itself, and therefore the amount of avoided crude oil is larger than the amount of crude oil used in the fuel chain. The fact that the energy is recorded as negative does definitely not imply that crude oil is produced in this fuel chain. The same goes for the FT diesel from cellulosic biomass fuel chain. The negative amount of natural gas in this fuel chain is explained by the amount of avoided natural gas due to the byproduct electricity. The amount of avoided energy is larger than the amount of natural gas that is used in the fuel chain. In the ethanol from cellulosic biomass fuel chain, more natural gas and coal are avoided due to the production of electricity than there was used in the fuel chain. If we compare the three biomass-based fuel chains with each other, we find that although total energy use is the lowest in the sugary biomass fuel chain, the fossil fuel energy use is the highest in this chain.

With respect to the WTT and TTW emissions, shown in figure 10.7, the APEE method is particularly unfavourable for the ethanol from sugary biomass fuel chain. The animal feed that is produced as byproduct would normally have been made from biomass. During the growing of this biomass, carbon dioxide would have been taken up from the air. Due to the production of animal feed as byproduct from the production of ethanol, this uptake is prevented. The emissions that are avoided are negative emissions, and thus the total amount of emissions in the ethanol from sugary biomass fuel chain increases. For both fuel chains that use cellulosic biomass as input, the emissions are close to zero. In the FT diesel from natural gas fuel chain, the emissions are still considerably higher than those of the conventional fuel chains and the CNG fuel chain are. The division of emissions by substance in figure 10.8 shows that in all fuel chains carbon dioxide remains the most important emission. Furthermore the nitrous oxide emissions in the sugary biomass are much lower according to APEE than they are if byproducts are not accounted for.

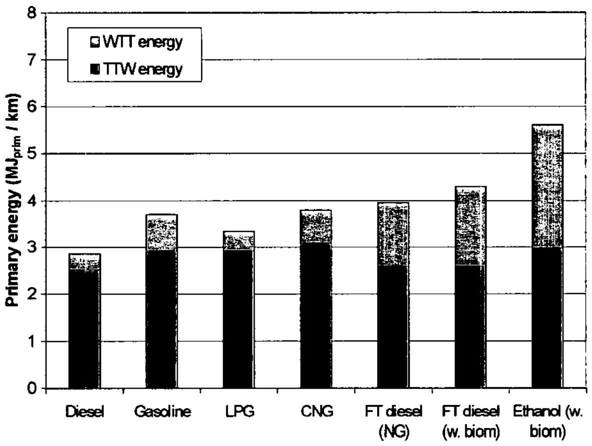

Figure 10.9: WTT and TTW energy use, with accounting for byproducts according to MVK

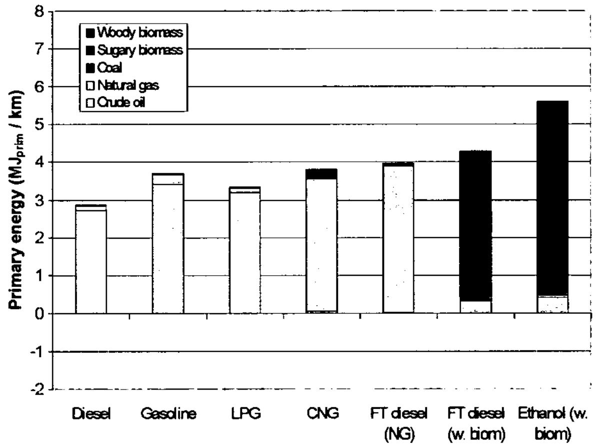

Figure 10.10: WTW energy use by primary feedstock, with accounting for byproducts according to MVK

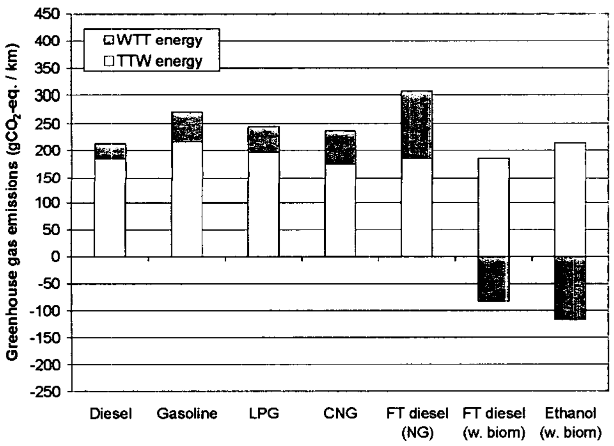

Figure 10.11: WTT and TTW emissions, with accounting for byproducts according to MVK

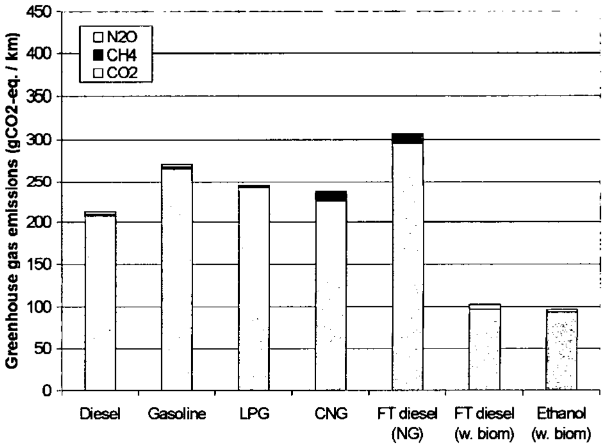

Figure 10.12: WTW emissions by source, with accounting for byproducts according to MVK

10.4 Results according to the Multiple Vehicle Kilometers method

The second way described in section 4.7 in which byproducts can be accounted for, is the method of Multiple Vehicle Kilometers (MVK). In this method, it is assumed that byproducts are used in another vehicle with another powertrain. In this way, the distance traveled with an amount of primary feedstock increases and thus the amount of primary feedstock per kilometer and the WTW emissions per kilometer decrease. On a system level, the system borders are extended, but in another way than in the APEE method. In the MVK method, the system is extended to include multiple TTW parts, one for each product and byproduct. The energies and emissions in the WTT part of the fuel chain are divided over the product and byproducts according to the number of kilometers that can be driven with a transportation fuel, relative to the total number of kilometers that can be driven with all outputs. The fuel chains of the byproducts are split from the fuel chain system so that only the main product is left. Although one will not encounter problems with doubtful efficiencies and double counting, this method has its own drawback, namely that it can only be applied to byproducts that can be used as energy carriers for transportation purposes. To some fuel chains, such as the ethanol from cellulosic biomass fuel chain in this study, this way of accounting for byproducts can not be applied.

The number of kilometers that can be driven with the byproducts gasoline and LPG is calculated with the TTW energy of respectively gasoline from crude oil and LPG from crude oil. For the byproduct electricity, it is assumed that it takes 0,60 MJ to travel a distance of 1 kilometer [TNO, 2002]. Animal feed is not suited as input in modern engines. It has been excluded from this analysis.

The WTT and TTW energies according to the MVK method can be found in figure 10.9 and 10.10. We see in figure 10.9 that in all fuel chains where byproducts are produced and that are included in this method, the WTT energy use is lower than it was in the APEE method. The total WTW energy use in both FT diesel fuel chains even approaches the WTW energy use in the gasoline and CNG fuel chains. According to this method, producing ethanol from cellulosic biomass consumes the most energy. In figure 10.10, the energy use per primary feedstock is shown. For the two biomass-based fuel chains we see that the fossil fuel use is almost equal.

Figure 10.11 and 10.12 provide information on the emissions according to the MVK method. In the FT diesel from natural gas fuel chain, the emissions are lower according to MVK than they are when byproducts are not accounted for. This fuel chain has very high positive WTT emissions in the base case, so when only a part of these emissions is taken into account, the emissions go down. In both fuel chains that are based on cellullosic biomass, the emissions according to MVK are higher than they are when byproducts are not accounted for. In these fuel chains, the WTT emissions are negative. When only a part of the emissions is taken into account, the emissions become less negative, and the total of WTT and TTW becomes more positive. We can also see in figure 10.12 that in the ethanol from cellulosic biomass fuel chain the emissions are lower than those in the FT diesel from cellulosic biomass fuel chain are. This is the same in the APEE method. It must be noted though that the absolute value of the emissions is for both fuel chains higher according to MVK than according to APEE.

10.5 Results according to the first Ratio of Energy Contents method

The third method introduced in section 4.7 is the first Ratio of Energy Contents method (REC1). In this method, the energies and emissions in the entire fuel chain are divided over the transportation fuel and the byproducts according to ratio of the energy contents in which they are produced. The system borders are not touched; no fuel chains or parts of fuel chains

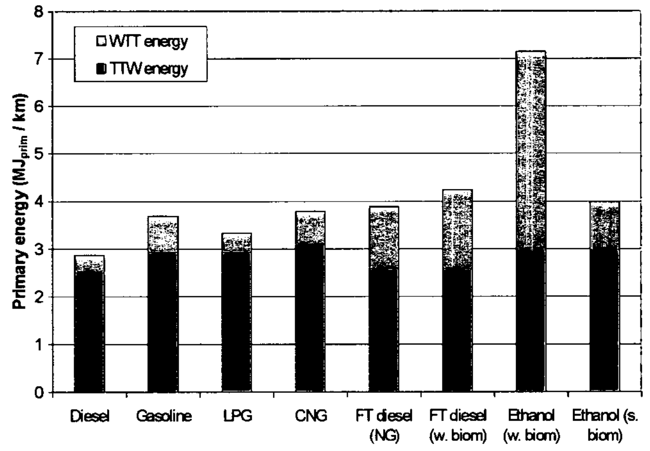

Figure 10.13: WTT and TTW energy use, with accounting for byproducts according to REC1

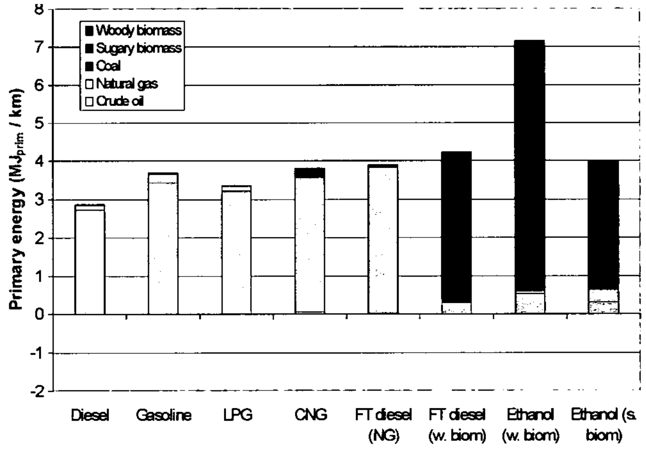

Figure 10.14: WTW energy use by primary feedstock, with accounting for byproducts according to REC1

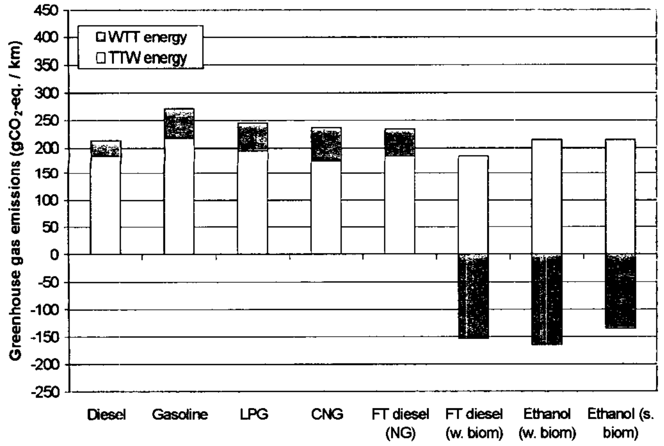

Figure 10.15: WTT and TTW emissions, with accounting for byproducts according to REC1

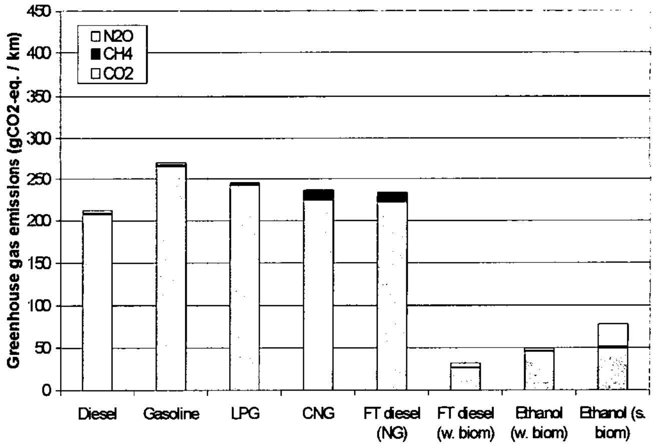

Figure 10.16: WTW emissions by source, with accounting for byproducts according to REC1

are added or subtracted from the existing fuel chain system. Therefore this method is applicable to all byproducts in all fuel chains.

Although this method is one of the fairest alternatives to account for byproducts, this one, too, has a disadvantage: it is too simplistic. The method treats all products and byproducts as if they pass trough the entire fuel chain, which they don't. The byproducts leave the fuel chain at the end of the step in which they are produced. In the REC1 method, they are treated as if they pass trough all steps of the fuel chain and thus too much energy and emissions are assigned to the byproducts. The results for the transportation fuels are a little flattered.

The WTW energy use according to the REC1 method is depicted in figure 10.13 and 10.14. The fuel chain that uses the most energy is the ethanol from cellulosic biomass fuel chain. This fuel chain is also the least efficient in the other two ways of accounting for byproducts. The difference in energy use between ethanol from sugary biomass and both FT diesel fuel chains is larger than it is according to APEE. In both methods, the production of FT diesel from natural gas is more favourable than the production of FT diesel from cellulosic biomass or the production of ethanol, no matter what feedstock is used for ethanol.

Information about the emissions according to the REC1 method is provided in figure 10.15 and 10.16. Just as in the MVK method, the emissions in the FT diesel from natural gas fuel chain are higher than the emissions in the gasoline and LPG fuel chain. In the case of the biomass fuel chains, the REC method leads to emissions in the ethanol from cellulosic biomass fuel chain that are clearly higher than the emissions in the FT diesel from cellulosic biomass fuel chain. In the other methods of accounting for byproducts, the emissions in both fuel chains were more or less equal. The emissions from the ethanol from sugary biomass fuel chain are the highest of all biomass-based fuel chains, although they are still much lower than the emissions in the fossil fuel based fuel chains.

10.6 Results according to the second Ratio of Energy Contents method

In section 4.7 we have seen that the original Ratio of Energy Contents is a simplification of the truth and that the method overestimates the energies and emissions that can be subscribed to the byproducts. Therefore a more sophisticated version of the REC method has been applied. In this version of the Ratio of Energy Contents method, indicated by REC2, the multiplication with the ratio of products and byproducts is only performed upstream of the step in which the byproducts are produced. After the step in which the byproducts are produced, all energies and emissions are subscribed in total to the transportation fuel.

However, in the fuel chains that are included in this study, the byproducts are produced in the last-but one step of each fuel chain. After production of the fuel and the byproducts, there is only a distribution step left. Because distribution is quite efficient, the differences in outcome between REC1 and REC2 are not very large. In the FT diesel from natural gas the difference in WTW energy is 0,01 MJ; in the other fuel chains with byproducts it is even smaller. In the case of emissions, the largest difference is 0,05 gCO_2-equivalents. This difference occurs in the ethanol from sugary biomass fuel chain. Although the differences between REC1 and REC2 are not very large in the fuel chains included in this study, it is important to note that the earlier the byproducts are produced in the fuel chain, the larger this effect becomes.

10.7 Summary and conclusions

In this chapter the results have been presented of all fuel chains that have been modelled in chapters 6, 7 and 8. Because some fuel chains have multiple outputs, they can not be compared straight away. In order to make a fair comparison, the byproducts have to be accounted for in such a way that there is only one output left, namely the transportation fuel of

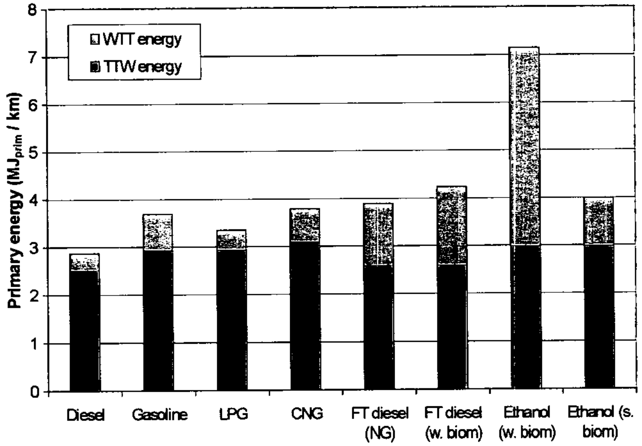

Figure 10.17: WTT and TTW energy use, with accounting for byproducts according to REC2

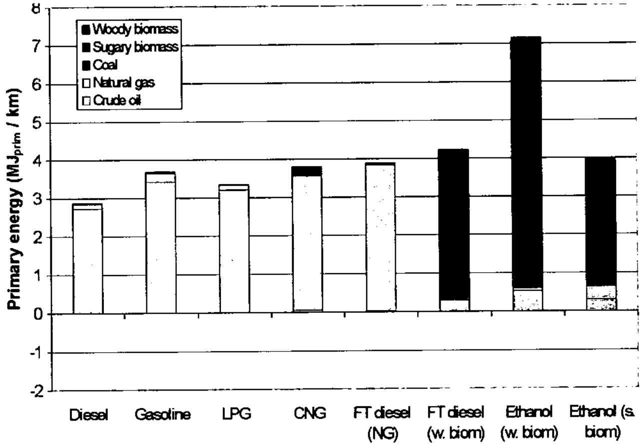

Figure 10.18: WTW energy use by primary feedstock, with accounting for byproducts according to REC2

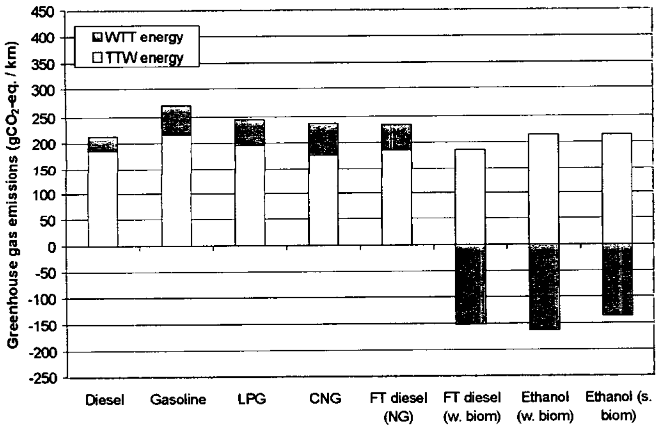

Figure 10.19: WTT and TTW emissions, with accounting for byproducts according to REC2

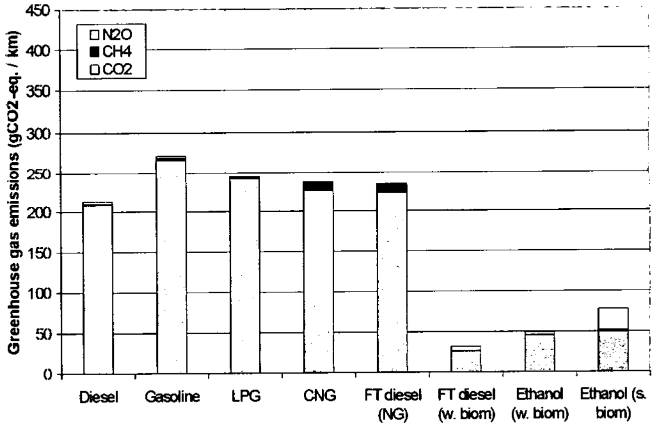

Figure 10.20: WTW emissions by source, with accounting for byproducts according to REC2

interest. In this chapter, four methods of accounting for byproducts have been presented. No matter what method of accounting is applied, only the WTT part of the fuel chain is adjusted. The TTW part is equal for all methods.

