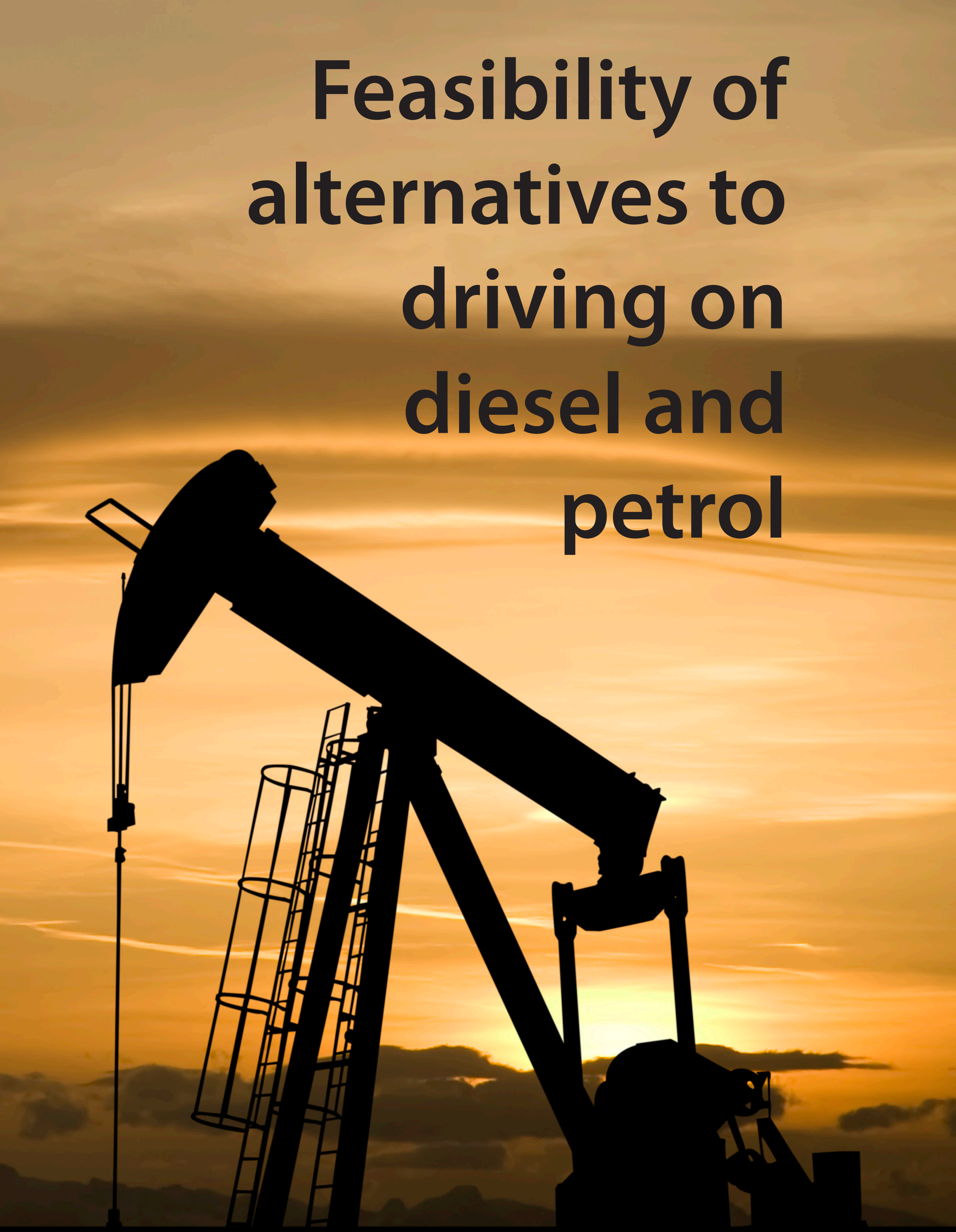

Feasibility of alternatives to driving on diesel and petrol

Oscar van Vliet

Feasibility of alternatives to driving on diesel and petrol

Haalbaarheid van alternatieven voor autorijden op diesel en benzine

(met een samenvatting in het Nederlands)

Proefschrift

ter verkrijging van de graad van doctor aan de Universiteit Utrecht

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te Uithoorn

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voor Rick,

die voortleeft in zijn kinderen.

Before enlightenment; chop wood, fetch water.
After enlightenment; chop wood, fetch water.

– Buddhist monk proverb

Preface

This thesis is the result of 5 years of research in the diverse and often polarised field of alternative fuels and drivetrains. This research was carried out as part of a joint project of the Copernicus Institute of Utrecht University entitled *Quantified backcasting: methodological design of transition strategies in the area of sustainable transportation chains*. The project was financially supported by the Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO) and SenterNovem (now part of Agentschap NL). It also benefitted from and contributed to the Dutch research project CATO (*CO_2 Afvang, Transport en Opslag*).

My part of the project was carried out at the department of Science, Technology and Society, and had two general research aims: (1) consistent analyses and comparison of techno-economic performance of alternative fuels and drivetrains and their impact on CO_2 emissions, and (2) application of technological learning in system analyses that use these fuels and drivetrain by means of bottom-up understanding of improvement possibilities. Roald Suurs and Sylvia Breukers worked on other parts of the project at the department of Innovation Sciences.

The original proposal called for a joint selection of feasible options for future fuels, fuel supply chains and drivetrains that were to be subsequently investigated. Due to timing and personnel issues, this joint selection did not happen at the start of the research period. Later on, the selection of options presented in chapter five and the theme of the chapter six were shaped in part by discussions with my colleagues in the department of Innovation Sciences.

The techno-economic comparison uses quantitative data ranging from the cost of transporting wood chips in developing countries to the efficiency of various Fischer-Tropsch processes and projections on the cost development of fuel cells. Building this data set took most of the allotted research time.

Possible future fuel production and drivetrain systems were identified and their potential costs and GHG emissions assessed with uncertainty margins. However, lack of publicly accessible data hampered the initial intention of constructing learning curves for the production of advanced fuels and drivetrains. The focus therefore shifted somewhat, to the question of how this fundamentally uncertain data can be made useable for policy decision making while keeping the nuance that the uncertainty margins provide. I hope that this thesis provides input to answer that question.

Wien, June 2010

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"Difficulty is the excuse history never accepts."

– Edward R. Murrow, comment after JFK's inaugural address

1. Introduction: Evolutionary transitions to new fuels and cars

1.1 Introduction

Globally, our road transport sector is powered almost exclusively by internal combustion engines (ICE) and more than 90% of these engines are powered by fuels derived from crude oil. Both the current cost and projected future costs of crude oil have risen sharply in the last years [1, 2, 3, 4, 5, 6]. Doubts about of security of imported crude oil supplies remain, and prices are expected to remain volatile but higher than in the past [7, 8].

Road transport is also a major source of greenhouse gases (GHG). In the European Union (EU), it is responsible for 18% of GHG emissions [9, 10]. Cars[1] produce just over 60% of road transport GHG emissions in the Netherlands [11]. Furthermore, road transport contributes to emissions of air pollutants such as NO_x, PM_{10} and volatile organic compounds [12, 13].

While overall EU GHG emissions have stabilised in recent years, both the demand for and the GHG emissions from transport have continued to grow [12, 14]. The total EU demand for road transport is expected to rise by 36% from 2006 to 2020, including modal shifting away from road transport [15, 16].

The current European passenger car has CO_2 emissions of around 140 g/km and the total European fleet emits some 930 Mtonnes of CO_2 per year [10, 17]. In order to reduce the emissions from cars, the European Union has issued legislation to progressively limit fuel consumption and reduce emissions of GHG and air pollutants [18, 19, 20, 21, 22].

Changing the cars, fuels and related infrastructure we use today is a complicated and expensive transition. Also, the cars, fuels and infrastructure depend on each other to work and be profitable (c.f. [23]). Replacing these could make a lot of existing capital redundant [24]. Because of the interdependence of cars, fuels and infrastructure, alternative solutions must evolve together. Colloquially, changing transport is hampered by sunk costs and a chicken-and-egg problem.

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[1] Cars, as used in this thesis, include private and leased passenger automobiles, and fleet passenger cars like taxis. Cars exclude vans, trucks, semi-trailers, buses, motorbikes, mopeds and special purpose vehicles.

Extrapolating these conditions into the future, we see that change in transportation is path-dependent, and choosing a particular alternative now may lock in or lock out future alternatives[2] [26, 27, 28].

However, some possible solutions that could be affordable and efficient in the long term are currently not yet mature and still expensive. Adopting these solutions *en masse* now could be (much) more financially expensive in the short term than keeping existing fuels and cars. Individual motorists in particular, may not find alternative solutions that are potentially affordable and efficient in the long run to be feasible or acceptable now. For example, *very* few motorists will buy a €80 000 hydrogen fuel cell-powered compact car with no extra features and for which there are only some dozen refuelling stations in the whole of Europe.

With favourable market developments and greater demand, alternatives should become cheaper in the future as experience accumulates with using and manufacturing the technologies involved [29]. Greater demand also leads to higher return on investment in refuelling infrastructure. However, the future affordability and efficiency of very immature alternatives cannot be taken for granted, as they partially depend on scientific and technological breakthroughs which are hard to predict.

To reduce dependence on crude oil in transport, the use of electricity and hydrogen in cars has been advocated for decades [30, 31, 32]. Electric motors have been used to drive cars as far back as the 1890s [32], though the existing electricity distribution grid may need strengthening if large numbers of cars are to be charged at peak times [33]. Hydrogen can be converted to electricity in a fuel cell (FC) car with high efficiency, generating no tailpipe CO_2 emissions and hardly any other pollutants [34]. However, a costly infrastructure to produce, distribute and store hydrogen will be required, as well as breakthroughs in on-board storage and fuel cell technology [35, 36, 37, 38].

Hydrogen and electricity can be produced from a wide variety of energy sources, fossil (including nuclear) and renewable. Both can therefore decrease the dependence on crude oil and increase energy security [39, 40]. However, costs of fuel cells and batteries remain high. Researchers give varied and uncertain appraisals of the development of the costs of alternative drivetrains [41, 42, 43, 44, 37, 45].

In response, the current focus of thinking on car and fuel alternatives in scientific literature seems to be moving away from the visionary, large scale systems implementations to a more short-term

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[2] Multiple equilibrium states can be visualised as a (fitness) landscape in which a local optimum is a valley. Each optimum has a basin of attraction, a collection of system states for which the preferred heading of change is towards that optimum, much like a drainage basin of a river (c.f. 25) However, due to technological learning, supply limitations and returns to scale, the contours of the transportation landscape are constantly changing.

incremental strategy [46, 47, 40, 48, 49]. There is a growing interest and investment in combinations of drop-in replacements for oil-derived fuels, especially biofuels, and (plug-in) hybrid cars that reduce fuel demand.

This shift in focus may be explained by the lack of progress in on-board hydrogen storage and PEM fuel cell development not living up to expectations of the 1990s and early 2000s, and the large costs associated with a hydrogen distribution network [42, 38, 50, 37, 51, 23]. In addition, many stakeholders are either invested in particular alternatives or susceptible to externally generated hype cycles of utopian visions followed by disappointment [38, 52, 53]. Long-term visions and expectations, rather than practical achievements, have been the main drivers behind the development of hydrogen as a transport fuel in the Netherlands. [52, 54]. Together with uncertainties about (projected) performance of alternatives, hype cycles have contributed to a lack of stable consensus on feasible short- to medium-term solutions, as opposed to long-term visions [53, 55, 56].