If we look at total energy use, the diesel fuel chain is the most efficient of all fuel chains. The WTW energy use in this fuel chain uses 2,87 MJ/km. Diesel is followed by LPG, gasoline and CNG. In all methods of accounting for byproducts, the ethanol from cellulosic biomass uses the most energy. Furthermore all methods of accounting for byproducts show that it is more efficient to produce FT diesel from natural gas than it is to produce it from cellulosic biomass. Finally, in all methods of accounting for byproducts where ethanol from sugary biomass is included, this is the most efficient biomass-based fuel chain.

However, if we don't look at total fuel use but at fossil fuel use, the picture is quite different. In all cases, the biomass-based fuels use the least fossil energy. Also, in all three methods the order is the same: FT diesel from cellulosic biomass uses the least fossil fuels of all, followed by ethanol from cellulosic biomass. Ethanol from sugary biomass uses the most fossil energy of the biomass-based fuels. The fossil fuel based fuels use only fossil fuels and therefore their ranking is equal to that in the total energy use: diesel uses the least fossil energy, followed by respectively LPG and gasoline. The FT diesel from natural gas fuel chain uses the most fossil energy of all.

In the case of greenhouse gas emissions, the emissions are lowest in the biomass based fuel chains. Of all biomass-based fuels, the ethanol from sugary biomass fuel chain uses the most fossil fuels and consequently emits the most emissions. This means that converting cellulosic biomass to transportation fuels creates fewer emissions than converting sugary biomass to a transportation fuel. However, whether it is better to convert cellulosic biomass to FT diesel or ethanol is not very clear. According to the Avoided Primary Energy and Emissions method and the Multiple Vehicle Kilometers method, ethanol results in the lowest emissions. With both Ratio of Energy Contents methods, conversion to FT diesel results in the lowest emissions. Of the fossil fuels, diesel results in the lowest emissions. According to APEE and MVK, diesel is followed by CNG, LPG, gasoline and FT diesel from natural gas respectively. According to both Ratio of Energy Contents methods, however, FT diesel from natural gas occupies the second place in the ranking in stead of the fifth.

11 Benchmarking and sensitivity analysis

11.1 Introduction

As a supplement to the presentation of the results in the previous chapter, this chapter is devoted to benchmarking and sensitivity analysis. The central question is twofold: at first to what extend the results from this study are comparable to the results from other studies. Second, how the results from the analysis change if parameters in the model are changed. The first question will be answered in section 2, where the results from this study are compared to the results obtained by a study from General Motors. Section 3 and 4 are dedicated to the second question. In section 3, some parameters in a number of fuel chains are changed. The changes involve transportation distances and modes of transportation, but also properties of the primary inputs. In section 4, the influence of emissions of methane and nitrous oxide on the total greenhouse gas emissions is investigated. In this section, the question is answered whether it is important or not to have accurate data on emissions of methane and nitrous oxide. In section 5, the results are summarised and some conclusions are drawn.

11.2 Comparison of results with the results from another study

In this section, the results obtained by this study will be compared to results obtained by a study performed by General Motors [GM Europe, 2002]. The study by General Motors is targeted at Europe. It is by many seen as a major publication in the field of WTW analyses. For this reason the General Motors study has been chosen to compare the results of this study with. Five out of eight pathways modelled in this study are also completely modelled in the study performed by General Motors. These are the diesel fuel chain, the gasoline fuel chain, the CNG fuel chain and both FT diesel fuel chains. The GM study does not include the LPG fuel chain and the ethanol from sugary biomass fuel chain. The ethanol from cellulosic biomass is partly included in the General Motors study. The WTT part is included, but instead of using ethanol in a spark ignition engine as this study does, the General Motors study uses ethanol in a fuel cell. These powertrains are very different and therefore can not be compared. However, the WTT results for the ethanol from cellulosic biomass fuel chain from the General Motors study are included in the comparison. In the General Motors study, byproducts are accounted for according to Avoided Primary Energy and Emissions principles. Therefore the results from the General Motors study are compared with the results according to the Avoided Primary Energy and Emissions method from section 10.2 in this study.

As can be seen in table 11.1, the results from the General Motors study and this study are compared at four aspects: the WTT energy use, the TTW energy use, the WTW energy use and the WTW results relative to the results for gasoline. As for the WTT results, the results in some fuel chains are quite similar, but in other fuel chains rather large differences exist. For the diesel fuel chain, the results are very close. In the gasoline fuel chain, the difference between the results of both studies is 0,10 MJ per MJ of gasoline. This is primarily due to the losses in the refinery. The General Motors study assumes the total losses in the refinery to equal only 0,10 MJ per MJ of gasoline. In this study, the refinery uses 0,15 MJ of process energy. Including the production of the process fuels brings the total primary energy use due to refining of crude oil to gasoline to 0,20 MJ.

	[GM Europe, 2002]				This study			
	WTT (MJ_{prim}/ MJ)	TTW (MJ / km)	WTW [10] (MJ_{prim}/ km)	Relative to gasoline	WTT (MJ_{prim}/ MJ)	TTW (MJ / km)	WTW (MJ_{prim}/ km)	Relative to gasoline
Diesel	1,12[1]	1,96[6]	2,20	77,6	1,14	2,51	2,87	77,8
Gasoline	1,16[1]	2,44[7]	2,83	100,0	1,26	2,93	3,69	100,0
LPG	-	-	-	-	1,14	2,93	3,34	90,5
CNG	1,12[2]	2,23[8]	2,50	88,2	1,23	3,10	3,79	102,7
FT diesel (ng)	1,69[3]	1,92[9]	3,24	114,6	1,65	2,59	4,27	115,7
FT diesel (w. bio)	2,23[4]	1,92[9]	4,28	151,3	1,86	2,59	4,82	130,6
Ethanol (w. bio)	2,99[5]	-	-	-	2,41	2,98	7,18	194,6
Ethanol (s. bio)	-	-	-	-	1,44	2,98	4,28	116,0

Table 11.1: comparison of results obtained by General Motors and this study

[1]: sulphur content < 10 ppm

[2]: EU natural gas mix, p_{in}=4,0 MPa

[3]: from remote location

[4]: HCL, diesel/naphta from residual woody biomass via FT synthesis

[5]: E100, enzymatic hydrolysis of lignocellulose (plantation of poplar)

[6]: DI (direct injection) diesel MTA (automated manual transmission)

[7]: gasoline MTA

[8]: monofuel CNG ICE MTA

[9]: FT diesel MTA

[10]: calculated as the products of the WTT and TTW number

In the CNG fuel chain, the difference between the results from the General Motors study and this study equals 0,11 MJ. That means that in this study, the amount of energy consumed in the fuel chain system is estimated to be twice as much as in the General Motors study. However, direct process fuel use in this study equals 0,12 MJ. The remainder 0,11 MJ of primary inputs comes from the production of the process fuels. The reason that the production of the process fuels is so energy-intensive is that a lot of electricity is used. The production and distribution of electricity require over 2 MJ per MJ of electricity. The influence of the choice of process fuels on the results in the CNG fuel chain will be discusses more thoroughly in section 4.

The results of both studies in the FT diesel from natural gas fuel chain are almost similar. The results in both studies for the other FT diesel fuel chain are quite different, however. Like with the gasoline fuel chain, the difference can be almost entirely subscribed to the conversion step. In this study, the direct primary input in the conversion step is assumed to equal 1,45 MJ per MJ of FT diesel. The General Motors study assumes energy losses as low as 1,14 MJ per MJ of FT diesel. It could be that this difference is due to the way in which byproducts are accounted for. The General Motors study does state that byproducts are accounted for according to the Avoided Primary Energy and Emissions principles, but does not mention what quantities of byproducts are produced and how exactly the Avoided Primary Energy and Emissions are calculated. In the ethanol fuel chain the differences between the General Motors study and this study are again quite large, but now it is the other way around: the General Motors predicts energy use to be higher than this study does. The difference can again be contributed as good as entirely to the conversion step.

For the Tank to Wheel data, the General Motors study consequently assumes energy use to be lower than this study does. This is because both studies use different driving cycles. The data from TNO that are used in this study are based on real-world driving behaviour. The driving cycle consists of representative parts of urban, rural and highway driving, with representative driving dynamics, and includes effects of cold start at representative ambient conditions in the Netherlands. In the General Motors study, the EZE-cycle is used, which is the standard driving cycle for type approval tests. This cycle is not representative for real-life use of vehicles. For all fuels, the data from General Motors are lower than those from the TNO-study.

Because the estimates of the General Motors study are lower than the results in this study, both in the WTT part and in the TTW part of the fuel cycle, the WTW results are also lower. Given these differences, it is not strange that the results in the uttermost left columns differ, too. We see in table 11.1 that the ratio between diesel and gasoline is as good as equal in both studies. In the case of CNG, the GM study predicts the WTW results to be better than those of gasoline, whereas this study predicts energy use to be higher for CNG than for gasoline. The difference lies in the TTW data. There is also a big difference in the FT diesel from cellulosic biomass fuel chain, although in this case this study is more optimistic than the GM study. In this fuel chain, the difference lies mainly in the WTT part, which this study assumes to be more efficient than the GM study does.

The study by General Motors not only looks at energy flows but also at emissions. However, the study only provides data on total greenhouse gas emissions. These data are compared with the data obtained in this study. An overview of all data is provided in table 11.2. For the WTT data, the general picture equals that of the energy flows: the data provided by the General Motors study are more optimistic than the data resulting from this study. In the case of the CNG fuel chain, the emissions are very depending on the use of process fuels, as we will see later on in this chapter. In the TTW part, the difference between the results from General Motors and this study can be explained by the fuel economy. General Motors assumes that less fuel is needed to travel one unit of distance than this study does, and consequently the emissions predicted by General Motors are lower than those from this study are. Overall, the WTW emissions predicted by General Motors are lower than those predicted by this study.

As for the emissions relative to gasoline, the General Motors predicts better performances for the CNG fuel chain and both FT diesel fuel chains than this study does. In the General Motors study, CNG shows better results than diesel, which is not the case in this study. The largest difference lies within the FT diesel from natural gas fuel chain: the General Motors study predicts that this fuel chain performs better than gasoline, while this study predicts the emissions to be over 40% higher than the emissions from the gasoline fuel chain. For both the WTT part as the TTW part, the General Motors study is more optimistic than this study is.

	[GM Europe, 2002]				This study			
	WTT (g/MJ_{prim})	TTW (g/km)	WTW [10] (g/km)	Relative to gasoline	WTT (g/MJ_{prim})	TTW (g/km)	WTW (g/km)	Relative to gasoline
Diesel	10,2[1]	159[6]	179,0	82,5	10,9	185	212,6	78,4
Gasoline	13,1[1]	185[7]	217,0	100,0	21,9	216	271,3	100,0
LPG	-	-	-	-	19,9	195	245,0	90,3
CNG	7,9[2]	131[8]	148,6	68,5	20,5	176	236,5	87,2
FT diesel (ng)	29,8[3]	140[9]	197,2	90,9	63,5	185	381,8	140,7
FT diesel (w. bio)	-61,7[4]	140[9]	21,5	9,9	-68,0	185	51,4	18,9
Ethanol (w. bio)	-55,7[5]	-	-	-	-76,2	214	52,6	19,4
Ethanol (s. bio)	-	-	-	-	-7,0	214	136,3	50,2

Table 11.2: comparison of greenhouse gas results obtained by General Motors and this study
For footnotes: see table 11.1

11.3 Sensitivity analysis

So far, eight fuel chains of transportation fuels have been modelled. For each fuel chain, a 'base case' has been determined in chapter 5. However, these 'base cases' are not the only possible fuel chain definitions. There exist many variations, some of which will be investigated in this section. There are four fuel chains for which alternatives will be investigated: the CNG fuel chain and all biomass-based fuel chains. The cases that will be examined in this section are:

<u>CNG from natural gas</u>: four variations to the CNG fuel chain are discussed in this chapter:
- Natural gas from a high-calorific European mix. The natural gas is transported over a medium distance by pipeline.
- Natural gas from a high-calorific Russian natural gas. This natural gas is transported over a long distance.
- High-calorific natural gas from the Middle East. This natural gas too, is transported over a long distance.
- Low-calorific natural gas from the Dutch average natural gas mix. In this case, the change in parameters is not in transportation distance or composition of the natural gas, but in compression stage. In stead of compressing natural gas with electricity, it is compressed using natural gas.

<u>Fischer-Tropsch diesel from cellulosic biomass</u>: in stead of growing the biomass in the Netherlands, two alternatives are investigated in which biomass is grown in the Baltic states:
- Biomass is grown in the Baltic states and transported to the Netherlands by ship. It is converted to FT diesel in the Randstad area in the Netherlands and distributed all over the Netherlands by truck.
- Biomass is grown in the Baltic states and transported to a plant in the Baltic states. There it is converted, after which it is transported to the Netherlands by ship and distributed here by truck.

<u>Ethanol from cellulosic biomass</u>: the same as the FT diesel chain: two alternatives in which biomass is grown in the Baltic states:
- Biomass is grown in the Baltic states and transported to the Netherlands by ship. It is converted to ethanol in the Randstad area in the Netherlands and distributed all over the Netherlands by truck.
- Biomass is grown in the Baltic states and transported to a plant in the Baltic states. There it is converted, after which it is transported to the Netherlands by ship and distributed here by truck.

<u>Ethanol from cellulosic biomass</u>: again the variables to be altered are the places where the biomass is grown and where it is converted to ethanol:
- Biomass is grown in the Baltic states and transported to the Netherlands by ship. It is converted tot ethanol in the Randstad area in the Netherlands and distributed all over the Netherlands by truck.
- Biomass is grown in the Baltic states and transported to a plant in the Baltic states. There it is converted, after which it is transported to the Netherlands by ship and distributed here by truck.

For all cases, the new WTT and WTW results are calculated without accounting for byproducts. In this way, the influence of changing parameters on the energy flows through the fuel chain is best represented.

Variations to the CNG fuel chain

In the base case of the CNG fuel chain, low calorific natural gas is used. This natural gas is taken from the average mix as is currently used in the Netherlands. However, if natural gas would be introduced as transportation fuel on a large scale, this would probably be taken not only from the current Dutch mix, but also from other gas fields. These gases have other heating values, other carbon contents and are transported over another distance. In this section, it is investigated how the choice of natural gas influences the WTW results.

Natural gas from the EU-mix

The first mix of interest here is the current mix that is used in the European Union. According to the study performed by General Motors, five countries recover over 90 percent of all natural gas used in the European Union [GM Europe, 2002]. These countries are the United Kingdom, Norway, Algeria, Russia and the Netherlands. It is assumed that the mix of natural gases of these five countries is representative for all natural gas in the European Union. With the shares of each gas, the LHV and the carbon dioxide equivalent content, the properties of the EU-mix can be calculated. The LHVs and the carbon dioxide equivalent contents have been obtained from the study by General Motors. The average transportation distance is obtained from the internet [How far is it?, 2003]. The properties of the individual gases and of the EU-mix can be found in table 11.3.

As we see in the table, the average transportation distance in the Netherlands is assumed to equal 150 kilometers. This seems much in a country as small as the Netherlands, but all natural gas is distributed from Groningen. Groningen is not situated centrally in the Netherlands and therefore the distribution of natural gas is higher than, for example, gasoline. With the data on energy use needed to transport natural gas in the Netherlands from section 6.2, it is calculated that transportation of natural gas of the EU-mix consumes 0,023 MJ of process fuels per MJ of natural gas transported. It is assumed that the division of process energies over electricity and natural gas is equal to the division of process energies needed to transport natural gas from the Dutch mix. With the LHV of the EU-mix, the carbon dioxide equivalent content of the EU-mix, the total amount of process energy and the division of process energies, WTW results can be calculated. These are depicted in table 11.4. As we see in the table, the WTW use of natural gas and coal increase. The use of coal increases because the electricity that is used during transportation has been generated using coal. Because the increase in energy use is of fossil origin, the total greenhouse gas emissions increase, too.