The present focus in this socio-technological development draws on the notion that a gradual transition, that builds on existing infrastructure and technology (especially cars), is more feasible to implement. Logic dictates that an evolutionary development, changing as few elements of the cars, fuels and related infrastructure at the same time as possible, would make for the least invasive transition [24, 25]. This would also appeal to motorists, who generally prefer not to sacrifice comfort or performance [57, 58, 59].

At the same time, higher oil prices generate intense interest in development of new technologies to produce transport fuels, as the transportation fuels market is worth hundreds of thousands of millions annually and holds large business opportunities. Higher oil prices also make fuel economy a more important attribute for cars.

Figure 1.1 shows the actors involved in the well-to-wheel (WTW) chain of driving. Table 1.1 shows which alternatives require changes from motorists and the trio of car manufacturers, fuel producers and fuel distributors. Fischer-Tropsch synthetic diesel and petrol, methanol, ethanol, biodiesel, and hybrid cars are the alternatives that affect one or two out of four. DME, methane or natural gas, electric cars, and hydrogen cars affect all of them (to varying degrees), and may therefore be more difficult to implement.

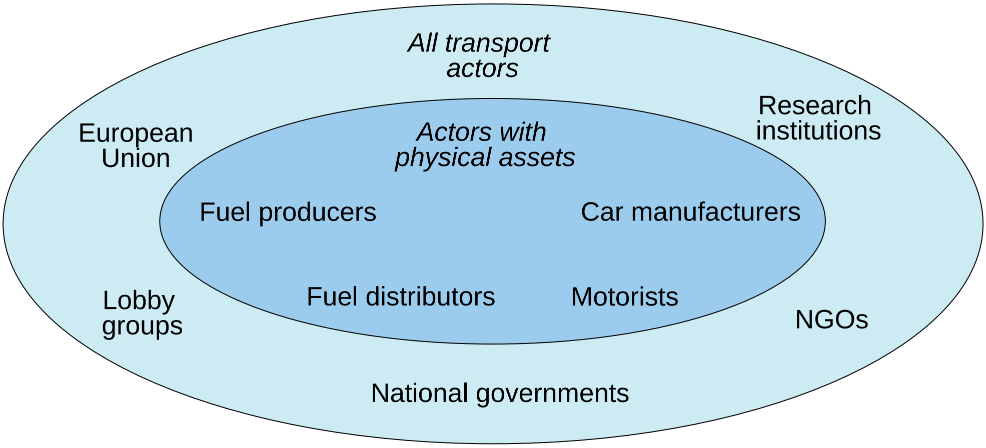

Figure 1.1: Main actors involved in transition to alternative fuels and cars. Outer ring: actors with influence but not physical assets. Inner ring: actors with physical assets.

Actor	Car manufacturers	Fuel producers	Fuel distributors	Motorists
Alternative fuels and drivetrains causing significant changes	Dimethylether fuel Methane/NG fuel Hybrid drivetrain Electric drivetrain Fuel cell drivetrain (hydrogen-fuelled)	Fischer-Tropsch fuels Methanol fuel Dimethylether fuel Methane/NG fuel Hydrogen fuel Electricity as fuel Biodiesel fuel Ethanol fuel	Dimethylether fuel Methane/NG fuel Hydrogen fuel Electricity as fuel	Hybrid drivetrain Dimethylether fuel Methane/NG fuel Electric driving Hydrogen driving

Table 1.1: Alternatives causing significant changes per actor, from approximately least to most invasive (see Appendix 1 for a description of the vehicle adaptations required to drive on for various fuels).

The potential downside to the evolutionary transition is that the final reductions in GHG emissions and crude oil imports that result from this transition may not be as large or fast as in the case of a 'clean' break from our existing road transport system.

To allow for a comprehensive analysis, all options in table 1.1 except natural gas (NG) are examined in this thesis[3]. Outside the scope of this thesis, but potentially just as important for reducing GHG emissions and reducing oil consumption, are ways to reduce the demand for vehicle kilometres, such as reducing overall transport demand or shifting a share of road transport to other transport modalities [5].

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[3] A WTW analysis of natural gas for transportation has already been presented by Hekkert et al. [24].

1.2 Options for an evolutionary transition

First generation biofuels (ethanol from sugar or starch crops, biodiesel from vegetable oils) make up the largest share of alternative fuels at this time, with production of 286 PJ of biodiesel and 54 PJ of ethanol in the EU in 2008 and a worldwide biofuel production equivalent to 1.8 EJ in 2009 [60, 61, 5]. Brazilian ethanol from sugarcane is fully competitive [62, 63, 64] and ethanol from other sources (such as corn) is competitive given sufficiently high oil prices and/or agricultural subsidies. Ethanol is increasingly used in, for example, Brazil, USA and Sweden. Plant-derived oils and biodiesel are also used, particularly in Germany [65].

Current non-renewable alternative fuels that are on the market in volume are Fischer-Tropsch (FT) fuels from natural gas (gas-to-liquid, or GTL), for example in South Africa, Malaysia, Nigeria and Qatar, FT fuels from coal (coal-to-liquid, or CTL), for example in South Africa and China, and products derived from tar sands or oil shale (syncrude), which are produced in large volumes in Canada [66, 67, 68].

It is expected that in the medium term, second generation biofuels (cellulosic ethanol, Fischer-Tropsch from biomass) can be produced affordably on a large scale [69, 70, 71]. Second generation fuels can be grown using less land and from more diverse soils and climates [72, 73, 74]. However, sustainable production of any biofuels is constrained by impacts on natural habitats, food security, ecology and water consumption [75, 76, 77, 78]. Constrained feedstock availability and financial barriers have slowed down investment in second generation biofuels in recent years [79]. The future of this market depends on the fuels and production technologies that can break out from demonstration scale experiments and achieve real market penetration. In addition, the use of alternative fuels alone does not consistently reduce emissions of local air pollutants, which could have been a driver for large scale adoption [80, 81].

For hybrid cars, cumulative global sales by the market leader alone surpassed 2 million in 2009 [82], and many other manufacturers are adding hybrid cars to their model range nowadays. Plug-in hybrid cars, particularly versions of the Toyota Prius [83, 84], have existed for some time. The Chevrolet Volt (Opel Ampera in Europe) is the first plug-in hybrid electric car by a major car manufacturer, due to go on sale in late 2010 [85].

It is likely that some combination of fuel and vehicle alternatives will be the most feasible path to lower emissions from cars and reduced oil consumption, with the mix changing over time as technology and circumstances progress. Many scenarios have been made with such combinations [86, 87, 88, 89, 90]. However, the underlying assumptions and data sets used in these forecasts do not help us to find out what is the least invasive combination of alternatives.

A trade-off will be needed between final goals for reduction in GHG emissions and crude oil consumption, costs of implementing these goals, and invasiveness of the transition required to attain them. Backcasting from these goals, a least-effort transition scenario can be constructed.

Given this context, the central question for this thesis is:

> *How and to what extent can we achieve meaningful reductions in GHG emissions from car use and diversify our energy resources for transport, preferably via an evolutionary transition, thereby avoiding a radical (and potentially expensive) renovation of our road transport system?*

Cost and GHG emissions of transportation options are quantifiable variables that *prima facie* enable design of a transition in road transport. However, the transition is complicated by three issues that are encountered repeatedly in investigating the central question:

- Competition between alternatives in a path-dependent system, which extends beyond the choice of fuels or drivetrains. For example, if we assume no competition for supply, co-firing biomass in a power plant reduces CO_2 emissions more than using it for biofuels [45]. Furthermore, dominance of one option can keep resources (e.g. money, feedstocks, attention) away from developing and producing alternatives.

- Uncertainty in the current and projected efficiencies, costs and GHG emissions resulting from the use of alternative fuels and drivetrains. These uncertainties make it difficult to distinguish the costs and GHG emissions of alternative fuels and vehicles and thereby to choose among them in an early stage ('picking the winners').

- Barriers to implementation other than cost, such as availability of energy resources (such as biomass) and underground CO_2 storage capacity to reduce GHG emissions, infrastructure needs and public acceptance of alternatives. While cost is important, more issues than cost inform the choices made in the real world. However, some transportation actors are more interested in reducing environmental emissions or import dependency than others.

1.3 Research work

Five studies have been completed to examine the central question and are presented in this thesis:

In chapter 2: *Fischer-Tropsch diesel production in a well-to-wheel perspective*, several fuel alternatives for a transition in transport are examined. Costs and emissions of Fischer-Tropsch synthetic diesel and petrol are considered using WTW analysis. Conversion of biomass to intermediates, and conversion of biomass intermediates, natural gas and coal to FT fuels are examined in detail by calculating mass and energy balances. Factored estimation is used to determine the costs of process units. FT fuel costs depend largely on the feedstock used and the scale of the FT plant, while emissions depend on the feedstock used and the use of carbon capture and storage (CCS). Large uncertainties persist in both sets of results.

In chapter 3: *Techno-economic comparison of series hybrid, fuel cell and regular cars*, several vehicle alternatives for a transition in transport are examined. The potential development of hybrid cars into series- and plug-in hybrids, and of fuel cell hydrogen cars is examined using WTW analysis. Efficiency and cost of these cars are assessed by analysing the efficiency and costs of drivetrain components in detail. The annual cost of driving these cars is compared with and without existing Dutch tax incentives. Results show that advantages of series hybrids are that it allows for a smaller and lighter ICE, lower fuel consumption and maintenance requirements, and easy onward development into electric or fuel cell cars. Disadvantages are its unfamiliarity with motorists and car mechanics, the extensive redesign of the vehicle platform required, and (for now) higher purchasing costs.

In chapter 4: *Energy use, cost and CO_2 emissions of electric cars*, more vehicle alternatives for a transition in transport are examined. Costs, emissions and effects on electricity infrastructure of plug-in hybrids and battery powered electric vehicles are examined using WTW analysis. Efficiency and cost of vehicles are calculated as in Chapter 3, and effects on electricity infrastructure are examined by matching existing demand plus charging patterns to existing generation capacity for grid electricity. Results show that costs are dominated by the costs of batteries. Another finding is that if coordinated charging is successfully introduced, few additional investments into transmission or generation capacity are needed. CO_2 emissions from charging depend largely on the generation capacity used, and less on the charging pattern.

In chapter 5: *Combining hybrid cars and synthetic fuels with electricity generation and carbon capture and storage*, long term transition paths are determined by integrating WTW data collected in chapters 2, 3 and 4 into the MARKAL-NL-UU optimisation model of the Dutch electricity and heat system. Linear programming is used to calculate system solutions with the lowest net present value. Results show that to halve CO_2 emissions from power and transportation, biofuels are preferred and hybrid cars are used if insufficient low-carbon fuels are available. Lowest system cost is achieved by using the least-cost CO_2 emissions reduction options in transportation, even if that reduces biomass and CO_2 storage capacity available for electricity generation.