	Share[1]	LHV[1] (MJ/m^3)	CO_2 -content[1] (gCO_2/MJ)	Average transportation distance to the Netherlands[2] (km)
Algeria	14,4	33,80	55,28	1800
Netherlands	22,0	31,50	56,11	150
Norway	11,8	38,80	57,22	1000
Russia	21,4	35,90	55,28	7000
United Kingdom	30,4	38,80	57,22	750
Average EU-mix	-	35,85	56,28	2150

Table 11.3: some properties of the average EU-mix of natural gas

Source 1: [GM Europe, 2002]

Source 2: [How far is it?, 2003]

	Base case (MJ$_{prim}$/km)	Natural gas from EU mix (MJ$_{prim}$/km)	Natural gas from Middle East (MJ$_{prim}$/km)	Natural gas from Russia (MJ$_{prim}$/km)
Crude oil	0,05	0,06	0,06	0,07
Natural gas	2,98	3,62	3,67	3,90
Coal	0,20	0,24	0,25	0,28
Total	3,23	3,93	3,98	4,24
Total greenhouse gas emissions (gCO_2-eq./km)	*201,5*	*245,3*	*252,2*	*261,5*

Table 11.4: WTW results for four gas compositions and according transportation distances in the CNG fuel chain

Natural gas from the Middle-East

An alternative to the use of natural gas from the EU-mix is the use of natural gas from the Middle East. In this case, natural gas from Iran is used. This natural gas has a LHV of 38,80 MJ/m^3. The carbon dioxide equivalent content of the natural gas equals 57,22 gCO_2/MJ. With an average transportation distance of 4000 kilometers [How far is it?, 2003], the energy use during transportation becomes 0,042 MJ per MJ of natural gas. The same composition of process fuels is assumed as in transportation of Dutch natural gas. With these data, new WTW results can be calculated. These can be seen in table 11.4. Due to the increased transportation distance and consequent increased energy use as compared to natural gas from the EU-mix, the WTW energy use and emissions have increased.

Natural gas from Russia

The third natural gas source to be included in the sensitivity analysis is natural gas from Russia. This natural gas has a heating value of 35,90 MJ/m^3 and carbon dioxide equivalent content of 55,28 gCO_2/MJ. The average distance that has to be traveled by Russian natural gas in order to reach the Netherlands equals 7000 kilometers. With this distance, energy use rises up to 0,075 MJ per MJ of transported natural gas. Leakages are not included in this number so actual energy use will probably be even higher. The composition of process fuels is assumed to equal the composition of process fuels in the Dutch natural gas mix. The new WTW energy use becomes 4,24 MJ/km. The new greenhouse gas emissions become 261,5 gCO_2-eq./km.

Compression by natural gas

The origin of natural gas and its heating values are not the only important variables in the CNG fuel chain. The choice of process fuel is very important, too. In literature there is especially much ambiguity about the process fuels that are used during compression. Some studies mention that compression takes place entirely by natural gas, some say it takes place entirely by electricity and there are also studies that assume a mix of natural gas and electricity. In the base case of this study, it was assumed that compression takes place by electricity. In this variation to the base case, it is assumed that compression takes place by natural gas.

By changing the fractions of process fuels in the data on the compression step in the CNG fuel chain, WTW results can be calculated for compression by natural gas. The results of the calculation can be found in table 11.5. As we see, compression by natural gas is much more efficient than compression by electricity. This is because the production of natural gas is much more efficient than the production of electricity. In the same way, compression by natural gas leads to much lower greenhouse gas emissions than compression by electricity.

	Base case (MJ_{prim}/km)	Compression by natural gas
Crude oil	0,06	0,02
Natural gas	3,50	3,48
Coal	0,23	0,06
Total	3,79	3,56
Total greenhouse gas emissions (gCO_2-eq./km)	*236,5*	*213,0*

Table 11.5: WTW results for compression with electricity and natural gas

Variations to the FT diesel from cellulosic biomass fuel chain

Growing in the Baltic states, conversion in the Netherlands

In the first variation to the FT diesel chain, only the second step in the fuel chain changes. Transportation no longer takes place just by truck but by a combination of truck and ship. First the biomass is transported from the plantation to a port by truck and next it is transported to the Netherlands. For the transportation by truck in the Baltic, the same distance is assumed as the distance in the Netherlands, which is 240 kilometers two-way. The energy use of a ship is determined at 3,015 $J/MJ_{crude\ oil}$-km [Gave, 1999]. With the fuel specifications from appendix D we find that this number equals 129,3 $J/kg_{crude\ oil}$-km. It is assumed that the energy needed to transport a product correlates with the weight of the transported product. This means that it takes as much energy to transport 1 kg of crude oil as it takes to transport 1 kg of biomass. Again appendix D is used to find that it takes 7,196 J to transport 1 MJ of biomass over a distance of 1 kilometer. The distance between the Baltic states and the Netherlands is obtained from the internet [How far is it?, 2003] and equals 1500 km one-way. It is assumed that the kind of cargo-ship that transports biomass can find another cargo in the Netherlands. Therefore only the one-way distance has to be assigned to biomass. With this information, the total amount of energy needed to transport 1 MJ of biomass can be calculated to equal 0,011 MJ. Because ships sail on heavy fuel oil, it is assumed that heavy fuel oil is the only relevant process fuel in this step. This energy use is on top of the energy use by truck. The new WTW results can be found in table 11.6. As we see in the table, the new WTW energy is 0,08 MJ higher than the old one. The total increase comes from crude oil. Because crude oil is a fossil fuel, the greenhouse gas emissions increase, too.

Growing in the Baltic states, conversion in the Baltic states

In the second variation, biomass is not only grown in the Baltic, but also converted there. In this case, biomass is grown in the Baltic and transported to a central plant in the Baltic. It is assumed that the plant is situated in the area where cultivation of biomass takes place and that the distance between the plantation and the FT plant equals 240 kilometers two-way. After conversion in the Baltic states, the biomass is distributed. This includes a transport of 1500 kilometers by ship, before distribution in the ordinary way from the Randstad area. With the fuel specifications of appendix D, it can be calculated that the transport of FT diesel by ship consumes 3,005 $J/MJ_{FT\ diesel}$-km. The energy needed to transport the FT diesel from the Baltic to the Netherlands becomes 0,008 MJ. This number is on top of the 0,005 MJ that was already needed. With these data, the new WTW results can be calculated. They are shown in table 11.6. As the table shows, it is energetically more efficient to produce the FT diesel in the Baltic and to transport the FT diesel to the Netherlands than to transport biomass to the Netherlands and convert it here. Due to the increased transportation distances, both cases require more energy than the base case. The use of more fossil energy brings along increased emissions. As we see in figure 11.6, the total greenhouse gas emissions increase in both cases. The increase is largest in the case where biomass is transported by ship.

	Base case (MJ$_{prim}$/km)	Biomass grown in Baltic, conversion in Netherlands (MJ$_{prim}$/km)	Biomass grown in Baltic, conversion in Baltic (MJ$_{prim}$/km)
Crude oil	0,50	0,58	0,55
Natural gas	0,07	0,07	0,07
Coal	0,02	0,02	0,02
Biomass	6,34	6,34	6,34
Total	6,93	7,01	6,98
Total greenhouse gas emissions (gCO_2-eq./km)	*51,4*	*57,2*	*54,6*

Table 11.6: WTW results for three cases in the FT diesel from cellulosic biomass fuel chain

Variations to the ethanol from cellulosic biomass fuel chain

Growing in the Baltic states, conversion in the Netherlands

The same variations that have been applied to the FT diesel from cellulosic biomass fuel chain, are also applied to the ethanol from cellulosic biomass fuel chain. In the first case, biomass is grown in the Baltic states. It is transported to a port by diesel truck. The average transportation distance equals 240 kilometers two-way. This transportation consumes 0,016 MJ diesel per MJ biomass. After arrival at the port, it is transported by ship to the Netherlands. The distance equals 1500 kilometers one-way. Only the one-way distance is assigned to biomass because it is assumed that the ship can pick up another cargo in the Netherlands. Heavy fuel oil is the only transportation fuel. 0,011 MJ of it is needed to transport 1 MJ of biomass. With this information, the new WTW results can be calculated. They are shown in table 11.7. Like with FT diesel from cellulosic biomass, the use of crude oil and the total greenhouse gas emissions increase.

Growing in the Baltic states, conversion in the Baltic states

In the second case biomass is grown in the Baltic states. After harvesting, it is transported to a central ethanol plant near the biomass plantation. The average distance is assumed to equal 240 kilometers two-way. Transportation takes place entirely by diesel truck. The biomass is converted to ethanol in the Baltic. From the ethanol plant, the ethanol is transported to a port. The distance is assumed to equal 240 kilometers two-way. From the port, the ethanol is transported by ship to the Netherlands. In the Netherlands, it is distributed as usual. The new WTW results are shown in table 11.7. As we can see in the table, energy use and emissions are higher than they are in the base case, but somewhat lower than they are when biomass is grown in the Baltic but converted to ethanol in the Netherlands.

	Base case (MJ$_{prim}$/km)	Biomass grown in Baltic, conversion in Netherlands (MJ$_{prim}$/km)	Biomass grown in Baltic, conversion in Baltic (MJ$_{prim}$/km)
Crude oil	0,57	0,65	0,63
Natural gas	0,08	0,08	0,07
Coal	0,03	0,03	0,03
Biomass	7,01	7,01	7,01
Total	7,69	7,76	7,74
Total greenhouse gas emissions (gCO_2-eq./km)	*52,6*	*58,9*	*57,3*

Table 11.7: WTW results for three cases in the ethanol from cellulosic biomass fuel chain

	Base case (MJ$_{prim}$/km)	Biomass grown in Baltic, conversion in Netherlands (MJ$_{prim}$/km)	Biomass grown in Baltic, conversion in Baltic (MJ$_{prim}$/km)
Crude oil	0,53	0,60	0,55
Natural gas	0,61	0,61	0,61
Coal	0,13	0,14	0,14
Biomass	5,73	5,72	5,72
Total	7,00	7,07	7,01
Total greenhouse gas emissions (gCO_2-eq./km)	*136,3*	*141,4*	*138,0*

Table 11.8: WTW results for three cases in the ethanol from sugary biomass fuel chain

Variations to the ethanol from sugary biomass fuel chain

Growing in the Baltic states, conversion in the Netherlands

The same cases are repeated, but this time with sugary biomass. With the fuel specifications from appendix D, it is calculated that transportation of sugary biomass per ship consumes 7,607 J/MJ$_{biomass}$-km. With this information, the new WTW results can be calculated. They are shown in table 11.8. Like with the other fuel chains, the use of crude oil increases. Consequently, the greenhouse gas emissions increase.

Growing in the Baltic states, conversion in the Baltic states

In the second case, biomass is grown and converted to ethanol in the Baltic states. The ethanol is transported to the Netherlands by truck and by ship, and distributed here by truck. The new WTW results for this case are also shown in table 11.8. As we see in the table, the base case in which biomass is grown and converted in the Netherlands is the most efficient and results in the least emissions. Growing biomass in the Baltic states, transporting it to the Netherlands and converting it here to ethanol is least efficient.

11.4 The influence of uncertainty in data on emissions of methane and nitrous oxide on total greenhouse gas emissions

As we have seen in the modeling of data on emissions in chapters 6 to 9, data on emissions of methane and nitrous oxide are very often poorly mapped. They are incomplete and contain a high level of uncertainty. In some cases, the value for an emission mentioned by one source is more than 10 times as high or as low as the value mentioned by another source in literature. On the other hand, the figures in chapter 10 show us that carbon dioxide is by far the most important greenhouse gas emission. It could be therefore, that it doesn't differ so much whether the numbers that are used for emissions of methane and nitrous oxide are a little bit higher or lower. We will find out in this section if this is the case or not.

In this section we look at the influence of the height of emissions of methane and nitrous oxide on the total greenhouse gas emissions. This is done by determining confidence intervals for the emissions in the individual steps in all fuel chains, both of the 8 fuel chains of the transportation fuels and the fuel chains of the process fuels that have been described in chapter 9. For those steps where there are data available from several sources, the lowest value mentionned in literature is taken as lower bound of a confidence interval whereas the highest value found in literature is taken as upper bound. The average of the lower bound and the upper bound is taken as best estimate. If there is only one source that provides data on emissions, then the number mentioned by this source is taken as best estimate. The lower bound is determined as the best estimate minus 5 percent; the upper bound as the best estimate plus 5 percent. By calculating equation (29) of chapter 4 with all the lower bounds from the individual steps, lower bound values for the WTT emissions can be found. Repeating equation (29) with all the values of the best estimates results in WTT values for the best estimates. Finally, all upper bound values of all emissions are used to calculate upper bound values for the WTT emissions. For the TTW emissions, the values that are used in chapter 6 to 9 are used as best estimate. The upper and lower bound are calculated by respectively adding or subtracting 5 percent of the best estimate. Multiplying in each fuel chain the lower bound value of the WTT results with the lower bound value of the TTW results brings the lower bound of the WTW result. The same goes for the values of the best estimates and the values of the upper bounds. With the results from these calculations, figure 11.2 to 11.4 can be put together. The upper and lower bounds of the confidence intervals are depicted by the horizontal black markers. The height of the confidence interval is denoted by the vertical black line. Figure 11.1 shows the carbon dioxide emissions as a reference.

Figure 11.2 denotes the confidence intervals for methane emissions. As we see in the figure, the confidence interval is in most fuel chains quite substantial. In the LPG fuel chain, the upper bound is even 46 percent higher than the best estimate. However, if we compare the absolute values of the methane emissions with the absolute values of the carbon dioxide emissions, we see that the methane emissions are very small compared to the carbon dioxide emissions. This means that the confidence interval of methane will be very small on the total amount of greenhouse gas emissions. In the case of the nitrous oxide emissions, depicted in

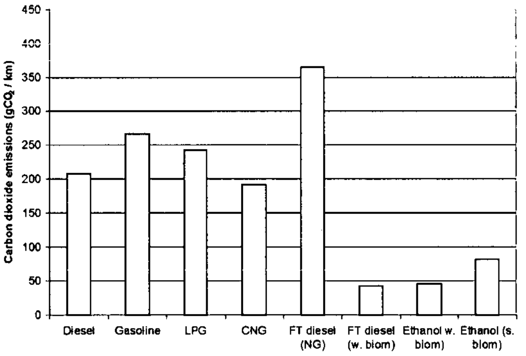

Figure 11.1: carbon dioxide emissions in the WTW chain[5]

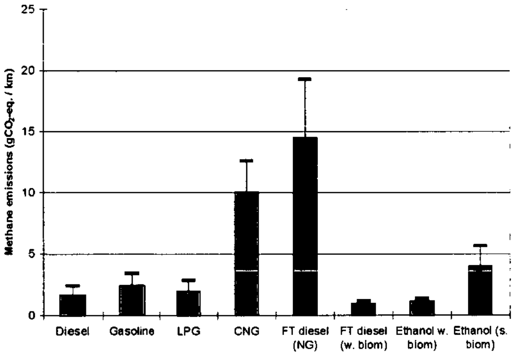

Figure 11.2: methane emissions in the WTW chain[5]

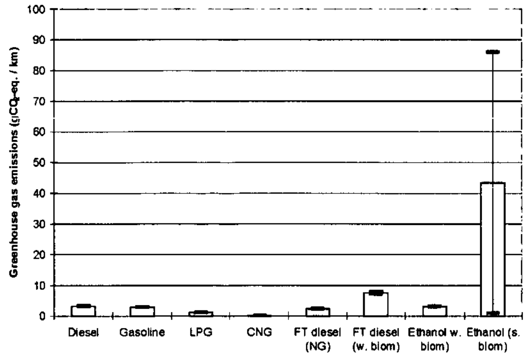

Figure 11.3: nitrous oxide emissions in the WTT chain[5]

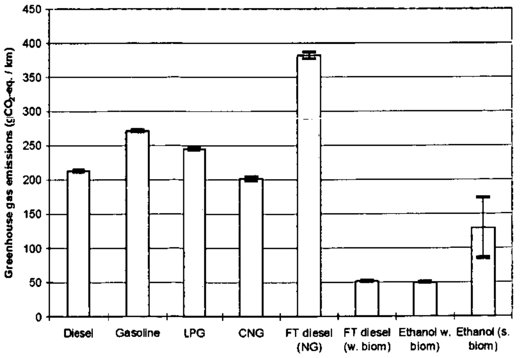

Figure 11.4: greenhouse gas emissions in the WTT chain[5]

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[5] All results are without crediting of byproducts

figure 11.3, the confidence intervals are small, except that of the fuel chain that is based on sugary biomass. Nitrous oxide emissions are very small as compared to emissions of carbon dioxide. Therefore the confidence intervals, that are even smaller, are almost negligible. In figure 11.4 the carbon emissions, methane emissions and nitrous oxide emissions have been summed into the total greenhouse gas emissions. In all fuel chains but one we see that the confidence intervals are very small. They don't drastically affect the outcomes, as we had anticipated. Only in the ethanol from sugary biomass fuel chain the confidence is large. This is due to two reasons: first of all the net carbon dioxide emissions are low in this fuel chain and therefore the shares of methane and nitrous oxide emissions are larger. Second, the confidence interval of nitrous oxide is very large. For this fuel chain, more data are needed to make a reliable estimate of the emissions. For the other fuel chains, the uncertainty in data on emissions of methane and nitrous oxide do not seriously affect the outcomes. Therefore the uncertainty is acceptable.

11.5 Summary and conclusions

This chapter has taken a closer look at the results from the model as presented in chapter 10. In section 2, the results from this study have been compared with the results obtained by a study from General Motors. It turned out that in most cases, General Motors assumes a higher efficiency in the conversion step than this study does. Therefore almost all WTT results are more positive than the results from this study. For the TTW efficiencies, General Motors has used a standard driving cycle. The TTW efficiencies used in this study are also based on a standard driving cycle, but the efficiencies have been corrected with more urban driving circumstances and a cold start effect, to better represent real world driving behaviour. The efficiency of this real world driving behaviour is lower than the efficiency measured in the standard driving cycle. Because both the WTT results and the TTW results of the General Motors study tend to be lower than the results from this study, the WTW results are lower, too.