In chapter 6: *Multi-agent simulation of adoption of alternatives to diesel and petrol*, the role of motorists in the acceptance of alternative fuels is considered. Using an agent-based model, the co-evolution of demand for and production capacity of drop-in replacement fuels is examined with motorists represented by simple agents. On the supply side, limited resources are converted and blended into fuel in conversion plants using different technologies. On the demand side, heterogeneous motorists choose fuels based on their price, popularity and perceived effect on vehicle performance and environment. In the resulting simulations, adoption of alternative fuels is most often confined to niche markets. Availability and cost of energy resources, as well as motorists' attitudes have the strongest influence on fuel adoption rates, and consistency in measures to support adoption was found to be crucial.

A summary and synthesis are made from insights gained from the previous chapters in chapter 7: *Summary and conclusions: Defining evolutionary strategies towards new fuels and cars*.

Appendix 1: Alternative fuel options

Table 1.2 shows a selection of fuels for transportation, feedstock options to produce these fuels, and vehicle adaptations required to enable cars to run on these fuel. Fuel alternatives are shown in order of increasing scope of the modification required. After-market installation of equipment to allow driving on ethanol, biodiesel, LPG and compressed natural gas is routinely performed on commercial basis. Drop-in replacement is therefore a sliding scale.

Electric cars are seen as easier to introduce than hydrogen cars because the distribution infrastructure for electricity is already present. Furthermore, these cars can be considered an extension of hybrid cars that are already on the market. Plug-in hybrids (that use grid-charged batteries for short distances and normal engine for long distance driving) have most of the advantages of both normal hybrids and electric cars, but are more expensive than hybrid cars.

Fuel	**Feedstock**	**Vehicle adaptations**
Classic diesel and petrol	Crude oil[1]	None
Diesel and petrol from tar sands or oil shale	Very heavy crude oil, partially hydrogenated[1]	None
FT diesel and petrol	Coal, natural gas, biomass[1]	None
Biodiesel 20% blend	Rapeseed, soy, sunflower, oil palm, jatropha	Upgrade gaskets and hoses on old cars
Biodiesel 99% blend		Idem, and use a biodiesel that does not solidify in cold weather.
Ethanol 10% blend	Sugar cane, corn (future: any biomass)	None
Ethanol 85% blend		Increase fuel flow[2], small petrol tank for cold starts, fuel gauge (corrosion-proof linings required)
Liquefied Petroleum Gas (LPG)	Crude oil (refinery by-product) [1]	Double intake manifold / injection system, medium pressure tank (3-15 bar) (compatible lubrication system required)
Dimethyl Ether (DME)	Oil, coal, natural gas, biomass[1]	
Compressed natural gas (CNG) / Methane	Natural gas	Double intake manifold / injection system, high pressure tank (200-300 bar)[2]
Electricity	Oil, coal, natural gas, biomass[1]	Battery-fed, fully electric engine
Hydrogen (H_2)		High pressure tank (300-600 bar), fuel cell-fed, fully electric engine[3]

[1] GHG emissions from the production of these fuels can be reduced by application of carbon capture and storage (CCS). [2] The engine compression ratio must be increased to achieve optimal fuel efficiency when running on ethanol or natural gas. [3] Hydrogen can be used in a combustion engine much like CNG (for example, in the BMW 7), but this has a very low WTW energy efficiency.

Table 1.2: Possible feedstocks of alternative fuels and vehicle adaptations required to use that fuel.

"The economical assessment of future technologies, in a trade competitive domain, is probably among the most risky challenge ever proposed to a crystal ball."

- Mahieu, Larivé, Edwards & Rouveirolles, *Wheel-to-wheel analysis of future automotive fuels and powertrains in the European Context*

2. Fischer-Tropsch diesel production in a well-to-wheel perspective

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This chapter is an updated version of the publication: van Vliet OPR, Faaij APC, Turkenburg WC. *Fischer-Tropsch diesel production in a well-to-wheel perspective: a carbon, energy flow and cost analysis*. Energy Conversion & Management 2009;50:855-76. http://dx.doi.org/10.1016/j.enconman.2009.01.008

2.1 Introduction

2.1.1 Challenges

Transportation contributes 21% of greenhouse gas emissions in Europe and continues to grow [91]. More than 90% of these emissions are due to road traffic, and these have grown by 22% in the period of 1990-2002 [92]. Road transport also produces appreciable quantities of fine particulate matter, volatile organic compounds and other forms of pollution [93]. Environmental problems and other factors, like high oil prices, insecurity about the stability of the oil supply chain and doubts about the sufficiency of oil stocks on the long term put the existing transportation fuel system under pressure.

Consequently, a search is ongoing for alternatives, like new and cleaner fuels. Many alternative fuels, such as biodiesel, DME, ethanol, hydrogen, natural gas and Fischer-Tropsch (FT) fuels have been proposed, researched and compared, see for example [94, 95, 24, 96, 97, 98]. Studies have shown that the alternatives that use the lowest amounts of fossil energy and allow for the strongest reduction in greenhouse gas (GHG) emissions require radical and expensive changes in our vehicles and/or fuel logistics. Other alternatives, such as natural gas, or bio-based DME or FT fuels in hybrid cars may require more total energy per km driven than existing systems, but have the potential to reduce GHG emissions considerably [45].

Well-to-wheel (WTW) studies have been published that examine the potential of FT diesel, see [45, 99, 100, 101]. However, very few of these have gone into sufficient technological and/or economic detail to make the chains mutually comparable and to trace possible developments into the future. Likewise, modelling studies have been made of (limited sets of configurations of) FT plants but these lack a chain-wide perspective, see [99, 102, 69].

Therefore, in this chapter we will make a comprehensive study of the potential of Fischer-Tropsch diesel as a replacement for diesel from crude oil in Europe. We are interested in FT diesel because it is fully compatible with existing vehicles and infrastructure, which is conducive to implementation in the short term. FT diesel can be made from a wide range of feedstocks, including natural gas, coal and biomass, allowing for a gradual transition between energy sources.

FT diesel is well suited to the existing market, as FT diesel has a high cetane number and does not contain sulphur or nitrogen. At the same time, the market share of diesel fuels in the EU is expected to grow considerably, while marginal fossil diesel production at EU refineries is stretched and relatively inefficient and oil prices may remain high [45, 103, 3]. This situation presents an entry point for the FT alternative.

2.1.2 History and current activities

Fischer-Tropsch fuel production was first started in 1935 at the Ruhrchemie company. A total of nine plants were built in Germany, and shut down in 1945. These were coal-to-liquid (CTL) plants [104]. After WWII, Fischer-Tropsch (FT) fuels have been produced primarily from coal in South Africa, in order to reduce the nation's dependence on foreign oil. The economic success of the Sasol plants in South Africa largely coincided with the relatively high oil prices in the late 70s and early 80s that made investment in synthetic fuels favourable [105]. Investment costs were otherwise prohibitive [106]. From the early 1990s, gas-to-liquids (GTL) plants have been constructed to use natural gas as feedstock, to capitalize on (what were at the time) stranded gas reserves [66]. Commercial activities have thus historically been limited to situations where feedstocks were cheap and liquid fossil fuels were expensive.

The only FT fuel that was commercially available in 2007 in the EU is GTL product from the Bintulu plant which is a constituent of the V-Power brand from Shell. As of 2007, companies like Shell, Sasol Chevron, ConocoPhilips and Total are all working on GTL and CTL plants. Large scale GTL activity is underway, especially in Qatar [68, 66]. In addition to confirmed projects, large CTL plants in China (for example in Ningxia Hui) and India are being planned (ibid.). CHOREN Industries in Germany and others experiment with the use of biomass as a feedstock for FT fuel production (biomass-to-liquid or BTL) [107].

Development of FT production could also benefit from improvements in technologies such as gasification and gas cleaning that are used in other commercial activities. However, due to the large projects and investments involved, the speed of implementation of new technologies is limited (see Dry [105], for example).

2.1.3 Research questions

This chapter aims to trace development path for FT diesel, based on data on existing technologies and bottom-up simulations of new technologies. For the narrative in this chapter, it is assumed that increases in diesel demand will be covered to a significant degree by FT fuel plants, fed initially with natural gas and coal, but increasingly with biomass. Potential WTW chains will be compared with regard to cost and the emissions of GHG for various options to produce FT diesel with existing and emerging technology (such as carbon capture and storage). We aim to answer the following questions:

What are the (main determinants of) GHG emissions and costs of FT based chains?
What competitive and climate-friendly FT chains can replace fossil-based diesel?

In section 2.2 we will describe the methodology used to analyze WTW chains. Section 2.3 details our source data on feedstock supply, conversion to FT fuel and distribution, and driving. The resulting configurations and chain-wide results are examined in section 2.4. Variations and uncertainties in the results are discussed in section 2.5. The results are summarized and conclusions drawn in section 2.6.

2.2 Methods

2.2.1 Well-to-wheel chain analysis

The methodology to make WTW comparisons is essentially a specialized form of comparative life-cycle analysis. The functional unit in this study is 1 km of transportation delivered in an average EU car. To make a fair comparison between technology options, resource requirements, emissions and costs should be considered over the entire well-to-wheel (WTW) chain, as presented in figure 2.1.

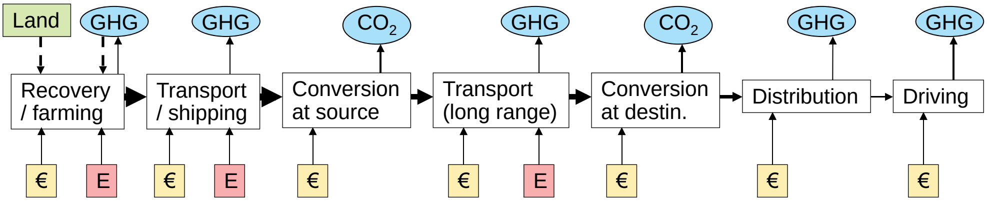

Figure 2.1: WTW analysis: chain inputs and emissions (E = fossil energy, € = money).

In this study, the total chain energy use (MJ/km), fossil and renewable energy requirement (MJ/km), cost (€/km), GHG emissions (g CO_2 equivalent/km) are calculated as follows:

- Energy use is determined by accumulating resource requirements from wheel to well, thus starting from driving:

$$e_{total} = e_{driving}\left(1 + e_{distribution}\right)\left(1 + e_{conversion\ to\ fuel}\right)\left(1 + e_{conversion\ to\ intermediate}\right) \qquad (2.1)$$

- We assume that distribution uses the diesel produced in an earlier step and that conversion plants do not require energy inputs other than the main feedstock. The latter is not entirely true in the real world [45, 108] but greatly simplifies the analysis.
- For local transport at the source and long range transport, energy use is counted as separate fossil energy input. Local transport is assumed to use diesel, and long range transport is assumed to use heavy fuel oil (HFO) for ships and diesel for trains. CO_2 emissions from fuel production are accounted for.

- Recovery/farming energy is counted as fossil energy input. Production inputs are accounted for on a case specific basis because of the divergent nature of the feedstocks.
- GHG emissions for recovery/farming include sequestration effects for biomass. We assume that it is possible to make biomass available for the BTL process in a carbon neutral way.

Ideally, energy and materials included in the construction of facilities, infrastructure and vehicles should also be included. It is known that around 80% of the energy for a conventional petrol-driven car comes from fuel. The remaining share comes from manufacture, maintenance and end-of-life [109]. Because the variation in vehicles is kept to a minimum in this study (all are functionally equivalent) and the aim is to provide a comparison rather than absolute numbers, only the driving share of energy is taken into account in this study.