Section 3 contains calculations on alternative cases for a number of fuel chains. For the CNG fuel chain, results have been calculated for three high-calorific natural gases: natural gas from the current EU-mix, natural gas from the Middle East and natural gas from Russia. The main finding is that energy use and emissions increase with increasing transportation distance. From the last case on the CNG fuel chain we learn that using natural gas to compress the CNG in stead of electricity can seriously cut back on energy and emissions. By using natural gas during compression, the WTT energy use drops to 1,14 MJ per MJ_{CNG} in stead of the current 1,22 MJ/MJ_{CNG}.

In the biomass fuel chains, the origin of the biomass has been changed. For each biomass-based fuel chain two cases have been calculated: in the first case biomass is grown in the Baltic states, transported to the Netherlands, and converted and distributed here. In the second case, biomass is grown and converted to transportation fuel in the Baltic states and only afterwards transported to the Netherlands. For all three fuel chains the results were equal: growing biomass in the Netherlands is the most efficient and results in the least emissions, followed by growing biomass in the Baltic states and converting it in the Baltic states. It must be remarked though that the differences are not very large, in neither of the fuel chains.

Finally, section 4 has been dedicated to emissions of methane and nitrous oxide. Very often these emissions are poorly mapped or incomplete. To assess the effects of these ambiguities on the total greenhouse gas emissions, the emissions of methane and nitrous oxide have been calculated using confidence intervals. This analysis has shown that, except for emissions in the ethanol from sugary biomass fuel chain, the effects of variations in the emissions of methane and nitrous oxide are very small. Therefore the assessment of total greenhouse gas emissions is not badly damaged by some uncertainties in the emissions of methane and nitrous oxide. Only in the ethanol from sugary biomass fuel chain, where emissions of nitrous oxide have high levels, the influence of emissions other than carbon dioxide can be clearly distinguished. In this fuel chain, more research is needed in order to better determine the exact height of the emissions.

12 Operating costs

12.1 Introduction

Whether or not a fuel can be successfully introduced and sustained depends not only on the efficiency with which it is produced and the emissions that are released during production and use, but also on the costs of the fuel. In this chapter, an indication is made of the costs of the fuel chains that are included in the model. The costs that are included in the assessment are all operating costs, that is production costs and capital costs. The costs of buying and maintaining the vehicle are left beyond consideration, which means that the TTW costs are assumed to be zero in this study. The final outcome of the calculations will be lower than what a consumer has to pay for the fuel at the refueling station. This is because the price that one has to pay for the fuel at the refueling station includes taxes and profits, both of which may be quite high in some cases.

In section 2, the operating costs of diesel, gasoline and LPG are assessed. In section 3, CNG and Fischer-Tropsch (FT) diesel based on natural gas are discussed. Section 4 is dedicated to FT diesel based on cellulosic biomass, ethanol from cellulosic biomass and ethanol from sugary biomass. Finally, the most important results are summarized in section 5

12.2 Crude oil based fuels: diesel, gasoline and LPG

In chapter 6, three fuel chains based on crude oil have been discussed: the production of diesel from crude oil, the production of gasoline from crude oil and the production of LPG from crude oil. We have seen that all three fuel chains consist of four steps: extraction of crude oil, transportation of crude oil from the place of extraction to the refinery, production of diesel, gasoline or LPG and finally distribution. However, in calculating the production costs of diesel, gasoline and LPG, only three stages are distinguished: the purchase of crude oil by the refinery, production of the fuel and distribution [IEA, 1999], [Weiss, 2000]. No separate costs are calculated for the extraction step and the transportation step. Instead, cost calculations start with the price that the refinery has to pay to purchase the crude oil.

The costs of lifting and transportation, together with the profit margin of the oil company, constitute the price that has to be paid for a barrel of crude. Crude oil prices have a high uncertainty factor. In the last 20 years, costs have varied between 10 US$ per barrel and 40 US$ per barrel [Weiss, 2000]. Therefore it is very hard to predict how prices will develop in the future. Weiss assumes an average price of 22 US$/bbl, the International Energy Agency assumes an average price of 17 to 20 US$/bbl and $(S\&T)^2$ Consultants assumes 18 US$/bbl [Weiss, 2000]; [IEA, 1999]; [$(S\&T)^2$, 2003]. This study assumes their average, which is 19,5 US$/bbl. With the volume of a barrel of crude of 159 liter, the energy content of crude oil from appendix D and an assumed 5-year average exchange rate of 0,972 US$/€ [Marketwatch, 2003], the price of crude comes down to 3,48 €/$GJ_{cr.\ oil}$.

The second component of the production costs consists of the costs of production made by the refinery. These consist of variable and fixed operating costs and maintenance costs. A refinery always produces a mix of diesel, gasoline and LPG and therefore the costs made by the refinery have to be divided over the various products. In chapter 6 we have seen that the assignment of process energies to the various products is based on the amount of processing a product needs. In the assignment of costs, this strategy is only partly followed. In many refineries, diesel and gasoline are the main outputs of the refinery with LPG being merely an unavoidable byproduct for which refineries are glad to find a buyer. Therefore the part of the costs assigned to LPG is less than proportionally. The remaining part of the costs is divided over diesel and gasoline, whereby the amount of processing is taken into account. In this way, the International Energy Agency assigns 5,56 €/GJ to diesel, 6,07 €/GJ to gasoline and 4,32 €/GJ to LPG [IEA, 1999]. Weiss mentions 1,68 €/GJ for diesel and 2,52 €/GJ for gasoline [Weiss, 2000]. Weiss doesn't mention costs for LPG. The Energy Information Administration mentions estimates of operating costs of 1,20 €/GJ for diesel and 2,19 €/GJ for gasoline [EIA, 2000]. When these three sources are compared, the numbers mentioned by the International Energy Agency seem very high. This study therefore calculates with the average value of only the data from Weiss and the Energy Information Administration. This is 1,44 €/GJ$_{diesel}$ for diesel and 2,36 €/GJ$_{gasoline}$ for gasoline. For LPG, a value of 1,12 €/GJ$_{LPG}$ is assumed. This value is based on the ratio between the LPG refining costs and the diesel refining costs, both provided by the International Energy Agency, and the average refining costs for diesel as assumed in this study.

The last source of costs is the distribution of diesel, gasoline and LPG. In comparison with the other costs, these costs are relatively stable. The International Energy Agency estimates distribution costs to be 1,30 €/GJ for both diesel and gasoline [IEA, 2001]. The estimate of Weiss is with 1,21 €/GJ for diesel and 1,27 €/GJ for gasoline somewhat lower, but close enough to believe these data to be reliable [Weiss, 2000]. For this stage, the estimates mentioned by Weiss are used. The distribution costs of LPG are assumed to be equal to those of gasoline.

Now that the operation costs in the individual stages are known, they can be summed. The results of the summation are values for the WTT costs. Because the TTW costs are zero, the WTT costs are equal to the WTW costs based on energy content. However, because the refinery uses more than 1 unit of crude to produce 1 unit of transportation fuel, the costs for crude are multiplied with the amount of crude that is used in the production step. In the diesel fuel chain, 1,041 GJ of crude is used in the production step to produce 1 GJ of diesel. Therefore the costs of crude of 3,48 €/GJ are multiplied with 1,041. This brings the total costs for crude oil in the diesel chain to 3,62 €/GJ. Summed with the operating costs made in the refinery and the distribution costs, the WTT production costs of diesel equal 6,27 €/GJ. In the same way, the WTT production costs of gasoline and LPG are calculated. The gasoline fuel chain uses 1,113 GJ of crude to produce 1 GJ of gasoline which brings the total costs at 7,50 €/GJ. In the LPG fuel chain, with a crude oil consumption of 1,048 GJ per GJ of LPG, the total production costs equal 6,04 €/GJ. By multiplying these values with the energy consumption of respectively diesel, gasoline and LPG in the TTW part of their fuel chains, the WTW costs based on traveled distance can be calculated. These values are 0,016 €/km for diesel, 0,022 €/km for gasoline and 0,018 €/km for LPG. The most important results are summarized in table 12.1.

	Diesel (€/GJ$_{diesel}$)	Gasoline (€/GJ$_{gasoline}$)	LPG (€/GJ$_{LPG}$)
Crude oil costs	3,62	3,87	3,65
Production costs	1,44	2,36	1,12
Distribution costs	1,21	1,27	1,27
WTT	6,27	7,50	6,04
WTW (€/km)	*0,016*	*0,022*	*0,018*

Table 12.1: summary of data on production costs for diesel, gasoline and LPG

12.3 Natural gas based fuels: CNG and FT diesel

Compressed Natural Gas

The next fuel chain included in the model is Compressed Natural Gas (CNG). As we have seen in chapter 7, the production of CNG consists of four steps; recovery of raw natural gas, processing of natural gas, transportation from the point of recovery and processing to the refueling station and finally compression. In the assessment of costs the recovery of raw natural gas and processing of raw gas to pipeline quality gas are often treated together.

The costs for recovery of raw natural gas and processing it to pipeline quality include costs for labour, for maintenance of machinery and equipment and costs for materials, supply and consumed energy. The International Energy Agency estimates the costs for recovery and production at 4,14 €/GJ [IEA, 2001]. Another source from the International Energy Agency mentions a number that is somewhat higher, namely 4,42 €/GJ [IEA, 1999]. From the website from Gasunie Trade and Supply, the company that takes care of all transportation of natural gas in the Netherlands, we learn that the average price at which Gasunie Trade & Supply bought their natural gas equaled 13,5 eurocent per cubic metre [Gasunie b, 2003]. This equals 4,27 €/GJ. All three numbers indicate similar values. In the calculations made in this study, the value from Gasunie Trade & Supply are used.

The next stage for which costs can be determined is the transportation of natural gas. Natural gas is usually transported by pipeline. The construction of a pipeline requires huge investments that increase proportionally with the length of the pipeline. Therefore the number of pipelines is limited and so is their length: there exists no such thing as a pipeline around the world. So, unlike crude oil that is traded at a world market, natural gas is traded in regional markets. Four main trade markets can be distinguished: those of North America, Europe (including Russia), Asia/Pacific and Latin America [IEA, 2001]. In this study, only the European gas market is of importance. The costs for transportation of natural gas are partly built up of depreciation of the investments and partly of pipeline operating costs. The latter vary according to the number of compressor stations, local economic conditions such as labour cost and the rate of capacity utilisation [IEA, 2001]. The average transportation distance of Dutch natural gas is relatively small and therefore the costs are not very high. From the annual report of Gasunie Trade & Supply we learn that the difference between the natural gas purchases and natural gas sales equals 390 million Euro [Gasunie c, 2003]. Except for the company's profit of 36 million Euro, it is assumed that this difference can be entirely contributed to the costs involved in the transportation of natural gas. Dividing the costs over the sales volume results in a value for the transportation costs of 0,14 €/GJ [Gasunie c, 2003].

The natural gas has now arrived at the refueling station where it is compressed and fuelled into vehicles. The costs of this last step are estimated by Weiss to equal 4,12 €/GJ [Weiss, 2000]. According to a study by CH-IV however, these cost are only 1,26 to 2,95 €/GJ, which is considerably lower [CH-IV, 2003]. French indicates the costs for compression and refueling to equal 1,94 €/GJ [French, 1990]. From the last two sources, it is assumed that 2,00 €/GJ is a reasonable estimate.

	CNG ($€/GJ_{CNG}$)
Recovery and processing	4,29
Transportation	0,14
Compression	2,00
WTT	6,43
WTW (€/km)	*0,017*

Table 12.2: summary of data on production costs for CNG

With the estimate of the costs of compression, the data on the individual stages are completed. By summing these data, the WTT costs are obtained. The energy use in the fuel chain should be included in the summation. In order to have 1 unit of fuel in the tank of a vehicle, 1,004 units of natural gas of pipeline quality are needed. Therefore the costs of natural gas of pipeline quality are multiplied with 1,004. The losses during transportation are accounted for in the same way. Per unit of natural gas, 0,001 unit is lost during transportation. Therefore the costs of transportation are multiplied with 1,001. No relevant amounts of natural gas are lost during compression. Summing the costs in the way just described results in WTT costs of 6,43 €/GJ. With the fuel economy of a CNG fuelled vehicle, the costs per kilometer can be calculated. These equal 0,017 €/km. It must be remarked, though, that these costs depend heavily on the costs of transportation. In this case, the transportation distance is assumed to be small, which results in low overall costs for CNG. If the transportation distance increases, the costs go up rapidly. A summary of the results is provided in table 12.2.

Fischer-Tropsch diesel from natural gas

The fifth fuel chain discussed here is Fischer-Tropsch diesel (FT diesel) that is made from natural gas. We have seen in previous chapters that this fuel chain consumes a lot more energy than the four fuel chains discussed before. We will now find out whether the production of FT diesel is also expensive. The FT diesel fuel chain consists of five steps: recovery of natural gas, processing of natural gas to pipeline quality, transportation of natural gas to the Randstad area, production of FT diesel and finally distribution. The first three steps in the fuel chain are covered by two types of costs: those for recovery and processing of natural gas and those for transportation of natural gas. In the first part of this section we have seen that 4,27 €/GJ$_{\text{natural gas}}$ is a reasonable estimate for the costs of recovery and processing of natural gas. The costs of transportation have been estimated at 0,14 €/GJ$_{\text{natural gas}}$.

The next stage for which costs can be determined is the production step. A typical cost-breakdown for a FT-plant consists of five elements: cost for feedstock, for the production of syngas, for the conversion of syngas to products in the FT-reaction, cost for the upgrading of products and finally overall operating costs. Table 12.3 shows some data on the cost-breakdown of a FT-plant. All data are recorded in costs per barrel of product, whereby the barrel of product consists of a mix of diesel and other products. The electricity that is also produced in the FT-plant is already accounted for. As we see in the table, the purchase of the feedstock is included in two sources. Both sources however use associated natural gas or stranded natural gas. These are accumulations of natural gas with limited economical value. The natural gas used in this study is much more expensive. Therefore the data on the costs of the feedstock mentioned by Arthur D. Little and Gasco are left beyond consideration. Furthermore the data mentioned by Choi are quite high in comparison to the other sources, especially his estimate of the production costs of syngas. This number is left beyond

	Arthur D. Little, 1998 (€/barrel FT diesel)	Gasco, 1999 (€/barrel FT diesel)	Choi, 1997 (€/barrel FT diesel)	This study (€/barrel FT diesel)
Feedstock	3,8	3,7		
Syngas	6,3	5,1	9,7	5,7
FT reaction	3,3	3,2	3,3	3,3
Upgrading products	0,9	0,9	1,7	1,0
Operating costs	4,2	4,3	5,0	4,5
Total	18,5	17,2		
Total without feedstock	14,7	13,5	19,7	14,5

Table 12.3: data on the production costs of FT diesel

	FT diesel (ng) (€/$GJ_{FTdiesel}$)
Recovery and processing	6,29
Transportation	0,21
FT diesel production	2,67
Distribution	1,21
WTT	10,38
WTW (€/km)	*0,027*

Table 12.4: summary of data on production costs for FT diesel from natural gas (after accounting for byproducts)

consideration, too. The values that are assumed in this study are shown in the uttermost right column of table 12.3. The total costs for the whole production step are estimated at 14,5 €/barrel. With the product mix that was described in section 7.3 and the fuel specifications from appendix D, it can be calculated that the energy content of a barrel equals 5,44 GJ. By dividing the production costs evenly over the FT diesel and the byproducts we find production costs for 1 GJ of product of 2,67 €/GJ.

There is only 1 step left in the fuel chain for which the costs have to be assessed: the distribution step. FT diesel is distributed in the same way as diesel that is made from crude oil, namely by truck. Also, the transportation distance is comparable, for it is assumed that both the refinery and the FT plant are situated in the Randstad area. Therefore the distribution costs of FT diesel are identical to those of diesel made from crude oil, which is 1,21 €/$GJ_{FTdiesel}$.

In order to obtain the WTT costs, the costs of the individual steps have to be summed. However, the amount of energy that is used in the fuel chain has to be taken into account. The FT diesel fuel chain uses 2,289 units of natural gas of pipeline quality in order to deliver 1 unit of FT diesel to a vehicle. Therefore the costs for recovery and processing of natural gas have to be multiplied with 2,289. In the same way, the transportation costs have to be multiplied with 2,282. This brings the costs for the feedstock entering the production step at 10,10 €/GJ. However, not only diesel is produced in the production step. The diesel output equals only 64,4% of the total output of the step. According to the Ratio of Energy Content principles, only 64,4% of the feedstock costs are subscribed to the diesel production. This brings the feedstock costs at 6,50 €/$GJ_{FTdiesel}$. Summing the feedstock costs, the production costs and the distribution costs results in WTT costs of 10,38 €/$GJ_{FTdiesel}$. With the fuel economy of a FT diesel fuelled vehicle, this comes down to 0,027 €/km. The results are summarized in table 12.4.

12.4 Biomass based fuel chains: FT diesel & ethanol

FT diesel from cellulosic biomass

FT diesel can not only be produced from natural gas, but also from cellulosic biomass. In this case the fuel chain consists of four steps: growing (and harvesting) of cellulosic biomass, transportation of the biomass to a central plant in the Randstad area, production of FT diesel and distribution of FT diesel. Like in many studies, the steps for which costs are determined are not identical to the steps that are used in energy analyses. In this fuel chain, three steps are distinguished for costs: the costs that the FT plant has to pay for cellulosic biomass, the conversion costs and the distribution costs of diesel.

The costs that the FT plant has to pay for cellulosic biomass include growing the biomass, harvesting it and transporting it to the FT plant. The costs of growing cellulosic biomass depend on a lot of factors, among others on the species of biomass, the yield per hectare per year, the climate in which the biomass is grown and availability and access to water and nutrients [IEA, 1999]. In their own calculations, the International Energy Agency uses an estimate of feedstock costs of 3,60 €/$GJ_{biomass}$. In the BIGFiT project, a value of 4,12 €/GJ was assumed [BIGFiT, 2002]. A study performed for the Dutch ministry of Economic Affairs reports values ranging from 4 €/GJ to 4,75 €/GJ [Minez, 2003]. A study performed by ECN reports a value of 3,90 €/GJ. From all these values it becomes clear that the costs for cellulosic biomass lie around 4,00 €/$GJ_{biomass}$. This latter value is used by this study.

The next stage is the production of FT diesel. In the previous section, we have seen a cost-breakdown for a FT-plant. These costs are applicable both to FT diesel that is made from natural gas and to FT diesel that is made from cellulosic biomass, as long as costs of the feedstock are left beyond consideration. In doing so, the production costs of FT diesel without feedstock costs have been estimated to be 14,5 €/bbl. With the energy content of a barrel of 5,44 GJ and the assumption that the costs are evenly divided over all products, we find production costs for FT diesel of 2,67 €/GJ.

The last costs that have to be included in the analysis are the costs of distribution. Because FT diesel is distributed in the same way as diesel that is made from crude oil and because the distribution distances are comparable, the distribution costs of FT diesel are assumed to be equal to those of diesel. This is 1,21 €/$GJ_{FTdiesel}$.

Now that the data on the individual stages are known, they can be combined in order to calculate WTT costs. However, the energy flow through the fuel chain has to be taken into account. 1 GJ of biomass feedstock costs 4 €. The conversion of biomass to products requires 2,449 units of biomass for each unit of diesel produced. Therefore the feedstock costs have to be multiplied with 2,449. On the other hand, the production of FT diesel results not only in diesel but also in byproducts. For each unit of diesel produced, 0,63 MJ of byproducts are produced. This means that the diesel output of the production step is only 64,4 % of the total output. According to the principles of Ratio of Energy Content, only 64,4 % of the feedstock costs are assigned to diesel. By taking all these considerations into account, the value for the feedstock costs of a $GJ_{Ftdiesel}$ is calculated to be 6,50 €/GJ. With the production costs and the distribution costs, total WTT costs equal 10,39 €/$GJ_{Ftdiesel}$, which is almost identical to the WTT costs of FT diesel made from natural gas. The WTW costs based on energy content are identical to the WTT costs. By multiplying the WTW costs based on energy content with the fuel economy of a FT diesel fuelled car the WTW costs based on traveled distance can be calculated. These equal 0,027 €/km. A summary of the results can be found in table 12.5.

	FT diesel (bio) (€/$GJ_{FTdiesel}$)
Growing and transportation	6,50
FT diesel production	2,67
Distribution	1,21
WTT	10,39
WTW (€/km)	*0,027*

Table 12.5: summary of data on production costs for FT diesel from cellulosic biomass (after accounting for byproducts)

Ethanol from cellulosic biomass

Cellulosic biomass can not only be used to produce FT diesel, but also ethanol. The ethanol from cellulosic biomass fuel chain consists of four steps: growing of the biomass, transportation of biomass to a central plant, conversion to ethanol and finally distribution of ethanol. The costs for the first two steps are not calculated separately, but only together. In the previous section we have seen that these costs equal 4 €/GJ$_{biomass}$.

The costs for conversion of cellulosic biomass to ethanol are built up according to the process stages. They can be divided into costs for pretreatment, costs for the actual conversion and costs for upgrading of products. Data provided by Wyman and Reith are shown in table 12.6 [Wyman, 1999]; [Reith, 2002]. The production of excess electricity is already accounted for in the data. Therefore the total costs mentioned in table 12.6 can be totally subscribed to ethanol. As we see in the table, the numbers provided by the two sources are quite comparable. Therefore their average is used by this study.

The final stage in the production process is the distribution of ethanol. Because ethanol is produced in the Randstad area, like gasoline, and used as alternative for gasoline-fuelled vehicles, it is assumed that the costs of distribution of ethanol are comparable to those for distribution of gasoline. This value equals 1,27 €/GJ.

Now that data on the individual steps are complete, the data can be summed. However, the energy flows through the fuel chain have to be taken into account. In order to produce 1 unit of ethanol, 2,353 units of biomass are needed. Therefore the costs of biomass are multiplied with 2,353. Because this amount of biomass results not only in the production of ethanol but also in the production of electricity, this amount has to be corrected for the electricity production. The ethanol yield equals 93% of output of the production step. Therefore 93% of the biomass input is assigned to ethanol. In the costs of conversion of biomass to ethanol, the output of electricity has already been accounted for. The costs for conversion and distribution are already relative to 1 unit of fuel leaving the fuel chain so no additional calculations have to be made. By summing the data on the individual steps, the WTT costs can be obtained. These equal 19,46 €/GJ. The WTW costs per unit of energy are identical to the WTT costs. With the fuel economy of an ethanol fuelled vehicle, the WTW costs per unit of distance traveled can be calculated. These equal 0,055 €/km. A summary of the results is provided in table 12.7.

	[Wyman, 1999] (€/GJ$_{ethnaol}$)	[Reith, 2002] (€/GJ$_{ethanol}$)	This study (€/GJ$_{ethanol}$)
Pretreatment	4,09	4,72	4,40
SSF fermentation	2,36	4,40	3,93
Upgrading	1,10		
Other processing	1,10	0,94	1,10
Total	8,49	8,49	9,43

Table 12.6: data on the production costs of ethanol from cellulosic biomass

Ethanol from sugary biomass

The last fuel chain included in the model is that of ethanol from sugary biomass. Like the ethanol from cellulosic biomass, this fuel chain consists of 4 steps in an energetic analysis: growing of biomass, transportation of biomass, conversion of biomass to ethanol and finally distribution of ethanol. However, like in so many fuel chains, the number of steps for which costs are calculated does not equal the number of steps in the energetic analysis. For costs, there are only three steps relevant: growing of biomass and transportation to the conversion plant, conversion and distribution.

	Ethanol (w bio) ($€/GJ_{ethanol}$)
Growing and transportation	8,75
Ethanol production	9,43
Distribution	1,27
WTT	19,46
WTW (€/km)	*0,055*

Table 12.7: summary of data on production costs for ethanol from cellulosic biomass (after accounting for byproducts)

Sugary biomass is more expensive to buy than cellulosic biomass. According to the International Energy Agency, the price that would have to be paid to buy sugary biomass equals 10,30 $€/GJ_{biomass}$ [IEA, 1999]. On the other hand, Enguidanos estimates the costs for biomass at only 5,41 $€/GJ_{biomass}$, which is only a little more than half of the estimate from the International Energy Agency [Enguidanos, 2002]. Elam mentions prices varying between 6,63 €/GJ and 10,56 €/GJ [Elam, 2000]. This last numbers suggest that the estimate made by Enguidanos is too low. In this study, a value of 9,00 €/GJ is assumed.

The next stage in the determination of operating costs is the costs for conversion. An overview of processing costs is provided in table 12.8. As the table shows, there are quite some differences in the distribution of costs over the various items. However, both cost-breakdowns results in a total of about 10 $€/GJ_{ethanol}$. This value is also used in this study.

The final stage for which costs have to be determined is distribution. For distribution, it does not matter whether the ethanol is made from cellulosic biomass or sugary biomass. In both cases, the distribution stage is identical. Before we have seen that distribution of ethanol requires 1,27 $€/GJ_{ethanol}$

With the data on the costs of the separate steps in the fuel chain, the total WTT results can be determined. The costs for sugary biomass have to be multiplied with 1,920 because the fuel chain uses 1,920 units of biomass to produce 1 unit of ethanol. However, together with the ethanol, animal feed is produced. The amount of biomass that is used in the fuel chain has to be corrected for the production of this byproduct. This is done according to the Ratio of Energy Contents principles. Because ethanol constitutes 56,9 % of the output on an energy basis, only 56,9 % of biomass input is contributed to ethanol. The data on the production and distribution on ethanol are already related to the output of the fuel chain and don't have to be recalculated. With these calculations, the WTT result becomes 21,10 €/GJ. This result is equal to the WTW results based on energy. The WTW results based on traveled distance can

	[Elam, 2000] (€/GJ)	[Enguidanos, 2002] (€/GJ)	This study (€/GJ)
Capital costs	0,57	-	
Energy	2,83	3,64-6,07	
Labour	2,36	0,61-0,97	
Chemicals	1,42	-	
Overhead	0,94	1,21-2,18	
Maintenance	2,36	0,97-1,21	
Total	10,48	6,43-10,43	10,00

Table 12.8: data on the production costs of ethanol from cellulosic biomass

	Ethanol (s bio) ($€/GJ_{ethanol}$)
Growing and transportation	9,83
Ethanol production	10,00
Distribution	1,27
WTT	21,10
WTW (€/km)	*0,060*

Table 12.9: summary of data on production costs for ethanol from sugary biomass (after accounting for byproducts)

be obtained by multiplying the WTW results based on energy with the fuel economy of an ethanol fuelled vehicle. The outcome of this calculation equals 0,060 €/km. A summary of the results is provided in table 12.9.

12.5 Summary and conclusions

In this chapter, the operating costs of the transportation fuels have been investigated. Only direct operating costs have been included in the analysis. Direct operating costs consist of production costs and capital costs. The WTT and WTW results for all fuel chains are shown in table 12.10. This table shows that the operating costs of diesel, gasoline, LPG and CNG are all low and that the differences between these fuel chains are small. The operating costs for FT diesel are about 0,027 €/km, irrespective of the primary feedstock that is used to produce the FT diesel. The operating costs for ethanol are the highest costs of all costs. The costs for the ethanol from sugary biomass are even more than three times as high as those in the diesel fuel chain or the LPG fuel chain. However, there can be a great difference between the operating costs and the price that a consumer has to pay at the refueling station. In the case of gasoline for example, the consumer has to pay 0,85 euro of taxes per liter of gasoline [Shell, 2004], which is no less than 26,38 €/GJ. This value is larger than the WTT operating costs in any fuel chain. This shows that by means of tax reductions, all fuels can compete with diesel, gasoline and LPG.

Not only the costs of a fuel per unit of travelled distance are interesting, but also the costs per kilogram of carbon dioxide. The latter are shown in the utmost right column of table 12.10. As the table shows, the costs of carbon dioxide are much lower in the fossil fuel based chains than they are in the biomass based fuel chains. The costs of carbon dioxide are lowest in the

	WTT costs (€/GJ)	WTW costs (€/km)	Carbon dioxide costs ($€/kg\ CO_2$)
Diesel	6,27	0,016	0,077
Gasoline	7,50	0,022	0,083
LPG	6,04	0,018	0,074
CNG	6,43	0,017	0,076
FT diesel (ng)	10,38	0,027	0,074
FT diesel (w. bio)	10,39	0,027	0,629
Ethanol (w. bio)	19,46	0,055	1,139
Ethanol (s. bio)	21,10	0,060	0,695

Table 12.10: summary of WTT and WTW operating costs and carbon dioxide costs for all fuel chains

FT-diesel from natural gas and the LPG fuel chain, closely followed by CNG and diesel. Gasoline has the highest costs per kilogram of carbon dioxide. In the biomass based fuel chains, costs are highest in the ethanol from cellulosic biomass fuel chains. In the FT-diesel from cellulosic biomass fuel chain and the ethanol from sugary biomass fuel chain, the costs are more or less comparable.

13 Well To Wheel calculations as aid in policy making

13.1 Introduction

In section 5.9 it was stated that the importance of Well to Wheel calculations is two-sided: on the one hand they provide insight into the energy use in the production and use of transportation fuels and into the associated emissions. On the other hand the outcomes of the calculations serve as input for further calculations. These calculations involve, among others, calculations on the total current and future emissions arising from transportation. In this chapter, an example of such calculations is provided. The emissions from a number of fuel mixes in the Dutch vehicle fleet in the year 2020 will be compared to the emissions from the vehicle fleet in the year 2002. The calculation shows how the emissions will evolve if the current fuel mix is contained and how changes in the fuel mix can influence the total emissions of the fleet. The goal of this chapter is to create more insight in the type of calculations that are made possible by Well to Wheel studies and in the added value of Well to Wheel calculations for policy purposes.

13.2 Current and future greenhouse gas emissions

This section starts by determing current greenhouse gas emissions from the Dutch vehicle fleet. These calculations are extended in the future to predict the greenhouse gas emissions in the year 2020. This is done for a number of fuel mixes to show the influence of fuel choice on fleet emissions.

Current emissions from the Dutch Vehicle fleet

The composition of the Dutch vehicle fleet on January 1st 2002 is shown in table 13.1 [CBS, 2003]. The table shows that gasoline is the dominant transportation fuel in the Netherlands, followed by diesel and LPG. The contribution of electric vehicles (436 vehicles) and of CNG fuelled vehicles (51 vehicles) is almost negligible. With the average number of kilometers driven each year by each type of fuel as depicted in table 13.1 and the total number of passenger cars in the Netherland of 6,71 million cars [CBS, 2003], the TTW and WTW greenhouse gas emissions from the Dutch vehicle fleet can be calculated. These are shown in table 13.2. The direct emissions from the total Dutch vehicle fleet equal 21,43 Mton CO_2-

	Composition of Dutch vehicle fleet (%)	Average number of kilometers driven per year (km/year)
Diesel	13,86	27.600
Gasoline	81,48	12.640
LPG	4,65	28.520
Electric	0,006	-
CNG	0,001	-
Total	100,00	

Table 13.1: some characteristics of the Dutch vehicle fleet
Source: [CBS, 2003]

	TTW emissions (Mton/yr)	WTW emissions (Mton/yr)
Diesel	4,75	5,46
Gasoline	14,94	18,75
LPG	1,73	2,18
CNG	0,00	0,00
Total	21,43	26,38

Table 13.2: direct and total greenhouse gas emissions from the Dutch vehicle fleet

equivalents per year. By including the emissions from the production of the fuels, the WTW emissions can be calculated. These become 26,38 Mton CO_2-equivalents per year.

Future emissions from the Dutch vehicle fleet

The future emissions from the Dutch vehicle fleet are more difficult to obtain. The year of interest is the year 2020. For this year, the WTW energies of all transportation fuels must be known, together with information on the number of cars in the vehicle fleet and the average number of kilometers driven per year per car.

For both the WTT and TTW efficiencies it is often stated that the efficiencies can be improved between now and the year 2020. Some studies record improvements up untill 30 % [UCS, 2001]. However, the production processes of diesel, gasoline and LPG have been known since years. In the past, the oil companies have made huge profits that enabled them to invest in the optimalisation of their production processes. Therefore it is not very likely that the WTT efficiency of diesel, gasoline and LPG will increase much. On the contrary, the efficiency improvements that can be realised are, at least partly, offset by the increased use of enhanced recovery techniques that will be needed to recover the oil from the ground. These techniques require more energy input than the primary extraction techniques. This will countereffect efficiency gains in other parts of the fuel cycle. This study assumes the net improvement in WTT efficiency for diesel, gasoline and LPG to be zero. The other fuel chains have not yet been introduced on a large scale in 2002. Under the assumption that they have been introduced on a large scale by 2020 it is likely that they will have benefited from economy of scale-advantages. It is also likely that research will have been done to optimise the production and that part of this research has been successful. Therefore this study assumes an improvement of 5% in the production process of CNG, FT diesel and ethanol.

Now the improvement in TTW efficieny has to be assessed. The European Commission aims to reduce carbon dioxide emissions from cars to 120 g/km for any vehicle by 2012 [EC, 2004].

	Improvement in WTT efficiency	New WTT energy use (MJ_{prim}/MJ)*	Improvement in TTW efficiency	New TTW energy use (MJ/km)
Diesel	0,0 %	1,14	10,0 %	2,26
Gasoline	0,0 %	1,26	10,0 %	2,64
LPG	0,0 %	1,14	10,0 %	2,63
CNG	5,0 %	1,21	10,0 %	2,79
FT diesel (ng)	5,0 %	1,48	10,0 %	2,33
FT diesel (w bio)	5,0 %	1,60	10,0 %	2,33
Ethanol (w bio)	5,0 %	2,33	10,0 %	2,69
Ethanol (s bio)	5,0 %	1,29	10,0 %	2,69

Table 13.3: improvement in WTT and TTW efficiencies 2002-2020

*: Byproducts have been accounted for according to the Ratio of Energy Contents principles

This means a reduction of about 20% as compared to current emission levels. It is expected by experts in the field that about half of this will be accomplished by the use of lighter materials and changes on the vehicle, and that the remaining 10% wil be accomplished by improving engine efficiency[6]. Therefore this study assumes an improvement in TTW energy use of 10% for each transportation fuel. An overview of the efficiency gains in WTT and TTW efficiencies as well as the new values of all WTT and TTW energies can be found in table 13.3.

The next data that have to be known are the average number of kilometers driven per car in the year 2020 and the number of cars on the road. For these data, numbers provided by the Dutch Transport Research Centre[7] are used. The numbers are based on a scenario made by the Dutch Centraal Plan Bureau, which is called European Co-ordination. The geographical scope of the scenario is restricted to the Netherlands, but the developments in the Netherlands are heavily influenced by the developments in the European Union. The increase in Gross Domestic Product is moderate, but employment is high. Population growth is, with only 0,5% per year, very low. The scenario is a base case scenario, which means that there are no additional policy measures that stimulate or restrain transportation. Based on this scenario, the Transport Research Centre estimates the average number of kilometers driven per car to have increased with 49% in 2020 in comparison with 1995 [AVV, 2001]. From Statistics Netherlands we learn that the average distance travelled per car in 1995 equalled 14.200 kilometers [CBS, 2003]. This means that the average distance travelled per car in the year 2020 will equal 21.200 kilometer per year. The study by the Transport Research Centre also predicts that there will be 8,8 million passenger cars by 2020 [AVV, 2001].

We now have all data that are needed to complete the calculation. The calculation will be performed for 10 cases. In the first 8 cases, it is assumed that all transportation takes place with 1 transportation fuel. In the 9th case, the division of fuels of the Dutch vehicle fleet of 2002 is assumed. In the 10th case, an adjusted 2002 division is assumed: the share of diesel in the 2002 mix has been replaced with FT diesel from cellulosic biomass while the shares of gasoline and LPG have been replaced with ethanol from sugary biomass. The results for all 10 cases are shown in table 13.4.