All GHG emissions of fuels used (also in transport) are calculated to include conversion from primary feedstocks (oil, natural gas, coal or biomass). We use production data for fossil diesel and HFO from Edwards et al. [45]. Non-CO_2 GHG emissions are also taken into account as CO_2 equivalents, as far as our data sources include these. Non-GHG emissions are not taken into account, with the exception that future diesel vehicles are assumed to have a particulate filter.

Because FT diesel can be used in the same engines that use fossil diesel, the chains have largely the same tank-to-wheel (TTW) parts. By contrast, the well-to-tank (WTT) parts are quite dissimilar. Seven basic WTT chains, eventually giving rise to 17 WTW variants that could be relevant for Western Europe, are addressed in this chapter:

1. Crude oil – shipped to Western Europe – refined to fossil diesel
2. Natural gas – converted to FT fuel – shipped to Western Europe
3. Coal – sent to port – shipped to Western Europe - converted to FT fuel
4. Biomass – converted to pellets – sent to port – shipped to Western Europe – converted to FT fuel
5. Biomass – converted to pellets – sent to port – converted to FT fuel – shipped to Western Europe
6. Biomass – converted to FT fuel – sent to port – shipped to Western Europe
7. Biomass – converted to TOPs – sent to port – shipped to Western Europe – converted to FT fuel

The complete set of chain variants is defined in section 2.4

2.2.2 Well-to-wheel chain links

In order to construct chains that reflect dynamic future development, narrative scenarios are constructed to provide a real-world reflection on the changes. The scenarios aim to address the aspects of each chain link that most strongly determine cost, energy efficiency and GHG emissions. Initially, these include feedstock choice, feedstock availability, as well as the scale of conversion plants, the applicability of carbon capture and storage (CCS) options and improvements in technology of FT synthesis plants and vehicles.

However, the chain links described in figure 2.1 represent aggregated processes. In order to take into account specific technological advances, for instance in catalyst chemistry or gas turbine design, a link must be disaggregated to a point where individual technologies can be distinguished. A conversion plant is therefore broken down to process units, which can be described and modelled as connected but more or less independent process units. Supporting units, such as an air separation unit and power island also need to be considered. For a chain with a BTL plant, figure 2.1 could break down into units as depicted in figure 2.2.

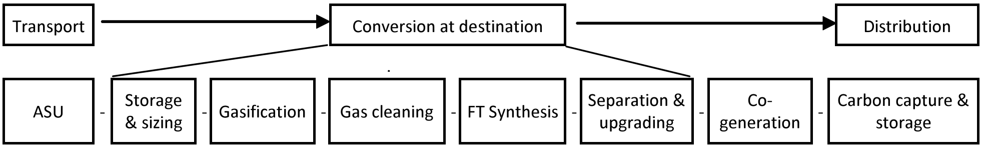

Figure 2.2: Example of the breakdown of a conversion link (figure 2.1) into process units, for the case of a BTL plant.

In theory, the various process steps such as gasification, gas cleaning and synthesis, are easily distinguished. In practice, secondary flows, such as heat, electricity, oxygen, hydrogen and carbon dioxide mean that the sub-processes are closely linked. In one case, 15 or more flows move back and forth between gasifier and synthesis unit [110]. Analogous disaggregated descriptions can be made for biomass production and transportation (see [74, 111]), or oil refining.

2.2.3 Calculation methods

Equations and assumptions that are not specific to a specific chain link are described below. Those that are specific to a single link are listed with the data for that link.

The conversion facilities (Fischer-Tropsch plants, pelletizing plants) are modelled with mass and energy balances in an Excel spreadsheet. Equipment costs, efficiency data and energy requirements were obtained from literature and the units are scaled to match the throughput. The total capital investment (TCI) is calculated using factored estimation [112]. With this method, a large installation is divided into discrete major components. The total capital investment is equal to the sum of the costs (C) of each of these components, with an added installation factor[4] (f) for relevant infrastructure, piping, controls, etc, and increased by 15% for contingencies[5].

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[4] Equipment costs quoted in literature come as one of the following [99]:

- Free on Board (FOB), for a bare process unit that is package and ready for transport;
- Inside Battery Limits (ISBL), which includes piping, instrumentation, etc;
- Outside Battery Limits (OSBL), which also includes land cost, power lines, sewage, etc.

$$\mathit{Total\ Capital\ Investment} = (1 + 0.15) \sum C_i \left(1 + f_i\right) \qquad (2.2)$$

Engineering costs (planning, installation, O&M) are expected to decline as designs mature. Current designs are already being copied to reduce engineering costs: Sasol essentially duplicated the 1977 Secunda facility for its 1983 East Plant facility [114], and Sasol-Chevron's new plants in Qatar and Nigeria use standardised integrated process units [115].

A load factor of 8000 operating hours per year is used in almost all our calculations to factor in maintenance downtime. For every operation in the chain, the scale is an important determinant of costs. Scaling factors from literature are used for each of the components. The costs of the components are scaled using following equation (2.3):

$$\mathit{Cost}_{original} / \mathit{Cost}_{scaled} = \left(\mathit{Size}_{original} / \mathit{Size}_{scaled}\right)^{\mathit{Scaling\ factor}} \qquad (2.3)$$

For costs stemming from the installation factor, a generic scaling factor of 0.82 is used in our study [116]. The scaled investment costs are annualized through equation (2.4) (DR% = discount rate percentage). To arrive at the total annual costs, 4%[6] of TCI is added as O&M costs. Electricity sales and CO_2 credit revenue (if any) are subtracted from the production costs. The annual costs are divided by the sum of naphtha and diesel production to calculate costs per unit of fuel (in €/GJ).

$$\mathit{Annualized\ Investment\ Costs} = \mathit{TCI} \frac{DR\%}{\left(1 - \left(DR\% + 1\right)^{-\mathit{Lifetime}}\right)} \qquad (2.4)$$

$$\mathit{Total\ Annual\ Costs} = \mathit{AIC} + \mathit{TCI} \times 4\% - \mathit{Electricity\ Sales} - \mathit{Carbon\ Credits} \qquad (2.5)$$

$$\mathit{Cost\ of\ Fuel} = \mathit{Total\ Annual\ Costs} / \mathit{Synfuels\ Production} \qquad (2.6)$$

Process energy requirement and CO_2 emissions are allocated (in $kgCO_{2eq}/GJ$) between diesel, petrol and exported electrical power on MW LHV and MW_e basis[7].

Installation factors therefore vary widely and are specific to each quoted price.

[5] We use higher contingencies than the 10% indicated by [36, 100 or 113], but we do not include R&D costs.

[6] Edwards et al. [45] indicate a range of 3% (low-tech) to 4.5% (high tech). Larson et al. [69] and Hamelinck et al. [117] use 4% O&M as well.

[7] The exported electrical power is equal to the total generation minus the electricity required to operate the conversion plant including any CCS equipment, if used. CO_2 emissions of the FT plant are credited with replacing emissions from baseline electricity production of 560 g CO_2/KWh in Western Europe (based on the Dutch power mix), 324 g CO_2/kWh in the Middle East (based on a 60% efficient natural gas combined

$$GHG\ of\ Production = \frac{\left(\sum Proces\ Emissions - Electricity_{baseline}\right)}{Synfuels\ Production} \qquad (2.7)$$

Harmonised EU-25 average consumer price indices from 1996 to 2005 [119] are used to compensate for inflation in data from before 2005. Costs in non-Euro currencies are converted to Euro first using Interbank currency exchange rates averaged over the entire year [120], and corrected for inflation afterwards. The cost per ton of avoided CO_2-equivalent emissions is defined as follows, using WTW €/km and CO_{2eq}/km values as input:

$$Cost\ of\ CO_{2eq}\ avoided = \frac{Cost_{case} - Cost_{reference}}{Emissions_{reference} - Emissions_{case}} \qquad (2.8)$$

Diesel used in the supply chains is assumed to cost 1 €/litre [121] and emit 3917 g CO_{2eq}/litre. Heavy fuel oil is assumed to cost 0.20 €/litre and emit 4210 g CO_{2eq}/litre.

2.3 WTW input data

We will first outline the data used for baseline oil-based diesel production and then detail the data related to (a) feedstock supply and logistics chains, (b) Fischer Tropsch conversion plants and (c) distribution and driving.

2.3.1 Oil-based diesel production

The baseline fossil diesel in this chapter is assumed to be made from Middle East oil. The technology for refining oil is evolving: refineries increase their efficiency by around 1% per year [45]. This advance is negated at least in part by the increasing use of sour and heavy crude oils that require more effort to process and by increasingly stringent fuel specifications [24]. Here we assume that the former trend cancels out the latter: All refineries use 0.1 $MJ/MJ_{diesel\ produced}$ and emit 8.60 g $CO_{2eq}/\ MJ_{diesel\ produced}$ [45].

The oil price for the base case is 80 $/bbl (price developments and their impact are addressed in section 2.5). The cost of refining fossil diesel is often quoted in relation to the price of crude oil. The price markup from refining is estimated at 20% [122] to 39% [123]. We assume a constant markup of 30%.

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cycle plant) and 0 in biomass growing areas (because biomass would produce carbon neutral electricity. Energy input for the FT plant is credited with the energy input from baseline electricity, which is calculated by dividing the exported electricity by the assumed generation efficiency of a stand-alone combined cycle power plant (40% in Western and Eastern Europe with CCS and 45% without, 60% in the Middle East, 40% on the coast in Latin America and 35% at a CGP), based on Damen et al. [118]. The impact of the allocation method is especially strong in the case of natural gas fed FT plants.

2.3.2 FT feedstock supply and logistics

We make FT fuels from three feedstocks: coal, natural gas and biomass (though use of the latter is at present still in a pre-commercial stage). The following options for feedstock and conversion choices are considered:

2.3.2.1 Fossil feedstocks

Both coal and natural gas are established commercial feedstocks for FT. Two examples are the Shell plant in Malaysia that uses stranded gas reserves and the Sasol plants in South Africa that use coal and natural gas.

Coal is assumed to be shipped to Europe from mining sites. Due to advantages of scale in port facilities, coal is converted in a large, centralized conversion plant. We use supply chain data for bituminous coal from JRC [45]. The production and delivery of bituminous coal requires 0.096 $MJ/MJ_{produced}$ and emits 15.33 g $CO_{2eq}/MJ_{produced}$. The cost of coal at the conversion plant gate is assumed to be 1.8 $€_{2005}/GJ$ [5].

Natural gas is assumed to be produced in the Middle-East, a region with very large gas reserves [124]. It is locally converted to FT diesel and shipped to Europe. The production of natural gas requires 0.024 $MJ/MJ_{produced}$ and emits 3.59 g $CO_{2eq}/MJ_{produced}$. The cost of natural gas at the conversion plant gate is assumed to be 1.05 $€_{2005}/GJ$[8].

2.3.2.2 Biomass feedstocks and intermediates

Biomass differs from oil and gas in that it is not recovered from a point source, but from a distributed area. After collection, it is driven by truck to a central gathering point (CGP), where it is processed. We assume that biomass supply develops as follows: At present, there are no large amounts of excess biomass available close to Western Europe (WE). The BTL chain therefore uses remote and thinly spread out residues from the forestry industry in Canada.

We also assume that by 2020 sustainable biomass production has been set up in Eastern Europe (EE, Ukraine or Romania), Latin America (LA, southern Brazil) or East Africa (Mozambique, treated as similar to LA), centred around plants that convert the wood to pellets for shipping to WE. Alternatively, wood is still converted to pellets to facilitate transportation, but the conversion to FT fuels is done at a facility on the Black Sea coast (EE) or on the Atlantic coast (LA). In LA biomass can also be converted to torrified wood pellets (TOPs) in modified pelletisation plants or converted directly to FT diesel at smaller FT plants in the farming areas.

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[8] Based on the cost for LNG in Japan of Middle-East origin [5, 3], projected at 8.7 €/GJ. Assumes that the cost of producing natural gas and bringing it to a seaside terminal is 20% of the total cost of supplying natural gas to a foreign terminal [124]. The cost of 1.05 €/GJ assumes the gas could be exported. Stranded gas costs can be as low as 0.17 €/GJ [125].

The properties of the biomass as well as data on most of the equipment are taken from the *Chains* model, as developed for the VIEWLS project [74, 111]. For farmed biomass, it is assumed that 30% of the surface area of a given region is used for energy crops. This leaves room for infrastructure, subsistence farming and/or higher value food crops in the same area.

We assume the development of a large market for biomass trade, with a baseline raw biomass cost of 1.9 €/GJ_{LHV} for forestry residues at the side of the road in Canada, 4.9 €/GJ_{LHV} for salix (willow or poplar) at a farm in Eastern Europe and 2.5 €/GJ_{LHV} for eucalyptus at a plantation in Latin America[9]. Initial efforts at market development can use the (limited volume of) biomass residues from agricultural processing that are available at little or no cost.

Preliminary calculations showed that transporting raw biomass is very uneconomic because of its low density[10]. Conversion to FT fuel early in the chain saves on logistics costs but limits the scale of a local FT plant, because feedstock supply is often considered the limiting factor for biomass gasification at a scale of hundreds of MW_{th} and upwards [99].

Conversion of biomass to an intermediate has been the subject of extensive study. Such processing affects the WTW chain by adding costs and energy use and by reducing transportation expenses. Options for biomass collection, intermediate conversion and shipping are explored by our institute (e.g. [74, 111,126]) and by others (e.g. [127]). Two processes for producing intermediates are considered here:

- Biomass pellet production entails heating small pieces of wood (downsized to about 10 mm) to around 100°C, at which point the lignin in the wood softens. By subsequent compression and cooling, a stable intermediate is formed [74]. Biomass pellets have a bulk density of 600-700 kg/m^3, about 2-3 times that of wood chips, and suffer less rotting (ibid).
- Torrefaction entails heating to moderate temperature (230-270°C for 10-40 min.) to produce a material like charcoal [128]. This material is easily densified into pellets (abbreviated as TOPs) [ibid, 129], which have a bulk density of up to 800 kg/m^3. The downside of torrefaction is that some energy is lost in the conversion process itself.

Use of (flash) pyrolysis to produce an intermediate for shipping is not included in this study because the cost of producing FT fuels by way of pyrolysis oil has been found to be higher than the costs associated with the use of plain or torrefied biomass pellets [111, 129, 126, 128].

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[9] Some publications have reported biomass cost per higher heating value (HHV). For comparison, residues cost 0.9 €/GJ_{HHV}, salix costs 2.5 €/GJ_{HHV} and eucalyptus costs 1.3 €/GJ_{HHV}.

[10] Compare the energy density of fresh salix bundles (1.5 GJ_{LHV}/m^3) and eucalyptus bundles (2.8 GJ_{LHV}/m^3) with the energy density of pellets (10 GJ_{LHV}/m^3), TOPs (17 GJ_{LHV}/m^3) and FT diesel (34 GJ_{LHV}/m^3).

Data on the efficiency and cost of equipment for producing intermediates are taken from Batidzirai et al. [126] and Uslu [129]. Costs for biomass storage are assumed to be negligible. Biomass losses during storage periods are not considered because of insufficient data.

Table 2.1 shows the parameters we use for the biomass farming and intermediate production. We assume that the biomass is harvested from trees which do not require significant agricultural inputs such as fertilisers. Additional carbon sequestration into roots and soil is not taken into account, neither are possible carbon losses from establishing biomass farms, nor emissions of greenhouse gasses that could be involved in the biological cycle such as methane and nitrous oxide[11].

The annualized investment costs for conversion are calculated using a 10% discount factor and a depreciation period of 10 years. Operation and maintenance cost (O&M) for the process units is 3%-40%. The proposed TOPs process has a high degree of heat integration and is therefore extremely efficient (92%, see [128, 129]) but the equipment is much more expensive than a conventional dryer for a pellet plant. Besides conversion, only long-range trucking contributes substantially to the cost of biomass chains. Two chains with FT production inside the country of origin, but not in the farming area, use pellets as an intermediate because the extra cost of transporting bundles of wood outweighs the losses from the conversion process.

2.3.2.3 Logistics of biomass supply

The biomass supply area and collection logistics are scaled to match seasonal availability and the input capacity of the pellet or TOPs plant, optimizing the size of the most expensive component for scale advantages. The following equation is used to determine the average collection distance (in km) (derived from [135]):

$$\mathit{Average\ Range} = \left(\mathit{CGP\ Facility\ Capacity} / \mathit{Yield\ per\ ha} / \mathit{Coverage\%} / \quad \times 1.3\right)^{1/2} \qquad (2.9)$$

The 1.3 in equation (2.9) is a factor to correct between the radius to the perimeter of a circular area and the average distance in an area where distance from the centre is counted through roads and other pathways.

Table 2.2 shows the parameters for the collection of raw biomass to the CGP, subsequent transportation of intermediates and FT diesel to a port facility in the country of origin, and long range shipping to Western Europe.

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[11] These emissions are highly uncertain and dependant on circumstances in practice [130, 131, 132, 133, 134].

Biomass supply chains - farming and CGP input data	**Canadian FR to pellets to WE**	**EE salix to pellets to WE**	**EE salix to local BTL**	**LA eucalyptus to pellets to WE**	**LA eucalyptus to local BTL**	**LA eucalyptus to TOPS to WE**	**LA eucalyptus to CGP BTL**
time frame	Present (2005)	Future (2020)					
biomass	Quebec forestry residue	Eastern Europe salix	Eastern Europe salix	Latin America eucalyptus	Latin America eucalyptus	Latin America eucalyptus	Latin America eucalyptus
coverage (% of land used for biomass production)	100%	30%	30%	30%	30%	30%	30%
production density (tonne/ha)[1]	0.0048	3.7	3.7	5.74	5.74	5.74	5.74
production cost (€2005/tonne)[1]	18.0	48.5	48.5	25.0	25.0	25.0	25.0
harvesting season	June-August	October-March	October-March	year round	year round	year round	year round
biomass form	PFF chips	salix bundles	salix bundles	eucal. bundles	eucal. bundles	eucal. bundles	eucal. bundles
LHV (GJ/tonne)[1]	10.0	10.5	10.5	10.7	10.7	10.7	10.7
moisture content (wt%)[1]	40%	37%	37%	35%	35%	35%	35%
density (kg/m3)[1]	240	160	160	280	280	280	280
cost (€2005/GJ LHV)	1.8	4.6	4.6	2.3	2.3	2.3	2.3
energy used (GJexp/GJprod)	0.0000	0.0045	0.0045	0.0003	0.0003	0.0003	0.0003
GHG (kg CO2eq/GJprod)[2]	-104	-109	-109	-111	-111	-111	-111
CGP facility scale (tonne/hr)*	19	26	26	17	17	25	none, immediate processing to FT diesel
processed at CGP into	pellets	pellets	pellets	pellets	pellets	TOPs	
LHV (GJ/tonne)[3]	16.2	16.2	16.2	16.2	16.2	21.6	
moisture content (wt%)[3]	7%	7%	7%	7%	7%	3%	
density (kg/m3)[3]	650	650	650	650	650	800	
cost (€2005/GJproduct)	1.4	1.1	1.1	0.4	0.4	1.5	
energy used (GJexp/GJproduct)	0.210	0.167	0.167	0.178	0.178	0.091	
GHG (kg CO2eq/GJproduct)	38	29	29	31	31	16	
processed at port into	none	none	FT diesel*	none	FT diesel*	none	none

* See text, FT plant are discussed in the next section of this chapter. [1] Data from [74], converted to LHV where needed. [2] Sum of emissions from primary energy used for production and harvesting and carbon sequestered in the biomass. [3] Data from [129].

Table 2.1: Data, cost, energy use, and GHG emissions for farming of biomass and conversion at central gathering point used in this study

Biomass supply chains - transport	**Canadian FR to pellets to WE**	**EE salix to pellets to WE**	**EE salix to local BTL**	**LA eucalyptus to pellets to WE**	**LA eucalyptus to local BTL**	**LA eucalyptus to TOPS to WE**	**LA eucalyptus to CGP BTL**
time frame	Present (2005)	Future (2020)					
trucking distance to CGP (km)*	186.9	20.4	20.4	18.7	18.7	23.1	44.2
cost (€2005/GJmoved)	1.7	0.3	0.3	0.2	0.2	0.2	0.3
energy used (GJexp/GJmoved)	0.0132	0.0017	0.0017	0.0012	0.0012	0.0015	0.0029
GHG (kg CO2eq/GJmoved)	1.00	0.13	0.13	0.09	0.09	0.12	0.22
transport distance to seaport or processing plant (km)[2]	none[1]	300 (train)	300 (train)	300 (push tug)	300 (push tug)	300 (push tug)	300 (class IV tanker)
cost (€2005/GJmoved)		0.4	0.4	0.1	0.1	0.1	0.1
energy used (GJexp/GJmoved)		0.0030	0.0030	0.0023	0.0023	0.0015	0.0021
GHG (kg CO2eq/GJmoved)		0.23	0.23	0.19	0.19	0.12	0.17
FT plant location[2]	Western Europe	Western Europe	local	Western Europe	local	Western Europe	local
transported by	bulk carrier	bulk carrier	bulk tanker	bulk carrier	bulk tanker	bulk carrier	bulk tanker
ocean shipping form[2]	pellets	pellets	FT diesel	pellets	FT diesel	TOPs	FT diesel
ocean shipping distance (km)	6000	6000	6000	12000	12000	12000	12000
cost (€2005/GJmoved)	0.2	0.2	0.1	0.2	0.1	0.2	0.1
energy used (GJexp/GJmoved)	0.0115	0.0115	0.0046	0.0230	0.0091	0.0167	0.0091
GHG (kg CO2eq/GJmoved)	0.94	0.94	0.37	1.87	0.74	1.36	0.74

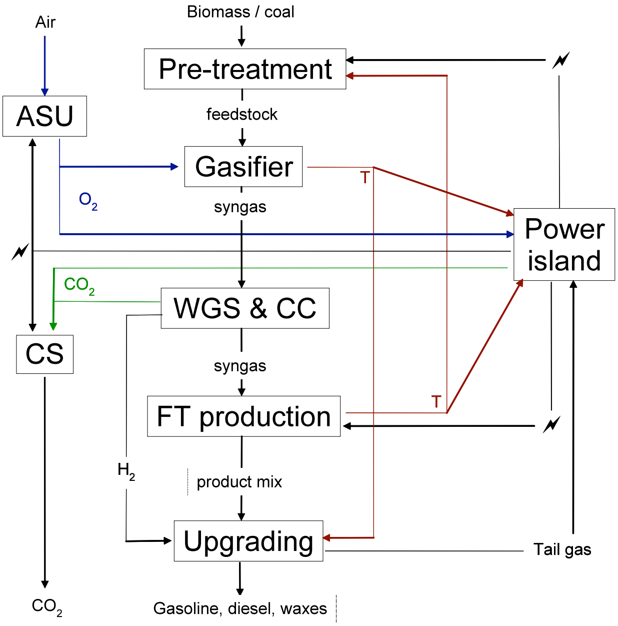
* See text. [1] It is assumed that port facilities for shipping wood internationally are already available at the collection point and these can also be used to ship the pellets. [2] Derived from data from [136] and [126]. Ocean shipping assumes Suezmax bulk carriers and tankers.