	TTW emissions (Mton/yr)	WTW emissions* (Mton/yr)
Diesel	31,04	35,66
Gasoline	36,35	45,61
LPG	32,69	41,09
CNG	29,57	39,77
FT diesel (ng)	31,08	64,11
FT diesel (w bio)	31,08	8,63
Ethanol (w bio)	35,92	8,85
Ethanol (s bio)	35,92	22,93
Fuel mix with 2002 shares of diesel, gasoline and LPG	35,44	44,02
Fuel mix with 2002 shares of FT diesel and ethanol	35,25	8,82

Table 13.4: direct and total emissions from the Dutch vehicle fleet in 2020 for a number of cases

*: Byproducts have been accounted for according to the Ratio of Energy Contents principles

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[6] Personal communication with H.C. van de Burgwal

[7] Adviesdienst Verkeer en Vervoer, AVV

We can see in table 13.4 that if the fuel mix as it is in 2002 is maintained untill the year 2020, the emissions will increase with two-thirds of the 2002-level. Increasing the diesel fraction in the fuel mix will have a somewhat lowering effect but the emissions will still be higher than today's emissions. In the same way, switching to CNG will give some advantage on the total emissions over using the current fuel mix, but the emissions from the total fleet will still be higher than current emissions. The only way to cut back on emissions is to use renewable fuels like ethanol, either from cellulosic biomass or sugary biomass, or FT diesel that is made from cellulosic biomass. By changing the entire fleet to ethanol from cellulosic biomass or FT-diesel from cellulosic biomass, the emissions drop to less than half the 2002-level. This is confirmed by the ninth case, in which diesel is substituted with FT-diesel from cellulosic biomass and gasoline and LPG are substituted with ethanol from sugary biomass. Unfortunately the chances that the entire vehicle fleet of the Netherlands will have switched to renewable fuels by 2020 are quite small. In order to keep the emissions of the fleet of 2020 on the level of emissions of 2002, 84,4% of gasoline fuelled vehicles in the year 2020 must be changed from gasoline to ethanol from cellulosic biomass. Calculations of this kind show that, provided that no policy measures are taken to restrain transportation, renewable fuels must be introduced in order to be able to stabilize emissions or to cut back on emissions.

14 Conclusions and recommendations

14.1 Conclusions

This study has attempted to answer the following research questions:

- How will energy demand and energy availability develop in the first half of this century?
- What are the energy use and greenhouse gas emissions from a selected number of conventional and renewable fuels in the WTW chain?
- What are the production costs of these fuels?

Energy demand and availability untill 2050

In order to determine how energy use could develop in the first half of the next century, several energy scenarios haven been compared. In all scenarios, primary energy use is expected to rise. The estimations vary between 561 EJ/year and 1150 EJ/year (for comparison: in 1990 the worldwide primary energy use equaled 387 EJ/year). The scenarios are not very optimistic about the introduction of renewable fuels: by 2020 the world still heavily depends on fossil fuels. By 2050 however, a transition away from the fossil fuels will have begun: shares of renewable energy use ranging from one-quarter up to half the world's energy use are recorded.

But how about the availability of energy carriers? In chapter 3 we have seen that there is enough oil for the coming decades. However, the reserves in Europe and North-America will get exhausted, thereby increasing the dependence on a limited number of oil-producing countries in the Middle-East. Besides reserves, there are also resources. Resources are quantities for which it is not yet possible to extract them in an economically and/or technically feasible way. In the case of crude oil, the numbers of resources are gigantic. If they become available, there is plenty of oil for centuries. In the case of natural gas, the known reserves are expected to last longer. They are also more evenly divided over the world. With resources of natural gas even larger than those of crude oil, the amount of natural gas present in the earths crust is enough to comply with any growth rate in any scenario. In the same way there are no shortages to be expected for coal.

Unlike fossil fuels, whose presence in the earths crust diminishes by every use mankind makes of them, biomass can be regrown after it was harvested. In the case of biomass, the availability of land for growing biomass and the growth rate of the biomass are determining factors for the availability. However, in the entire first half of this century the potential for biomass is larger than the anticipated use. Therefore no shortages are to be expected.

Advantages and disadvantages of the WTW model

In order to analyze energy use and greenhouse gas emissions in the WTW chain, a model has been developed. This model has some advantages over models used in other studies. The most important is that the model is very precise. Many studies calculate the WTT energy use by determining an efficiency for each individual step in the fuel chain, multiplying the efficiencies of the individual steps to obtain a WTT efficiency and taking the inverse of the WTT efficiency as the WTT energy use per unit of output. In the model that has been developed in this study, all energy flows are separately mapped. Only at the end of the calculation they are summed to obtain a total WTT result. This provides information with a much greater level of detail than the studies working with a product of chain step efficiencies.

The contribution of each feedstock to the total WTT energy use is calculated individually, which provides good insight in the energy use in a fuel chain. Also, byproducts are individually mapped. This provides the possibility to account for byproducts in different ways and to compare the results for different presentations.

Of course the model also has some disadvantages. First of all the impossibility of working with confidance intervals. In it's current form, the model requires specific values as input for all variables. However, the input often contains a certain level of uncertainty. The model as it is as yet does not provide the opportunity to reflect this uncertainty easily. Second, the level of detail is sometimes a disadvantage. In order to obtain detailed output, the model requires detailed input. It is sometimes hard to find this information.

Summary of WTW results

WTW energy use and emissions of all the fuel chains included in this study can not be compared straight away. In some of the fuel chains, byproducts are produced. Due to the byproducts, the fuel chains have different outputs. Before a fair comparison can be made, the byproducts have to be accounted for in some way. There are several methods to do so, three of which have been applied in this study. The different methods lead to different results and therefore no overall result can be determined. However, the results resemble each other close enough to draw some conclusions.

Off the fuel chains analysed in this study, the diesel fuel chain is the most efficient. Diesel is followed by LPG, gasoline and CNG respectively. In all methods of accounting for byproducts, the ethanol from cellulosic biomass fuel chain uses the most energy. Furthermore all methods of accounting for byproducts show that it is more efficient to produce FT diesel from natural gas than it is to produce it from cellulosic biomass. In those methods of accounting for byproducts where ethanol from sugary biomass is included, this is the most efficient biomass-based fuel chain.

Besides total energy use, the use of fossil energy inputs has been analysed. In all cases, the biomass based fuels use the least fossil energy. In all three methods of accounting for byproducts the order is the same: FT diesel from cellulosic biomass uses the least fossil fuels of all, followed by ethanol from cellulosic biomass. Ethanol from sugary biomass uses the most fossil energy of the biomass-based fuels. The fossil fuel based fuels use only fossil fuels and therefore their ranking is equal to that in the total energy use: diesel uses the least fossil energy, followed by respectively LPG and CNG. The FT diesel from natural gas fuel chain uses the most fossil energy of all.

The analysis of greenhouse gas emissions shows that these are lowest in the biomass based fuel chains. Of all biomass-based fuels, the ethanol from sugary biomass fuel chain uses the most fossil fuels and consequently emits the most emissions. This means that converting cellulosic biomass to transportation fuels creates less emissions than converting sugary biomass to a transportation fuel. However, whether it is better to convert cellulosic biomass to FT diesel or ethanol is not very clear. According to one method of accounting for byproducts, FT-diesel results in the lowest emissions. With the other methods of accounting for byproducts, conversion to ethanol results in the lowest emissions. Of the fossil fuels, respectively diesel and CNG result in the lowest WTW emissions. In most methods of accounting for byproducts, CNG is followed by LPG, gasoline and FT-diesel from natural gas. According to other methods however, FT diesel from natural gas creates the most emissions of all fuels.

Investigation of costs

In order to answer the third research question, the operating costs of the transportation fuels have been investigated. Only direct operating costs have been included in the analysis. For the fuel chains as they have been modelled in this study, the operating costs per unit of distance traveled with a fuel are smallest in the diesel fuel chain. Diesel is followed by the CNG fuel chain, LPG fuel chain and gasoline fuel chain respectively. Next are the operating costs of FT diesel, irrespective of the primary feedstock that is used to create the FT diesel with. The operating costs for ethanol are the highest costs of all costs. The costs for the ethanol from sugary biomass are even more than three times as high as those in the diesel fuel chain or the LPG fuel chain. However, there can be a great difference between the operating costs and the price that a consumer has to pay at the refueling station. In the Netherlands, taxes make up about 70 % of the current fuel prices. Reducing taxes or freeing some fuels from taxes can make all fuels included in this study competitive with the current Dutch fuel prices that have to be paid at the refueling station.

14.2 Recommendations

At the end of this research, the following recommendations for further investigations can be made:

- The sensitivity analysis on the influence of emissions of methane and nitrous oxide on the total greenhouse gas emissions, has shown that the influence is indeed significant is some fuel chains. These are especially the ethanol from sugary biomass fuel chain, and to a lesser extent the natural gas based fuel chains. It is recommended that more study is performed on the emissions in this fuel chains.
- The sensitivity analysis on the influence of the choice of process fuels in the compression stage of the CNG fuel chain shows that the choice of process fuels can meaningfully influence the WTW results of a fuel chain. It is recommended that extended sensitivity analysis is performed to map which process fuels are influential in which process steps.
- In this study, costs have been assessed separately for each individual fuel chain. However, in all fuel chains the same methodology has been applied. This methodology can be formalised into a quantitative model.

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Appendices

Appendix A: OPEC member countries

OPEC member countries include:

- Algeria
- Indonesia
- Iran
- Iraq
- Kuwait
- Libia
- Nigeria
- Qatar
- Saudi Arabia
- United Arab Emirates
- Venezuela

Source: [OPEC, 2003]

Appendix B: Classification of countries in the world over regions

North America
Canada, Greenland, St Pierre and Miquelon, United States.

Latin America
Antigua, Argentina, Bahamas, Barbados, Belize, Bermuda, Bolivia, Brazil, British Virgin Islands, Cayman Islands, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, Falkland Islands (Malvinas), French Guiana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Montserrat, Netherlands Antilles, Nicaragua, Panama (including Panama Canal Zone), Paraguay, Peru, Puerto Rico, St Kitts-Nevis-Anguilla, St Lucia, St Vincent, Suriname, Trinidad & Tobago, Turks and Caicos Islands, United States Virgin Islands, Uruguay, Venezuela.

Eastern Europe
Albania, Bulgaria, former Czechoslovakia (Czech Republic, Slovakia), Hungary, Poland, Romania, former Union of Soviet Socialist Republics (Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Kirgizstan, Latvia, Lithuania, Moldova, Russia, Tajikistan, Turkmenistan, Ukraine, Uzbekistan).

Western Europe
Austria, Belgium (including Luxembourg), Cyprus, Denmark (including Faroe Islands), Finland, France (including Andorra and Monaco), Germany, Gibraltar, Greece, Iceland, Ireland, Italy (including San Marino and Vatican City State [Holy See]), Malta, Netherlands, Norway (including Svalbard and Jan Mayen Islands), Portugal, Spain (including Canary Islands), Sweden, Switzerland (including Liechtenstein), Turkey, United Kingdom, former Yugoslavia (Bosnia and Herzegovina, Croatia, Macedonia [The Former Yugoslav Republic of], Serbia and Montenegro, and Slovenia).

Middle East
Bahrain, Islamic Republic of Iran, Iraq, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, United Arab Emirates (Abu Dhabi, Ajman, Dubai, Fujairah, Ras al-Khaimah, Sharjah, Umm al-Qaiwain), Yemen.

Africa
Algeria, Angola, Benin, Botswana, British Indian Ocean Territory, Burkina Faso, Burundi, Cameroon (United Republic of), Cape Verde, Central African Republic, Chad, Comoros, Congo (Republic of the), Congo (Democratic Republic of the), Djibouti, Egypt, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia (The), Ghana, Guinea, Guinea-Bissau, Ivory Coast, Kenya, Lesotho, Liberia, Socialist Peoples' Libyan Arab Jamahiriya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Reunion, Rwanda, St Helena, Sao Tome and Principe, Senegal, Seychelles, Sierre Leone, Somalia, South Africa, Sudan, Swaziland, Tanzania (United Republic of), Togo, Tunisia, Uganda, Western Sahara, Zambia, Zimbabwe.

Asia and Pacific
Afghanistan, American Samoa, Antarctica, Australia, Bangladesh, Bhutan, Brunei, Cambodia, Canton and Enderbury Islands, China (Republic of), Christmas Island, Cocos (Keeling) Islands, Cook Islands, Fiji, French Polynesia, Guam, Hong Kong, India, Indonesia, Japan, Johnston Island, Kiribati, Korea (Democratic People's Republic of), Korea (Republic of), Lao People's Democratic Republic, Macau, Malaysia, Maldives, Midway Islands, Mongolia, Myanmar (formerly Burma), Nauru, Nepal, New Caledonia, New Zealand, Niue, Norfolk Island, Pacific Islands (Trust Territory), Pakistan, Papua New Guinea, Philippines, Pitcairn Island, Samoa, Singapore, Solomon Islands, Sri Lanka, Taiwan, Thailand, Tokelau, Tonga, Tuvalu, Vanuatu, Vietnam, Wake Island, Wallis and Futuna Islands.

Source: [OPEC, 2002]

Appendix C: Nomenclature

a	Primary feedstock that enters the first step of a fuel chain
$aem_{i,s}^{CO_2}$	Amount of CO_2 emissions that are avoided through the production of byproduct of type s in fuel chain i
$aem_{i,s}^{v}$	Amount of emissions of substance of type v that are avoided through the production of byproduct of type s in fuel chain i
AP	Avoided product
$ape_{i,s}^{k}$	The amount of primary energy of type k that is avoided through the production of byproduct of type s in fuel chain i
$APEE$	Avoided primary energy and emissions
$b_{i,s,q}$	Amount of byproduct of type s produced in step q of fuel chain i, relative to 1 unit of fuel leaving the fuel chain
$B_{i,s,q}$	Absolute amount of byproduct s produced in step q of fuel chain i
$dd_{extra,s}$	Extra number of kilometers that can be driven per unit of main fuel i in fuel chain i
dd_i	Number of kilometers a vehicle can drive with 1 unit of fuel i
DD_i	Absolute number of kilometers driven with fuel of type i
$E_{by,i,s,q}$	Byproduct of type s produced in step q of fuel chain i
$E_{in,i,q}$	Ingoing energy in step q of fuel chain i
$E_{loss,i,q}$	Energy loss in step q of fuel chain i
$E_{process,i,j,q}$	Process energy of type j in step q of fuel chain i
$E_{out,i,q}$	Outgoing energy of step q of fuel chain i
$f_{i,q}$	Ingoing energy in step q of fuel chain i, relative to 1 unit of fuel leaving step q
$F_{i,q}$	Ingoing energy in step q of fuel chain i
$f_{i,q}^{REC2}$	Amount of ingoing energy in step q of fuel chain i that is needed to create the fraction of desired product in step q of fuel chain i
$F_{i,q}^{REC2}$	Amount of primary feedstock needed to produce 1 unit of desired product leaving step q of fuel chain i.
f_i^k	Ingoing energy of primary input of type k in fuel chain i per unit of fuel leaving the fuel chain
F_i^k	Ingoing energy of primary input of type k in fuel chain i
fdp_i	The fraction of desired product i in fuel chain i
$fdp_{i,q}$	The fraction of desired product i in step q of fuel chain i
$g_{i,j,q}$	Ingoing process energy in step q of fuel chain i, relative to 1 unit of output of that step
$G_{i,j,q}$	Process energy of process fuel of type j in step q of fuel chain i
$G_{i,j,q}^{REC2}$	Amount of process energy of type j needed to produce 1 unit of desired product leaving step q of fuel chain i.
GWP_v	Global Warming Potential of substance of type v
$H_{i,q}$	Outgoing energy of step q of fuel chain i
i	Fuel chain; $i = \{1,2,\ldots,m-1,m\}$
j	Process energy; $j \in i$

k	Primary feedstock; $k = \{1,2,...,n-1,n\}$
q	Step in a fuel chain; $q = \{1,2,...,r-1,r\}$
s	Byproduct, $s = \{1,2,...,t-1,t\}$
TTW	Tank to Wheel
$ttw_{emissions,i,CO_2}$	CO_2 emissions produced in the TTW part of fuel chain *i*, per unit of fuel
$ttw^{*}_{emissions,i,CO_2}$	CO_2 emissions produced in the TTW part of fuel chain *i*, per unit of distance travelled
$TTW_{emissions,i,CO_2}$	Absolute amount of CO_2 emissions produced in the TTW part of fuel chain *i*, produced over a distance DD_i
$ttw_{emissions,i,v}$	Emissions of substance of type *v* produced in the TTW part of fuel chain *i*, per unit of fuel
$ttw^{*}_{emissions,i,v}$	Emissions of substance of type *v* produced in the TTW part of fuel chain *i*, per unit of distance travelled
$TTW_{emissions,i,v}$	Absolute amount of emissions of substance of type *v* produced in the TTW part of fuel chain *i*, produced over a distance DD_i
$ttw_{energy,s}$	Energy consumption of byproduct of type *s* in a powertrain
$ttw_{energy,i}$	Fuel consumption of fuel *i* per unit of distance traveled
$TTW_{energy,i}$	Absolute energy consumption of fuel *i* in a powertrain, over a distance DD_i
v	Emission of substance of type *v*, $v = \{1,2,...,u-1,u\}$
$w_{i,v,q}$	Emission of substance of type *v* produced in step *q* of fuel chain *i*, relative to 1 unit of energy leaving that step
$W_{i,v,q}$	Emission of substance of type *v* produced in step *q* of fuel chain *i*
$W^{REC2}_{i,v,q}$	Emissions of substance of type *v* emerging from the production of 1 unit of desired product leaving step *q* of fuel chain *i*. The production of byproducts is left beyond consideration
WTT	Well to Tank
$wtt_{by,i}$	Sum of all normalised byproducts produced in the WTT system of fuel chain *i*
$WTT_{by,i}$	Sum of all byproducts produced in the WTT system of fuel chain *i*
$wtt_{by,i,s}$	Amount of byproduct of type *s* produced in the WTT system of fuel chain *i*, relative to 1 unit of energy leaving the fuel chain
$WTT_{by,i,s}$	Amount of byproduct of type *s* produced in the WTT system of fuel chain *i*
$wtt_{emissions,i}$	Total greenhouse gas emissions in the WTT system of fuel chain *i*, expressed in CO_2-equivalents, relative to 1 unit of fuel leaving the fuel chain
$WTT_{emissions,i}$	Emissions in fuel chain *i*, expressed in CO_2-equivalents
$wtt_{emissions,i,CO_2}$	WTT carbon dioxide emissions produced in the WTT system of fuel chain *i* per unit of energy leaving the fuel chain
$WTT_{emissions,i,CO_2}$	CO_2 emissions produced in the WTT system of fuel chain *i*
$wtt_{emissions,i,v}$	Emissions of substance of type *v* produced in the WTT system of fuel chain *i* per unit of energy leaving the fuel chain
$WTT_{emissions,i,v}$	Emissions of substance of type *v* produced in the WTT system of fuel chain *i*
$wtt^{CO_2}_{emissions,ap}$	WTT CO_2 emissions that result from the production of 1 unit of the avoided product
$wtt^{v}_{emissions,ap}$	WTT emissions of substance of type *v* that result from the production of 1 unit of the avoided product