Table 2.2: Data, cost, energy use and GHG emissions for transport of biomass, intermediates, and FT diesel used in this study

2.3.3 Fischer-Tropsch conversion

Production of Fischer-Tropsch fuels requires that the feedstock is gasified and the resulting synthesis gas catalytically converted to hydrocarbons. The process is less efficient but more flexible than biological processing [74] and produces a much higher quality fuel than hydrothermal upgrading [127] or direct coal liquefaction [137]. While only natural gas, coal and biomass are considered here, gasification can be made to work with many different feedstocks, including municipal waste [138].

Figure 2.3 depicts a schematic diagram of the structure of the CTL or BTL FT plant used in this study. Note that some elements are depicted in an aggregated fashion. For instance, the gasifier section includes gasification and gas cleaning. The same structure is applied mutatis mutandis to a GTL plant.



Note: ASU: air separation unit, WGS: water gas shift, CC: CO_2 capture, CS: CO_2 storage

Figure 2.3: General layout of an FT plant as used in this study

In our study, costs are calculated mostly for plants with a capacity of 400 and 2000 $MW_{th\ input}$. For larger plants, scale advantages are less pronounced, because much of the equipment would be installed in parallel sets. 2000 $MW_{th\ input}$ is equal to an output of around 16 000 barrels per day (bpd)[12].

2.3.3.1 Syngas production

For solid feedstocks (coal and biomass intermediates) three types of gasifiers are used in this study:

- Fluidized Bed gasifiers, which can be scaled to several hundred of MW_{th}. Temperature varies between 700°C and 1100°C. This type of gasifier produces considerable amounts of tar and aromatics [141] which makes extensive gas cleaning necessary. Moreover, it accepts a wide variety of feedstocks in large particles (up to 10 cm).
- Entrained Flow (EF) gasifiers, which are typically large units (up to several GW_{th}). The temperature usually exceeds 1300°C, leading to almost complete conversion of the feedstock to syngas. This type of gasifier requires very small (1 mm diameter maximum) particles and produces inert slag.
- Two-stage gasifiers, such as the Carbo-V® gasifier being developed by CHOREN Industries, combine feedstock flexibility with complete conversion but are also more complex to build [142].

Another option for syngas production is methane reforming. Dry [105] indicates that methane-fed plants are about 30% cheaper to build. There are possibilities to improve the conversion efficiency of these plants by using catalytic reformers. Even in this configuration, syngas production accounts for around half of the capital costs of a FT fuels plant [143]. Current plants fed with natural gas often use autothermal reformers (ATR) [144, 145, 143].

Key parameters for the various gasifiers and reformers used in this study are presented in table 2.3:

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[12] By comparison, the typical capacity of a coal power plant is 1000-1600 $MW_{th\ input}$, but two large refineries in the port of Rotterdam each process around 400,000 bpd (Shell corporate website, Exxon-Mobil corporate website). Sasol-Chevron indicate their integrated FT process can process around 15,000 bpd [115]. This will require scaling up of gasifiers, as those used in existing IGCC power plants (Puertollano, Buggenum) are in the range of 700 $MW_{th\ input}$ [139]. The only BTL plant under construction in 2007, CHOREN's Beta plant in Freiberg, has a capacity of around 45 $MW_{th\ input}$ [140].

Gasifier	IGT BFB	Shell EF		Carbo-V	ATR	
manufacturer	Institute of Gas Technology	Shell[5]		CHOREN Industries GmbH	none, modelled	
type	BFB	EF		two stage (EF)	CPOx[8]	CSR/POx[8]
feedstock(s)	eucalyptus wood	Coal	TOPs[6]	wood pellets	natural gas	
exit temperature (°C)	982	1427	1300	900	900	980
operating pressure[1] (bar)	34	25	40	25	20	35
cold gas efficiency[2] (LHV)	76.9%[4]	78.9%	75.0%	78.7%	69.4%	78.3%
unit cost (400 MW_{th} LHV, M€ 2005)[1]	38	81	129[1,6]	138[7]	45	79
scaling factor (R)	0,7	0,7		0,83[7]	0,7	
maximum scale (MW_{th})	400	1250		1500	600	
data source[3]	[146, 147]	[102, 148, 149]		[140, 108, 102, 129]	[147, 150]	

[1] For different operating pressures of the unit in the source data, we assume unit cost to increase linear with wall thickness, which is assumed to increase linear with pressure [99]. [2] Some carbon mass balances in the source data were incomplete and minor adjustments were made to compensate for this. For cold gas efficiency, this resulted in the parameters presented here. [3] Data sources provided parameters for syngas composition.
[4] Includes the conversion of methane in a modelled convective methane reformer, using additional oxygen. The LHV efficiency of the gasifier was 80% before reforming. In the untreated product gas, 8.2% of the volume and 44% of the heating value is contained in methane. [5] Using a GE gasifier for CTL, which is cheaper and less efficient (data from [102]), resulted in a 7% higher fossil energy use over the entire WTW chain and 1% lower fuel costs (due to lower electricity sales). CO_2 crediting slightly increases this difference. Using a different set of gas composition data (simulated by [151], chain-wide fossil energy use was 1%-6% lower and fuel costs were 2% lower to 3% higher, depending on the configuration chosen. Larson and Tingjin's data [102] were used because these include simulated as well as experimentally sampled data. [6] The elemental composition of torrefied wood is very similar to pyrolysis oil. Pyroil data are therefore used for the syngas composition as no data are available about the chemical behaviour of TOPs in an EF gasifier. [7] As no cost data were available, the two stage gasifier is assumed to be a combined ablative pyrolysis unit [129] and GE gasifier [102]. Parameters reflect the total from both subunits. [8] Left-side parameters represent a pre-reformer + partial oxidation reformer configuration (CPO_x), right-side parameters represent a combined steam reformer + catalytic partial oxidation reactor ($CSR\text{-}PO_x$) [147].

Table 2.3: Main parameters used in this study for syngas production using gasification of coal or biomass, or reforming of natural gas

All gasification systems are oxygen-blown, as previous research has indicated these to have superior performance [152, 141] and the presence of nitrogen in the synthesis gas is not desirable. All gasifiers are pressurized (at 20 bar or more) because it allows for a smaller gasifier and the FT synthesis requires a pressurized gas feed anyway [99, 102]. The selection of gasifier type ultimately depends on design choices such as scale, feedstock(s) and product mix [153, 154, 155].

Little improvement is expected in the efficiency of EF gasifiers [156], which is currently just below 80% for bituminous coal in a Shell EF gasifier [102] or biomass in a CHOREN multistage gasifier [140]. Existing autothermal reformers for natural gas may be replaced by catalytic reformers [143] and model calculations show possibilities for a natural gas conversion efficiency of at least 80% [147].

Gas cleaning facilities are used where required to reach a tar- and sulphur-free synthesis gas. The extent of the facilities depends on the gasifier type: only the fluidized bed gasifier requires tar removal, all except the ATR units need cyclones and dust filters and all plants have guard beds to protect the FT catalyst. A sour water-gas shift unit is included to provide the required H_2/CO ratio and assist in removing sulphur from the syngas. Cost data for the WGS unit are taken from [102], and for all other gas cleaning units from [99].

Advances are expected in gasifier peripherals. New feeding mechanisms [157, 158] and dry gas cleaning systems for fluidized bed gasifiers [159] are under development, but these have not yet been deployed on a commercial scale [69]. The model plant based on a bubbling fluidized bed (BFB) gasifier [146] uses a dry gas cleaning system (OLGA from ECN, see [159]).

2.3.3.2 FT synthesis

In 2007, two Fischer-Tropsch processes had a significant market share: the Shell Middle Distillate Synthesis (SMDS) process and the Sasol Slurry Phase Distillate (SPD) process. Both were developed since the 1980s and have been in commercial use since the 1990s [143, 160, 146]. SMDS uses a tubular fixed-bed reactor [143]. SPD uses a slurry reactor but a fixed-fluidized bed reactor has also been used [160]. Other processes have been designed by companies such as Syntroleum, but these are not yet applied commercially [161].

The Fischer-Tropsch process has become significantly cheaper and more efficient since it was invented. The most extreme improvement is in reactor design. New plants use low temperature FT processes with values for α[13] of at least 0.92 [105]. Moving from a multitubular to a slurry phase reactor has reduced construction costs, pressure drop and catalyst consumption by ¾, increased conversion and reduced maintenance requirements. On the downside, catalyst poisoning is more damaging in a slurry phase reactor [105], so syngas cleaning must be very reliable.

Upgrading of the FT product is required. In both process designs, a hydrotreating and hydrocracking unit is present to convert waxes to additional fuels [143, 160]. For the Shell heavy paraffin conversion (HPC) unit, the output share of diesel fuel was maximised. The diesel fraction has excellent fuel characteristics. The naphtha fraction is further reformed and isomerised to improve the octane number for use as petrol [114, 162].

Closer cooperation among producers, or the expiration of patents, may allow competing state of the art techniques to be combined in the future for a 'best of breed' facility. Based on literature descriptions [66, 105, 143, 146] the combination of a Sasol slurry phase reactor, a state of the art FT catalyst, and a Shell heavy paraffin converter unit may provide an optimal combination with

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[13] α is a measure of chain growth probability during the FT reaction, and depends on the catalyst used. Higher α produces a mix of heavier hydrocarbons [99]. Heavier mixes are preferred because it is easier to crack heavy hydrocarbon chains than join light ones.

regard to production cost, product flexibility and yield. In this study we assume a process of this kind is commercially available by 2020. Key parameters of the three FT processes are summarized in table 2.4.

FT process	**SMDS**	**SPD**	**Advanced FT**
process name	Shell Middle Distillate Synthesis	Slurry Phase Distillate (Sasol)	Slurry phase synthesis + heavy paraffin converter
α (inferred)	0.94[2]	0.92[2,3]	0.94
H2/CO ratio (mol/mol)	2.15	2.1	2.1
operating temperature (°C)	230	230	230
operating pressure (bar)	40[4]	25.2[5]	30[5]
syngas conversion (%)	92%	92%	95%
diesel selectivity[1] (wt %)	85%	70%	85%
cost	27.0[4]	16.2[4]	19.3
scaling factor (R)	1[4]	0.72[4]	0.72
reactor size (m^3)	208[4]	362[4]	362

[1] This is the fraction of final product that is diesel fuel after product workup. [2] From [143]. [3] Evidence has been reported of two different α-values guiding the process in a liquid phase reactor, with the increased value becoming dominant around a carbon chain length of 10 (C_{10+}) [160]. This was not taken into account in this chapter. [4] From [146]. [5] Assumed value, based on [105]

Table 2.4: Parameters for the three Fischer-Tropsch processes used in this study

2.3.3.3 Power island & air separation unit

Synfuels plants include a power island to provide for heat balancing and to generate electricity for both internal use and export. Electricity production is around 10% of LHV input for CTL and BTL plants and around 25% of LHV input for GTL plants. The power island burns the FT tail gas in a gas turbine. The remaining heat, together with the process heat from the gasifier and FT synthesis reactor, is used in a steam cycle. For simplicity, the air separation unit (ASU) and gas turbine are considered as separate units, although integration of the compressors would improve efficiency [see 163].

ASU data are taken from Bechtel [164][14]. A 5000 tonne/day unit is assumed to cost 178.2 M€$_{2005}$ (scaling factor of 0.7 up to 2045 tonne/day). The energy requirement is 375 kWh/tonne for 94.3% purity oxidant and 390 kWh/tonne for 99.5 purity oxidant.

Unlike in some other studies [141, 99], the recycling of FT tail gas to the gasifier (so-called long recycle) is not included in our study, and the tail gas is sent to the power island instead. We

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[14] Data cited in [99]. Cost data for ASU varied wildly: between five sources, quoted in [102] and [99], values were found from 54 M€$_{2005}$ to 294 M€$_{2005}$ for the same scale and purity.

choose this approach for three reasons: First of all, the cost per unit of fuel of once-through systems has been shown to be lower [99]. The increased costs for reforming the light components of the FT tail gas exceed the benefits of increased production. According to [102], the difference between once-through operation and recycling of unconverted syngas was calculated to be very small. Furthermore, the syngas in that process (DME production) does not require extra reforming. Second, the use (if selected) of carbon capture and storage (CCS) requires significant additional electricity, which is preferably generated on-site. Finally, we assume that excess electricity can readily be sold to the local electrical grid at 38 €/MWh[15].

2.3.3.4 Carbon capture and storage

FT fuel plants provide a unique opportunity for carbon capture and storage (CCS). The synthesis gas is stripped of CO_2 during gas cleaning in order to increase the partial pressure of the reactants in the FT section. The resulting stream of almost pure CO_2 from the Selexol unit is readily diverted to carbon storage, if desired [102], [168]. About 90%-92% of the CO_2 in the syngas stream can be removed in this way [169, 140]. Most of the remaining carbon is embodied in the FT product[16]. Because CO_2 is removed from the syngas stream to improve FT reactivity, a sizeable flow is available without significant additional costs.

We assume CCS is applied in future FT plants in Europe and Middle East, and not in facilities in Latin America. Following [102], CO_2 drying and compression consume 97.8 kWh per tonne of CO_2 sent to underground storage. A 400 tonne/hr unit costs 33.8 $M€_{2005}$ (scaling factor of 0.67). Costs for off-site transport are set at 3.30 €/tonne and storage at 2.41 €/tonne[17]. We assume a base CO_2 price of 15 €/tonne.

2.3.3.5 Mixed feedstocks

In order to increase flexibility, it would be desirable to have a single FT plant be able to use different feedstocks, particularly coal (being relatively cheap) and biomass (being CO_2 neutral). Two options for such integration are available. The first option is to have two separate gasifiers and merge the two syngas flows after gas cleaning (see also [171]). The second option is to feed

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[15] Exported electricity is sold at 38 €/MWh, based on 2005-2006 generation costs and Dutch spot market prices, and 2005-2007 industrial prices in the Netherlands, Belgium, Germany, Poland, Romania, Bulgaria and Brazil [165, 166, 167]. Income from electricity exports reduces the FT fuel cost. Also see [2].

[16] Plant CO_2 emissions are reduced by 75% (GTL) to 87%-89% (BTL and CTL) using CCS. Oxyfuel combustion could be used in the gas turbine: conversion costs for BTL and CTL are increased by 3%-4% and CO_2 emissions are reduced by >99%. Oxyfuel for GTL is not recommended because it requires a much larger ASU to burn an off-gas that largely consists of hydrogen.

[17] From IPCC [170]: Transport data is from section 4.6. We assume a 250 km pipeline carrying 4-5 Mtonne/year, mostly on-shore. Storage data is from section 5.9. We assume a mix of on-shore aquifers, on-shore gas fields and off-shore gas fields.

pre-treated biomass such as TOPS, which is much like coal in physical properties, together with coal in the same EF gasifier. Both options will be explored here, each based on a coal-fed plant with a share of its feedstock replaced by biomass. The mixed plants are indicated as XTL plants in the remainder of this chapter.

2.3.3.6 Configurations

Table 2.5 shows the most important choices made in this study for configuring the Fischer-Tropsch plants.

We assume that conversion to FT develops as follows: The 2005 FT plants are all based on existing plants; the 400 MW CTL plant resembles a Sasol plant (albeit with an EF gasifier), the 2000 MW GTL SMDS plant resembles the Shell Bintulu plant and the pellet fired 80 MW BTL plant resembles CHOREN's demonstration plant. By 2020, it is assumed that new synfuels plants are scaled up by an order of magnitude and use the most promising FT and upgrading processes in development today. We also included more advanced options, where CCS is used in plants located in current Annex B countries [172] and biomass-fired plants attain the same scale as coal or natural-gas based ones.

Estimates of various characteristics of the FT synfuels plants are included in table 2.6. The annualized investment costs are calculated using a 10% discount factor and a depreciation period of 10 years. Location factors (see [152], to compensate for differences in labour costs, equipment costs and infrastructure, are not taken into account. Labour and fixed costs of 2000 €/$MW_{th\ input}$ are assumed in addition to 4% O&M. With these assumptions, a BTL FT refinery with a capacity of 100 000 bpd would cost seven billion Euros.

Oil refineries emit 4-9 g CO_{2eq}/MJ of diesel fuel produced [135, 24]. The FT plants investigated in this chapter emit more. At >80 g CO_{2eq}/MJ, the carbon emissions from a coal-fed FT plant are an order of magnitude higher than from a baseline oil refinery. The same goes for BTL plants, but in this case the carbon was removed from the atmosphere before. GTL plants have lower emissions than coal or biomass based plants, but significantly more than oil refineries.

When CCS is used, all plants have similar and much reduced (9-15 g CO_2/MJ) emissions. The electricity requirement is 1-7% of plant energy input ($MW_e/MW_{th\ input}$), which reduces the available electricity for export. This is lower than for IGCC coal power stations, where near-total CCS is expected to carry an energy penalty of 11% [173] to 14% or more [170]. The break-even price of CO_2 at the plant gate for CCS was calculated to be about €6 per tonne.

	PTL 80 SMDS	**PTL 400**	**PTL 2000**	**PTL 2000 CCS**	**TTL 2000 CCS**	**BTL 300 CGP**	**CTL 400 SPD**	**CTL 2000**	**CTL 2000 CCS**	**GTL 2000 SMDS**	**GTL 2000**	**GTL 2000 CCS**	**XTL 20-80**	**XTL 50-50 CCS**
Feedstock material	FR pellets	wood pellets	Eucalyp. pellets	Salix pellets	TOPS	Eucalyp. chips	bituminous coal			ME natural gas			coal & pellets	coal & TOPS
Gasifier type[1]	Carbo-V	Carbo-V	Carbo-V	Carbo-V	Shell EF	IGT BFB	Shell EF	Shell EF	Shell EF	PR/SMR	CPOx	CPOx	Shell EF Carbo-V	Shell EF
Fischer-Tropsch process[2]	SMDS	Adv. FT	Adv. FT	Adv. FT	Adv. FT	Adv. FT	SPD	Adv. FT	Adv. FT	SMDS	Adv. FT	Adv. FT	Adv. FT	Adv. FT
CCS	no	no	no	yes	yes	no	no	no	yes	no	no	yes	no	yes
Scale (MWth_in)[3]	80	400	2000	2000	2000	300	400	2000	2000	2000	2000	2000	1595 400	1017 1015

[1] See table 2.3. [2] See table 2.4. [3] The XTL 20-80 plant is scaled to produce the same amount of FT fuel as the CTL 2000, while generating 400 MW_{th} with a biomass gasifier. The XTL 50-50 plant is scaled to produce the same output as the CTL 2000 CCS, but uses TOPS for half the feedstock of the EF gasifier.

Table 2.5: FT conversion plant configurations used in this study

	PTL 80 SMDS	PTL 400	PTL 2000	PTL 2000 CCS	TTL 2000 CCS	BTL 300 CGP	CTL 400 SPD	CTL 2000	CTL 2000 CCS	GTL 2000 SMDS	GTL 2000	GTL 2000 CCS	XTL 20-80	XTL 50-50 CCS
Feed volume (ktonne/day)	0.46	2.30	11.51	11.51	8.00	2.22	1.37	6.87	6.87	3.45	3.45	3.45	6.22 1.56	3.78 3.77
Feed2fuel energy conversion (%)[1]	49%	51%	51%	51%	50%	52%	49%	52%	52%	31%[2]	39%[2]	39%[2]	51%	51%
Diesel output (b/d)	554	2854	14268	14268	13659	2136	2189	14098	14098	8429	10723	10723	14098	14098
Electricy exported (MW_e)	5	27	133	89	148	22	39	144	109	447	422	408	142	123
Total capital req. (M€ 2005)	135	390	1397	1436	1351	273	423	1370	1403	1221	1143	1161	1411	1476
Fuel conversion cost (€/GJ)	32	17	12	12	11	16	20	12	12	12	9	9	12	12
Feed/product (kg/kg)	5.02	4.89	4.89	5.09	3.49	6.26	2.95	2.93	3.02	1.62	1.43	1.45	3.32	3.28
Energy expended (MJ_{ex}/MJ)[1]	0.71	0.70	0.66	0.77	0.63	0.52	0.56	0.63	0.67	1.03	0.65	0.68	0.64	0.67
Diesel share in fuel output (%)	85%	85%	85%	85%	85%	85%	70%	85%	85%	85%	85%	85%	85%	85%
CO2 emissions (g/MJ)	122	116	136	15	11	122	88	86	11	38	17	5	92	11
CO2 captured (g/MJ)	0	0	0	121	75	0	0	0	80	0	0	14	0	79

[1] The apparent disparity between Feed2fuel conversion and Energy expended is a result of crediting for avoided stand-alone electricity generation. [2] Methane reforming produces an excess (+50%) of hydrogen, which is used to generate additional electricity.

Table 2.6: Calculated properties of the conversion plants investigated in this study

Figure 2.4 shows a breakdown of TCI. As expected, the gasification section (gasifier and ASU) is the most expensive part of a synfuels plant, followed by the power island. Both are largely mature technologies, and costs reductions per unit of fuel for later plants are mostly caused by scaling factors used in calculating equipment cost for larger plants. If the biomass is not converted upstream into an intermediate, the pre-treatment unit costs about one fifth of the total plant.