$wtt^{APEE}_{emissions,i}$	Total greenhouse gas emissions in the WTT part of fuel chain *i*, whereby avoided emissions are calculated according to the Avoided Primary Energy and Emissions method
$wtt^{APEE}_{emissions,i,CO_2}$	WTT CO_2 emissions in fuel chain *i*, whereby avoided emissions are calculated according to the Avoided Primary Energy and Emissions method
$wtt^{APEE}_{emissions,i,v}$	WTT emissions of substance of type *v* in fuel chain *i*, whereby avoided emissions are calculated according to the Avoided Primary Energy and Emissions method
$wtt^{MVK}_{emissions,i}$	Total greenhouse gas emissions in the WTT part of fuel chain *i*, whereby avoided emissions are calculated according to the Multiple Vehicle Kilometers method
$wtt^{MVK}_{emissions,i,CO_2}$	WTT CO_2 emissions in fuel chain *i*, whereby avoided emissions are calculated according to the Multiple Vehicle Kilometers method
$wtt^{MVK}_{emissions,i,v}$	WTT emissions of substance of type *v* in fuel chain *i*, whereby avoided emissions are calculated according to the Multiple Vehicle Kilometers method
$wtt^{REC1}_{emissions,i}$	Total greenhouse gas emissions in the WTT part of fuel chain *i*, whereby avoided emissions are calculated according to the first Ratio of Energy Contents method
$wtt^{REC1}_{emissions,i,CO_2}$	WTT CO_2 emissions in fuel chain *i*, whereby avoided emissions are calculated according to the first Ratio of Energy Contents method
$wtt^{REC1}_{emissions,i,v}$	WTT emissions of substance of type *v* in fuel chain *i*, whereby avoided emissions are calculated according to the first Ratio of Energy Contents method
$wtt^{REC2}_{emissions,i}$	Total greenhouse gas emissions in the WTT part of fuel chain *i*, whereby avoided emissions are calculated according to the second Ratio of Energy Contents method
$wtt^{REC2}_{emissions,i,CO_2}$	WTT CO_2 emissions in fuel chain *i*, whereby avoided emissions are calculated according to the second Ratio of Energy Contents method
$wtt^{REC2}_{emissions,i,v}$	WTT emissions of substance of type *v* in fuel chain *i*, whereby avoided emissions are calculated according to the second Ratio of Energy Contents method
$wtt_{energy,i}$	Primary energy input in the WTT system of fuel chain *i* per unit of fuel leaving the WTT system of the fuel chain
$WTT_{energy,i}$	Total amount of primary energy used in the WTT system of fuel chain *i*
$wtt^{k}_{energy,ap}$	Amount of primary energy of type *k* needed to create 1 unit of the avoided product of type *ap* in the WTT system of its fuel chain
$wtt^{k}_{energy,i}$	Amount of primary energy from primary feedstock of type *k* used in fuel chain *i*, relative to 1 unit of fuel leaving the WTT system of the fuel chain
$WTT^{k}_{energy,i}$	Amount of primary energy from primary feedstock of type *k* used in fuel chain *i*
$wtt^{APEE}_{energy,i}$	Total WTT energy use of primary feedstock in fuel chain *i*, whereby byproducts are subtracted from the fuel chain according to the Avoided Primary Energy and Emissions method
$wtt^{APEE,k}_{energy,i}$	WTT energy use of primary feedstock of type *k* in fuel chain *i*, whereby byproducts are subtracted from the fuel chain according to the Avoided Primary Energy and Emissions method
$wtt^{MVK}_{energy,i}$	Total WTT energy use of primary feedstock in fuel chain *i*, whereby byproducts are subtracted from the fuel chain according to the Multiple Vehicle Kilometers method

$wtt^{MVK,k}_{energy,i}$	WTT energy use of primary feedstock of type *k* in fuel chain *i*, whereby byproducts are subtracted from the fuel chain according to the Multiple Vehicle Kilometers method
$wtt^{REC1}_{energy,i}$	Total primary energy use in the WTT system of fuel chain *i* to produce 1 unit of fuel *i* according to the first Ratio of Energy Contents method
$wtt^{REC1,k}_{energy,i}$	WTT energy use of primary feedstock of type *k* in fuel chain *i*, whereby byproducts are accounted for according to the first Ratio of Energy Contents method
$wtt^{REC2}_{energy,i}$	Total primary energy use in the WTT system of fuel chain *i* to produce 1 unit of fuel *i* according to the second Ratio of Energy Contents method
$wtt^{REC2,k}_{energy,i}$	WTT energy use of primary feedstock of type *k* in fuel chain *i*, whereby byproducts are accounted for according to the second Ratio of Energy Contents method
WTW	Well to Wheel
$wtw_{emissions,i}$	Total greenhouse gas emissions produced in the WTW fuel chain *i*, per unit of fuel
$wtw_{emissions,i,CO_2}$	CO_2 emissions produced in the total WTW fuel chain *i*, per unit of fuel
$wtw_{emissions,i,v}$	Emissions of substance of type *v* produced in the total WTW fuel chain *i*, per unit of fuel
$wtw^{*}_{emissions,i}$	Total greenhouse gas emissions produced in the WTW fuel chain *i*, per unit of distance travelled
$wtw^{*}_{emissions,i,CO_2}$	CO_2 emissions produced in the total WTW fuel chain *i*, per unit of distance travelled
$wtw^{*}_{emissions,i,v}$	Emissions of substance of type *v* produced in the total WTW fuel chain *i*, per unit of distance travelled
$wtw^{APEE}_{emissions,i}$	Total greenhouse gas emissions in the total WTW fuel chain *i*, whereby avoided emissions are calculated according to the Avoided Primary Energy and Emissions method
$wtw^{APEE}_{emissions,i,CO_2}$	WTW CO_2 emissions in fuel chain *i*, whereby avoided emissions are calculated according to the Avoided Primary Energy and Emissions method
$wtw^{APEE}_{emissions,i,v}$	WTW emissions of substance of type *v* in fuel chain *i*, whereby avoided emissions are calculated according to the Avoided Primary Energy and Emissions method
$wtw^{MVK}_{emissions,i}$	Total greenhouse gas emissions in the total WTW fuel chain *i*, whereby avoided emissions are calculated according to the Multiple Vehicle Kilometers method
$wtw^{MVK}_{emissions,i,CO_2}$	WTW CO_2 emissions in fuel chain *i*, whereby avoided emissions are calculated according to the Multiple Vehicle Kilometers method
$wtw^{MVK}_{emissions,i,v}$	WTW emissions of substance of type *v* in fuel chain *i*, whereby avoided emissions are calculated according to the Multiple Vehicle Kilometers method
$wtw^{REC1}_{emissions,i}$	Total greenhouse gas emissions in the total WTW fuel chain *i*, whereby avoided emissions are calculated according to the first Ratio of Energy Contents method
$wtw^{REC1}_{emissions,i,CO_2}$	WTW CO_2 emissions in fuel chain *i*, whereby avoided emissions are calculated according to the first Ratio of Energy Contents method
$wtw^{REC1}_{emissions,i,v}$	WTW emissions of substance of type *v* in fuel chain *i*, whereby avoided emissions are calculated according to the first Ratio of Energy Contents method

$wtw^{REC2}_{emissions,i}$	Total greenhouse gas emissions in the total WTW fuel chain *i*, whereby avoided emissions are calculated according to the second Ratio of Energy Contents method
$wtw^{REC2}_{emissions,i,CO_2}$	WTW CO_2 emissions in fuel chain *i*, whereby avoided emissions are calculated according to the second Ratio of Energy Contents method
$wtw^{REC2}_{emissions,i,v}$	WTW emissions of substance of type *v* in fuel chain *i*, whereby avoided emissions are calculated according to the second Ratio of Energy Contents method
$wtw_{energy,i}$	Amount of primary energy used in the total WTW fuel chain of fuel *i*
$wtw_{energy,i,k}$	Amount of energy of primary feedstock *k* used in the total WTW fuel chain *i*
$wtw^{APEE}_{energy,i}$	Total WTW energy use in fuel chain *i*, whereby byproducts are subtracted from the fuel chain according to the Avoided Primary Energy and Emissions method
$wtw^{APEE,k}_{energy,i}$	WTW energy use of primary feedstock of type *k* in fuel chain *i*, whereby byproducts are subtracted from the fuel chain according to the Avoided Primary Energy and Emissions method
$wtw^{MVK}_{energy,i}$	Total WTW energy use in fuel chain *i*, whereby byproducts are subtracted from the fuel chain according to the Multiple Vehicle Kilometers method
$wtw^{MVK,k}_{energy,i}$	WTW energy use of primary feedstock of type *k* in fuel chain *i*, whereby byproducts are subtracted from the fuel chain according to the Multiple Vehicle Kilometers method
$wtw^{REC1}_{energy,i}$	Total WTW energy use in fuel chain *i*, whereby byproducts are subtracted from the fuel chain according to the first Ratio of Energy Contents method
$wtw^{REC1,k}_{energy,i}$	WTW energy use of primary feedstock of type *k* in fuel chain *i*, whereby byproducts are subtracted from the fuel chain according to the first Ratio of Energy Contents method
$wtw^{REC2}_{energy,i}$	Total WTW energy use in fuel chain *i*, whereby byproducts are subtracted from the fuel chain according to the second Ratio of Energy Contents method
$wtw^{REC2,k}_{energy,i}$	WTW energy use of primary feedstock of type *k* in fuel chain *i*, whereby byproducts are subtracted from the fuel chain according to the second Ratio of Energy Contents method
$Z_{i,v,q}$	Emission of substance of type *v* produced in step *q* of fuel chain *i*
σ_i	CO_2 content of fuel of type *i*
σ_k	CO_2 content of primary feedstock of type *k*
σ_s	CO_2 content of byproduct of type *s*

Appendix D: Overview of fuel chains, process fuels, primary feedstocks, byproducts and emissions

Fuel chains & process fuels

i, j	Fuel chain / process fuel	g CO_2 / MJ_{fuel}	HHV (MJ/l)	LHV (MJ/l)	HHV (MJ/kg)	LHV (MJ/kg)	density (kg/m^3)
1	Diesel	72,8	38,69	35,84	45,20	41,88	855,9
2	Gasoline	73,4	34,87	32,22	47,29	43,70	737,3
3	LPG	66,3	25,47	23,43	48,20	44,35	528,3
4	Heavy fuel oil	74,3	41,70	39,05	43,49	40,72	958,9
5	Natural gas	56,2	0,035	0,032	42,21	37,99	0,833
6	CNG	56,2	0,035	0,032	42,21	37,99	0,833
7	Ethanol from sugar rich biomass	71,3	23,57	21,20	29,78	26,78	791,5
8	Ethanol from cellulosic biomass	71,3	23,57	21,20	29,78	26,78	791,5
9	FT diesel from cellulosic biomass	70,7	35,84	33,14	46,55	43,03	770,1
10	Electricity	0,0	N/A	N/A	N/A	N/A	N/A
14	FT diesel from natural gas	70,7	35,84	33,14	46,55	43,03	770,1
18	Coal	85,3	N/A	N/A	21,70	19,53	N/A

Primary feedstocks

k	Primary feedstock	g CO_2 / MJ_{fuel}	HHV (MJ/l)	LHV (MJ/l)	HHV (MJ/kg)	LHV (MJ/kg)	density (kg/m^3)
1	Crude oil	72,8	38,52	36,26	45,57	42,89	845,4
2	Natural gas	56,2	0,035	0,032	42,21	37,99	0,833
3	Coal	112,7	N/A	N/A	21,70	19,53	N/A
4	Sugar rich biomass	93,2	N/A	N/A		17,00	N/A
5	Cellulosic biomass	101,1	N/A	N/A	18,81	17,97	N/A

Byproducts

s	Byproduct	g CO_2 / MJ_{fuel}	HHV (MJ/l)	LHV (MJ/l)	HHV (MJ/kg)	LHV (MJ/kg)	density (kg/m^3)
1	Animal feed	95,0	N/A	N/A	14,25	12,50	N/A
2	Green electricity	0,0	N/A	N/A	N/A	N/A	N/A
3	FT LPG	66,3	25,47	23,43	48,20	44,35	528,3
4	FT gasoline	73,4	34,87	32,22	47,29	43,70	737,3

Emissions

v	Emission	GWP (g CO_2-equivalent/MJ)
1	Methane, CH_4	23
2	Nitrous oxide, N_2O	296

Appendix E: Background information on the Fischer-Tropsch process

The production of Fischer-Tropsch diesel consists of three stages: production of syngas, conversion of syngas to Fischer-Tropsch products and upgrading of products. These stages will be discussed one by one.

Production of syngas

Syngas can be produced by a reaction of the feedstock with steam, oxygen, or a combination of steam and oxygen. The reaction with steam was originally developed with methane as feedstock and therefore has been called Steam-Methane Reforming (SMR). Although it can nowadays be applied to longer alkanes, too, the name has not changed. The reaction is represented as follows [Oukaci, 2002]; [Wang, 2002]:

$$C_mH_n + mH_2O \rightarrow (\tfrac{1}{2}n + m)H_2 + mCO \tag{75}$$

This reaction is endotherm and requires a cobalt catalyst. The reaction results in a relatively large amount of hydrogen. It therefore is ideal in situations where the feedstock has a low H/C ratio, like cellulosic biomass or coal. With methane as feedstock, the reaction results in a surplus of hydrogen and is less favourable.

The second way in which syngas can be produced, is a reaction between an alkane and oxygen, named POx, Partial Oxidation [Oukaci, 2002], [Wang, 2002]:

$$C_mH_n + \tfrac{1}{2}mO_2 \rightarrow \tfrac{1}{2}nH_2 + mCO \tag{76}$$

This reaction has the advantage that it runs without catalysts, but then it requires a high temperature (1200 to 1400 °C), and is therefore costly. Partial oxidation is a carbon monoxide contributor; the reaction results in relatively much carbon monoxide. This makes the reaction very suitable for methane as feedstock. Most feedstocks are solids, which means they have more than enough carbon but they lack hydrogen. These feedstocks benefit from hydrogen enhancers like steam methane reforming. With methane as feedstock, it is the other way around: methane has enough hydrogen, but has little carbon. With partial oxidation, the contribution of carbon monoxide in the syngas can be enhanced.

To overcome the disadvantages of Steam Methane Reforming and Partial Oxidation, a third reaction has been developed. This reaction is called Auto Thermal Reforming (ATR) and is actually a combination of the other two reactions [Oukaci, 2002]; [Wang, 2002]:

$$2C_mH_n + mH_2O + \tfrac{1}{2}mO_2 \rightarrow (m + n)H_2 + 2mCO \tag{77}$$

This reaction requires a cobalt catalyst, like the Steam Methane Reforming reaction, but runs at lower temperatures than Partial Oxidation, namely at a temperature between 900 and 1100 °C. The different reactions, SMR, POx and ATR can also be combined to obtain the desired hydrogen/carbon monoxide ratio in the syngas. If the feedstock contains impurities, not only hydrogen and carbon monoxide are formed, but also H_2S, NH_3, HCl, traces of other gases and ashes. These undesired components must be removed before the actual Fischer-

Tropsch reaction because the FT reaction requires a catalyst that can easily be damaged by the presence of components other than carbon monoxide and hydrogen.

Fischer-Tropsch reaction

The second stage in the production step of FT diesel is the Fischer-Tropsch reaction. This reaction can be written as [Oukaci, 2002]; [Wang, 2002]:

$$\left(\frac{n}{2}+m\right)H_2 + mCO \rightarrow C_mH_n + mH_2O \qquad (78)$$

The value of *m* constitutes the average length of the hydrocarbons that are formed. The main products of the Fischer-Tropsch reaction are alkanes, in which case *n* equals *2m+2*. Also, some fractions of alkenes are formed. In this case, *n* equals *2m*. For both alkanes and alkenes, water is formed as a byproduct. Parallel to the FT reaction, a second reaction takes place, namely the formation of alcohols [Oukaci, 2002]; [Wang, 2002]:

$$2mH_2 + mCO \rightarrow C_mH_{2m+1}OH + mH_2O \qquad (79)$$

Also in this reaction, water is formed as a byproduct. The Fischer-Tropsch reaction requires a catalyst to take place. So far, four catalysts have been identified: Nikkel (Ni), Iron (Fe), Cobalt (Co) and Ruthenium (Ru) [Oukaci, 2002]. Iron and cobalt catalysts are used most. Nikkel results in the formation of a high fraction of methane, which is not desired, especially not when the feedstock consists of methane. Ruthenium catalysts have been discovered only lately. At this moment, they are very expensive and little is known about their behaviour. Iron and cobalt catalysts are best known. Each has its own advantages and disadvantages. When an iron catalyst is used, the reaction products consist of a mixture of alkanes and alkenes, and some smaller fractions of alcohols. The preferred products are alkanes, so when an iron catalyst is used, a lot of upgrading of the products is needed to convert alkenes and alcohols to alkanes. The iron catalyst has a great advantage though: the presence of iron enables the water-gas shift (WGS) reaction to take place. The water-gas shift reaction converts water into carbon dioxide, thereby producing hydrogen and consuming carbon monoxide:

$$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad (80)$$

This reaction is an equilibrium reaction, which means that it can be used to convert carbon monoxide to hydrogen, but also to convert hydrogen to carbon monoxide. This gives it the ability to adjust the composition of the syngas. Very often when cellulosic biomass or coal is used as feedstock, the syngas is poor on hydrogen. By using iron catalysts in the Fischer-Tropsch reaction additional hydrogen can be supplied.

The other well-known catalyst is cobalt. The use of cobalt catalysts results in a product that consists almost entirely of alkanes, with only minor fractions of alkenes and alcohols. This means that the products require far less upgrading than they would if iron catalysts had been used. On the other hand, cobalt catalysts have no WGS activity. Therefore, the composition of the syngas can not be adjusted during this stage of the production step. In general, cobalt catalysts are used when the composition of the syngas is rater constant, as is the case with methane as feedstock. If biomass or coal are used as feedstock, there is a lot of variation in the composition of the feedstock and thus in the composition of the syngas. In this case, iron catalysts are the best option. Both iron and cobalt catalysts are sensitive to damage by contaminations in the syngas. In order to protect the catalysts, the syngas is purified from all contaminations. As a result, the Fischer-Tropsch products are very clean and contain virtually no sulpher, nitrogen or aromatic impurities [Wang, 2002].

In formula (78) and (79) we have seen that the production of alkanes, alkenes and alcohols all result in the formation of water as a byproduct. Because both the Fischer-Tropsch reaction and the reaction in which alcohols are formed are exothermal, a lot of heat is generated during the reaction. With a part of this heat, the water is turned into steam. This can either be used to produce syngas in the SMR reaction, or to generate electricity. In case biomass or other organic materials are used as feedstock, the electricity is green electricity, otherwise it is "grey" electricity.

The average length of the carbon chains is recorded by the value of *m* in equation (78). One should note however, that this is only an *average* value. The distribution of products over chains with different lengths is described by the Anderson-Schulz-Flory (ASF) distribution [Oukaci, 2002]; [Tijmensen, 2002]. The ASF-distribution describes the chain growth probability for each carbon length. The distribution has been determined from experimental data and is therefore not exact. It tends to underestimate methane yields and to overestimate the yield of chains with 2 carbon atoms [Oukaci, 2002]. The distribution can be described mathematically as follows:

$$C_p = \alpha^{p-1}(1-\alpha) \qquad (81)$$

With:

p: chain length expressed in number of carbon atoms

α: chain growth probability. $(1-\alpha)$ is the chance that the chain terminates. The longer the carbon chain becomes, the higher the chances are that it stops growing.

The chain growth probability depends on a number of factors, such as the type of catalyst, the hydrogen/carbon monoxide ratio in the syngas, temperature, pressure and reactor type. Figure A.1 shows the fractions of a number of carbon chain lengths as a function of the chain growth probability. We see that in case α equals zero, only methane is formed. By increasing the value of α the methane yield diminishes in favour of molecules with longer carbon chains. For example, at α=0,5 mostly molecules with carbon chains of two to four atoms are formed. The chains lengths keep increasing with increasing values of α, until finally at α=1 only waxes are formed, with chain lengths of 41 carbon atoms and more.

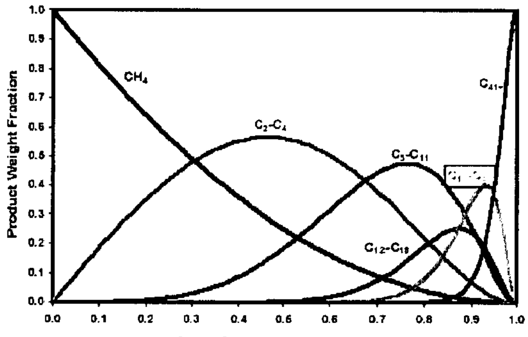

Figure A.1: product distribution as function of α

Source: [Oukaci, 2002]

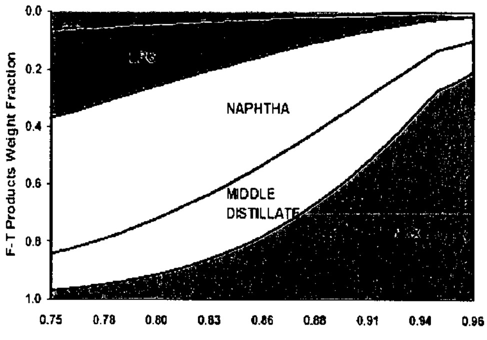

Figure A.2: cumulative product distribution for values of α between 0,75 and 0,96

Source: [Oukaci, 2002]

Figure A.2 shows the cumulative product distribution for values of α ranging from 0,75 to 0,96. By combining figure A.1 and A.2 we find that the yield of middle distillates reaches a maximum at about α=0,87. Besides middle distillates, a range of other products are produced. These include waxes, naphtha and smaller fractions of LPG and methane. Some of these products are upgraded to increase the diesel yield. This is done in the third stage of the production step.

Upgrading of products

The third stage in the production step consists of two main activities: upgrading of alkenes and alcohols to alkanes and upgrading of byproducts. In the description of the previous stage in the production step, we have seen that the use of iron catalysts results in quite considerable fractions of alkenes and alcohols. These are undesired fractions. In the upgrading stage, the alkenes and alcohols are converted to alkanes by means of isomerisation. In a hydrocracking installation, the double bond in alkenes and the carbon-hydroxy bond in alcohols is broken and replaced by hydrogen atoms. This process results in products that consist as good as entirely of alkanes. However, the alkanes are still a mixture of middle distillates, waxes, naphtha, and some lighter fractions. The middle distillates are the desired outcome. The lighter fractions are separated from the mixture as byproducts while the waxes are upgraded in such a way that they become middle distillates, too. The upgrading takes place in a hydrocracker. Actually two processes take place: cracking and isomerisation. Cracking is a process in which long carbon chains are cut into shorter pieces in the presence of a surplus of hydrogen. The hydrogen is needed to replace the broken carbon bonds. In the isomerisation process all carbon chains with side-branches are converted to straight chains. Like most processes, the cracking and isomerisation only work in the presence of a catalyst. Nikkel and cobalt are often used, either as stand-alone catalysts or in combination with Molybdeen (Mo) or Wolfraam (W) [van Asperen, 1999].

With the upgrading of waxes, the production step is finished. The final outcome of the step is a mixture of diesel and fractions of smaller hydrocarbons, such as gasoline and LPG. The excess heat is used to generate electricity.

Appendix F: Background information on the production of ethanol

Ethanol can be produced from two kinds of biomass: cellulosic biomass or sugary biomass. The conversion of cellulosic biomass to ethanol will be discussed first.

Production of ethanol from cellulosic biomass

Cellulosic biomass consists of three components: cellulose, hemicellulose and lignin. Two of these can be converted into sugars and fermented, namely cellulose and hemicellulose. Cellulose is a linear polymer of glucose. The orientation of the molecules towards each other and the frequently occurring hydrogen bonds make the molecule very strong and difficult to brake [Hamelinck, 2003]. Typically cellulose makes up 40 to 60 % of the weight of dry biomass. The other component that can be converted to ethanol is hemicellulose, which makes up 20 to 40 % of the weight of dry biomass. Hemicellulose consists of a mixture of short chains of a number of sugars that are highly branched. The sugars are pentoses (sugars with 5 carbon atoms) as well as hexoses (sugars with 6 carbon atoms). Some main occurring pentoses are xylose and arabinose. Of the hexoses, glucose and mannose occur frequently [Hamelinck, 2003]. The bonds between the sugars in hemicellulose can easily be broken. The third component of cellulosic biomass is lignin. Lignin accounts for 10 to 25 % of the weight of dry biomass. It consists of large polymers and serves to keep the cells together in the same way as cement works between bricks [Hamelinck, 2003]. It is possible to convert lignin to fuel additives. However, this requires complicated, expensive chemical processes which are currently far from optimal. Therefore lignin is usually burned to produce heat, steam or electricity.

The process in which ethanol is produced can be divided in three phases: pretreatment of cellulosic biomass, conversion by means of saccharification and fermentation and finally upgrading of products. These steps will be discussed one by one.

Pretreatment

Cellulosic biomass as such is not ready to be converted to ethanol and therefore it must be pretreated. Pretreatment consists of mechanical and physical pretreatment. Mechanical pretreatment consists of washing (if necessary), chipping and milling. The last two operations enlarge the surface of the biomass, thus facilitating future operations. Desired biomass particle sizes mentioned in literature vary from a few centimeters to a few millimeters [Hamelinck, 2003]. Physical pretreatment serves to open up the material and to weaken the strong bonds in the cellulose. This facilitates the saccharification of cellulose [Reith, 2002], [Hamelinck, 2003]. Physical pretreatment is a very important reaction step, but the exact working is not yet fully understood. Most pretreatment procedures are therefore experimentally developed. Common techniques include dilute acid treatment, alkaline treatment, ammonia treatment, organic solvent treatment, sulphur dioxide treatment and carbon dioxide treatment [Hamelinck, 2003]. These techniques are not elaborately discussed here. The results from all techniques are more or less similar: by opening up the biomass the cellulose is released and the bonds in the cellulose are weakened. Also, when water or steam has been added, the hemicellulose has already been converted to sugars. For pentoses, the following hydrolysis reaction applies:

$$(C_5H_8O_4)_n + nH_2O \rightarrow nC_5H_{10}O_5 \qquad (82)$$

Hexoses react according to:

$$(C_6H_{10}O_5)_n + nH_2O \rightarrow nC_6H_{12}O_6 \qquad (83)$$

The sugars that result from reaction (82) and (83) are mainly xylose, mannose, arabinose and galactose. The slurry also contains lignin and cellulose.

Hydrolysis and fermentation

The next phase is usually classified as hydrolysis. However, usually the hemicellulose has already been hydrolysed so this term actually refers to the hydrolysis of cellulose. In hydrolysis, also know as saccharification, the cellulose is converted to glucose. Because cellulose consists mainly of hexoses, this reaction is characterized by equation (83). A catalyst is required in order for the reaction to run properly. The most common used catalysts are dilute acid, concentrate acid or enzymes such as cellulase. The importance of physical pretreatment to successful hydrolysis is demonstrated by the following numbers: without physical pretreatment the hydrolyis yield lies below 20%. With pretreatment, the yield exceeds 90% [Hamelinck, 2003]. After completion of the hydrolysis the slurry still contains lignin and some cellulose that was not converted. These are separate from the slurry and burned to produce heat, steam and electricity. What remains is a solution that contains sugars. If the sugar concentration is below 8,5 vol.% the solution needs to be concentrated. This can be achieved by evaporation of the fluid in the solution [Reith, 2002].

Next the sugar solution is fermented to ethanol. Both the sugars with 5 carbon atoms, the pentoses, and the sugars with 6 carbon atoms, the hexoses, are converted to ethanol [Hamelinck, 2003]:

$$3C_5H_{10}O_5 \rightarrow 5C_2H_5OH + 5CO_2 \qquad (84)$$

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2 \qquad (85)$$

Both reactions require yeast, bacteria or other micro-organisms to run. The ethanol that is produced in these reactions can not yet be used as transportation fuel but needs some upgrading.

Upgrading of products

Upgrading consists of concentrating the ethanol content of the fermentation products and purifying it. During the production processes that have been applied so far, all kinds of enzymes, acids and other chemicals have been used. These have to be removed now. Furthermore, the fermentation product is concentrated by means of distillation, rectification and dehydration. Once all these process are finished, the final product consists of more than 99,9 vol.% pure ethanol [Reith, 2002]. The final outcomes of the entire production process consist of ethanol and a small amount of excess green electricity that was generated by burning the lignin and that was not used.

Process integration

In the process that has just been described, all process steps are passed separately. This is known as Separate Hydrolysis and Fermentation, or SHF. However, this is not the only way in which the process steps can be passed. Hydrolysis of cellulose and fermentation of hexoses can be combined in one reactor. This process is called SSF, Simultaneous Saccharification and Fermentation. In SSF, pentoses are fermented separately. Currently research is done to include the fermentation of pentoses in SSF, which results in SSCF, Simultaneous Saccharification and Co-Fermentation [Lynd, 1996]. Finally, if the hydrolysis is catalysed by cellulase, the production of this cellulase can be combined in the SSCF reactor. This total integration is referred to as Consolidated Bio Processing (CBP).

Production of ethanol from sugary biomass

The production of ethanol from sugary biomass is simpler than the production of ethanol from cellulosic biomass. The main difference is that sugary biomass does not contain cellulose and consequently does not require the extensive pretreatment that cellulosic biomass needs. In stead, sugary biomass contains starch and molasses. Like in the production of ethanol from cellulosic biomass, three stages can be distinguished: pretreatment, hydrolysis and fermentation and upgrading of products. As far as stages don't overlap with those from the production of ethanol from cellulosic biomass, they will be discussed.

Pretreatment

The pretreatment stage of the production of ethanol from sugary biomass is much simpler and much better developed than pretreatment in the production of ethanol from cellulosic biomass. The pretreatment starts with milling of the biomass to increase the surface and to facilitate production steps that are yet to come. The milled biomass is then mixed with water and enzymes and cooked. The product that results from this liquefaction process is called mash [$(S\&T)^2$, 2003].

Hydrolysis and fermentation

After the mash from the cookers has cooled down, it is ready for hydrolysis. With the aid of enzymes, the mash is hydrolysed. The main sugars that result from hydrolysis are glucose and fructose, both sugars with 6 carbon atoms [Reith, 2001]. Yeast is added and the sugars are fermented to ethanol according to reaction (85). Again this process step is simpler than the hydrolysis and fermentation step in the production of ethanol from cellulosic biomass. There is no lignin that has to be removed and there are no pentoses that have to be fermented.

Upgrading of products

The ethanol that has been produced in the previous production stage still contains much non-fermentable solids. These are separated in the upgrading stage. The ethanol is distilled and dehydrated which results in final products with over 99,9 vol.% ethanol [$(S\&T)^2$, 2003]. The non-fermentable solids are dried. They are known as Distillers Dried Grains and Solubles (DDGS) and sold as byproducts. It is commonly used as animal feed. There is no lignin used in this process and therefore there has no electricity been generated. Ethanol and animal feed are the only products resulting from the process.

Appendix G: Overview of electricity plants in the Netherlands, generating grey electricity

Electricity plant	Company	Reference
Amercentrale	Essent	[Essent, 2003]
Dongecentrale	Essent	[Essent, 2003]
Centrale Moerdijk	Essent	[Essent c, 2003]
Centrale Swentibold	Essent	[Essent d, 2003]
Clauscentrale	Essent	[Essent b, 2003]
Eemscentrale	Electrabel	[Electrabel, 2003]
Centrale Bergum	Electrabel	[Electrabel, 2003]
Centrale Harculo	Electrabel	[Electrabel, 2003]
Warmtekrachtcentrale Almere	Electrabel	[Electrabel, 2003]
Centrale Gelderland	Electrabel	[Electrabel, 2003]
Flevocentrale	Electrabel	[Electrabel, 2003]
Warmtekrachtcentrale Air Products	Electrabel	[Electrabel, 2003]
Centrale Amsterdam	Reliant	[Reliant, 2003]
Centrale Diemen	Reliant	[Reliant b, 2003]
Centrale Purmerend	Reliant	[Reliant c, 2003]
Centrale Utrecht	Reliant	[Reliant d, 2003]
Centrale Velsen	Reliant	[Reliant e, 2003]
Centrale IJmond	Reliant	[Reliant f, 2003]
Centrale Maasvlakte	E-on	[E-on, 2002]
RoCa	E-on	[E-on, 2002]
Centrale Leiden	E-on	[E-on, 2002]
Centrale Delft	E-on	[E-on, 2002]
Centrale Galileistraat	E-on	[E-on, 2002]
Centrale Den Haag	E-on	[E-on, 2002]
Nuon Power Buggenum	Nuon	[Nuon, 2002]
Kolen en biomassacentrale	EPZ	[EPZ, 2003]
Kerncentrale Borssele	EPZ	[EPZ, 2003]

	Input			**Production**
Electricity plant	*Natural gas*	*Coal*	*Other (fossil)*	
	10^6 m^3	kton	TJ	GWh
Amercentrale	95,9	2811,6	3003,6	8338
Dongecentrale	51,3			184
Centrale Moerdijk	307,9			1806
Centrale Swentibold	421,3			1345
Clauscentrale	573,8		118,8	2309
Eemscentrale	2632,2			11836
Centrale Bergum	473,7			1823
Centrale Harculo	192,6			686
Warmtekrachtcentrale Almere	177,7			599
Centrale Gelderland		1232,9	629,1	3125
Flevocentrale	0,0			0,0
Warmtekrachtcentrale Air Products	0,0			0,0
Centrale Amsterdam	372,1	1437,5	301,4	5360
Centrale Diemen	323,1			1414
Centrale Purmerend	90,2			296
Centrale Utrecht	749,0			2942
Centrale Velsen	484,4		17008,1	3532
Centrale IJmond			7287,2	808
Centrale Maasvlakte		2627,0	3307,9	7096
RoCa	382,0			1309
Centrale Leiden	72,0			225
Centrale Delft	0,0			3
Centrale Galileistraat	271,5			987
Centrale Den Haag	66,6			211
Nuon Power Buggenum	95,6	623,5		1195
Kolen en biomassacentrale	6,6	931,4	1333,7	2612
Kerncentrale Borssele			598,8	3687
Total	7840	9664	34589	63728

Average MJ of electricity	1,081	0,823	0,151	1,000