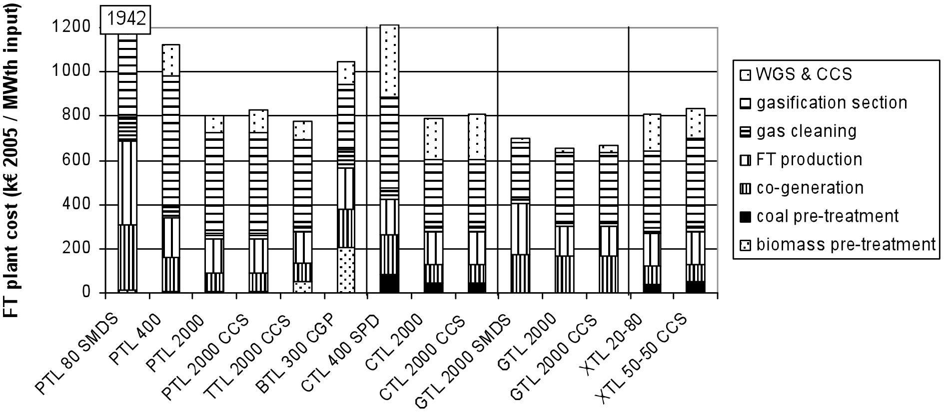

Figure 2.4: TCI breakdown of the conversion plants investigated in this study

2.3.4 Distribution and driving

Fischer-Tropsch fuels may be distributed pure, or blended with conventional diesel to improve fuel characteristics. In all cases, the distribution infrastructure is identical to the existing diesel network, e.g. ships for long distances and pipelines and trucks for end-point distribution.

While vehicles do not need to be adapted to run on FT diesel, fuel economy and GHG emissions are slightly different. Driving our existing vehicle fleet on (blends of) FT diesel will provide significant benefits to local air quality [174]. The emission reductions are listed in table 2.7. At the same time, the combination of hybrid technology and more efficient internal combustion engines [175] can reduce fuel consumption further.

	NO_x	PM_{10}	Hydrocarbons	CO
FT vs. fossil	-6.4%	-26% to -28%	-63%	-91%

Sources: [176, 174]

Table 2.7: Emission reductions with a standard VW Golf using Shell GTL diesel instead of fossil diesel.

To allow an easy comparison of WTW chains, we assume that vehicles with different drivetrains are identical in terms of safety features and amenities. The only difference in performance and weight is that the drivetrain parts are replaced in the different configurations[18] [45].

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[18] Some authors have discussed options to reduce vehicle mass [101, 177], but others [45, 100] have not. By contrast, real world cars have seen a substantial increase in mass over the last decades (see for example, [176]).

Pursuant to Weiss et al. [101], we assume the vehicle is driven 20 000 km per year. The vehicle retail price is annualized using an 10 year depreciation period and 10% discount rate. Maintenance, repair and tire estimated at 42 €/1000km [178], and insurance cost are not taken into account. Retail prices listed in table 2.8 approximate retail prices including VAT but not other taxes or license & registration.

$$Vehicle\,Cost = Retail\,Price \frac{DR\%}{\left(1-\left(DR\%+1\right)^{-Lifetime}\right)} \Big/ 20\,000 \qquad (2.10)$$

We use the fuel distribution and vehicle data developed by the EU's Joint Research Centre [45]. This data has been gathered in cooperation with major EU car manufacturers and the results are appropriate for European situations[19] and driving cycles. The fuel consumption and emissions used in this study were determined using the New European Driving Cycle (NEDC) for a 'median EU vehicle' (resembling a VW Golf). The widely used ADVISOR model from NREL was adapted to the EU situation for this purpose.

The 2002 vehicles from the JRC study are selected as representative for 2005 and a 2010 hybrid vehicle was selected to represent the average car in 2020. Table 2.8 shows the configurations of for both fossil diesel and FT driven cars. The fossil and FT pairs are largely identical except that cars fuelled with FT diesel emit around 3% less carbon. We assume a somewhat conservative 20% reduction in future fuel consumption: a reduction of around 25% is indicated by SRU [98].

Vehicle data	**current drive train**		**improved engine hybrid**	
year	Present (2005)		Future (2020)	
fuel type	fossil	FT	fossil	FT
particulate filter?	no	no	yes	yes
retail price	20300	20300	27590	27590
cost (€2005/km)	0.21	0.21	0.27	0.27
cost uncertainty			-16% to +-4%	-16% to +-4%
energy required (MJ/km)	1.83	1.83	1.46	1.46
energy uncertainty	-3% to +3%	-3% to +3%	-10% to +8%	-10% to +8%
GHG em. (CO2eq/km)	138	133	108	105
engine configuration (kW ICE + electric)	74	74	74 + 14	74 + 14
fuel consumption vs. current generation	-	-	-20%	-20%

Source: [45]

Table 2.8: Vehicle parameters used in this study.

We assume that drivetrain adoption develops as follows: Internal combustion engines will generally get better in the next 15 years, leading to more fuel-efficient cars. Hybrid cars, which achieve significant higher fuel economy, achieve a dominant market share. Some of the efficiency gains are negated by further increases in the weight of cars. All future cars are equipped with diesel particulate filters (DPF) to reduce air pollution.

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[19] Most WTW studies use US vehicles (with the average car resembling a Toyota Camry) and driving cycles.

2.4 Results

An overview of the various WTW chains that are investigated for this chapter can be found in table 2.9. The chains are a limited selection from the literally thousands of individual chains that could be defined (if considered in sufficient detail) and are intended to showcase what the authors consider reasonable developments in Fischer-Tropsch fuel production.

The results over the entire WTW chains can be found below in table 2.10 and the comparative figures 2.5, 2.7 and 2.9. Note that the calculated costs are not the same as prices paid by the consumer. VAT and various taxes are **not** included in the calculation and increase the effective cost of driving.

nr.	Source	Source transportation	Source conversion	Long range transportation	Destination conversion	Vehicle	Gasifier type	FT process	CCS?	Scale	Remarks
2005 chains (present)											
1	Middle East natural gas	pipeline (short distance)	**GTL plant**	fuel tanker (12000 km)	none	current drive train	ATR	SMDS	no	2000 MW	FT fuel exists within the niche markets where it emerged. It is used primarily as a compatible substitute with desirable
2	Bituminous coal	chains steps included in the source data			**CTL plant**		Shell EF	Sasol SPD		400 MW	
3	Canadian FR	truck (187 km average)	compression to pellets	ocean bulk carrier (6000 km)	**BTL plant**		Carbo-V	SMDS		80 MW	
2020 chains (future)											
4	Middle East natural gas	pipeline (short distance)	**GTL plant**	fuel tanker (12000 km)	none	improved engine hybrid	Cat. ATR	SPMDS (Sasol SPD synthesis with Shell HPC upgrading)	no	2000 MW	FT fuel has a significant share of the automotive fuel market. Gasification technology and CCS have not developed to potential. BTL plants are located in Western Europe
5	Bituminous coal	chains steps included in the source data			**CTL plant**		Shell EF				
6	Eastern Europe Salix	truck (20 km average)	compression to pellets	train (300 km) & bulk carrier (6000 km)	**BTL plant**		Carbo-V			400 MW	
7	Latin America Eucalyptus	truck (18 km average)	compression to pellets	IWW (300 km) & ocean bulk carrier (12000 km)							
8	Bituminous coal, Eastern Europe Salix	coal: chains steps included in the source data biomass: chain steps equal to chain 6			**XTL plant**		Shell EF & Carbo-V			1595 MW 400 MW	
9	Middle East natural gas	pipeline (short distance)	**GTL plant**	fuel tanker (12000 km)	none		Cat. ATR		yes	2000 MW	FT fuel has a significant share of the automotive fuel market. Biomass gasification technology has made improvements in scale and gas cleaning. CCS entered general use in Europe. BTL plants are also located in source regions.
10	Bituminous coal	chains steps included in the source data			**CTL plant**		Shell EF				
11	Eastern Europe Salix	truck (20 km) & train (300 km)	**BTL plant**	fuel tanker (6000 km)	none		Carbo-V				
12	Latin America Eucalyptus	truck (23 km average)	conversion to TOPS	IWW (300 km) & ocean bulk carrier (12000 km)	**BTL plant**		Shell EF				
13		truck (18 km) & ship (300 km)	**BTL plant**	fuel tanker (12000 km)	none		Carbo-V		no		
14		truck (44 km average)		IWW (300 km) & ocean fuel tanker (12000 km)			BFB			300 MW	
15	Bituminous coal, LA Eucalypt.	coal: chains steps included in the source data biomass: chain steps equal to chain 12			**XTL plant**		Shell EF		yes	1017 MW 1015 MW	
Reference chains											
A	Crude oil (at 9.24 €/GJ)	pipeline (short distance)	none	fuel tanker (12000 km)	Refinery	current drive train	not applicable, assuming current practice				Crude oil prices are equivalent to a $50.62/bbl price in 2005 (IEA, 2006).
B	Crude oil (at 9.24 €/GJ)					improved engine hybrid					

Note: All distribution inside the EU is done with fuel trucks

Table 2.9: Summary of the properties of the 17 WTW chains investigated in this study

nr.	Source	Conversion & transport	Vehicle	Fossil energy used (MJ/km)	Cost of fuel (€2005/l)*	Cost of fuel (€2005/GJ)*	Break-even oil price ($2005/bbl)	Cost of driving (€/km)	GHG emissions (gCO2eq/km)	Cost of avoided GHG (€/tonne
2005 chains (present)										
1	Middle East natural gas	Converted at source, shipped as fuel	current drive train	3.89	0.31	9.1	44	0.23	220	n/a
2	Bituminous coal	Shipped as coal, converted at destin.		3.17	0.56	16.4	79	0.24	343	n/a
3	Canadian FR	Shipped as pellets, converted at destin.		0.09	1.12	32.7	158	0.27	90	511
2020 chains (future)										
4	Middle East natural gas	Converted at source, shipped as fuel	improved engine hybrid	2.51	0.23	6.8	33	0.28	141	n/a
5	Bituminous coal	Shipped as coal, converted at destin.		2.63	0.38	11.0	53	0.29	270	n/a
6	Eastern Europe Salix	Shipped as pellets, converted at destination		0.05	0.85	24.8	120	0.31	36	195
7	Latin America Eucalyptus			0.07	0.64	18.5	90	0.30	32	92
8	Bituminous coal, Eastern Europe Salix	Shipped as coal and pellets, converted at destination		2.13	0.45	13.2	64	0.29	225	n/a
9	Middle East natural gas	Converted at source, shipped as fuel		2.56	0.23	6.7	33	0.28	123	-
10	Bituminous coal	Shipped as coal, converted at destin.		2.70	0.37	10.8	52	0.29	161	n/a
11	Eastern Europe Salix	Converted at source, shipped as fuel		0.03	0.70	20.3	98	0.30	-126	45
12	Latin America Eucalyptus	Shipped as TOPS, converted at destin.		0.05	0.51	14.8	72	0.29	-128	13
13		Converted at source, shipped as fuel		0.02	0.49	14.2	69	0.29	63	38
14		Converted at CGP, shipped as fuel		0.02	0.53	15.5	75	0.29	39	50
15	Bituminous coal, LA Eucalypt.	Shipped as coal and TOPS, converted at destination		1.37	0.46	13.4	65	0.29	13	12
Reference chains										
A	Crude oil (at 9.24 €/GJ)	Shipped as crude oil, refined at destin.	current drive train	2.11	0.45	12.5	63	0.23	164	n/a
B	Crude oil (at 9.24 €/GJ)		improved engine hybrid	1.68	0.45	12.5	63	0.29	129	n/a

[*] Cost of fuel excluding distribution costs

Table 2.10: Summary of WTW chain results for FT and crude oil-based diesel.

2.4.1 Well to wheel energy use

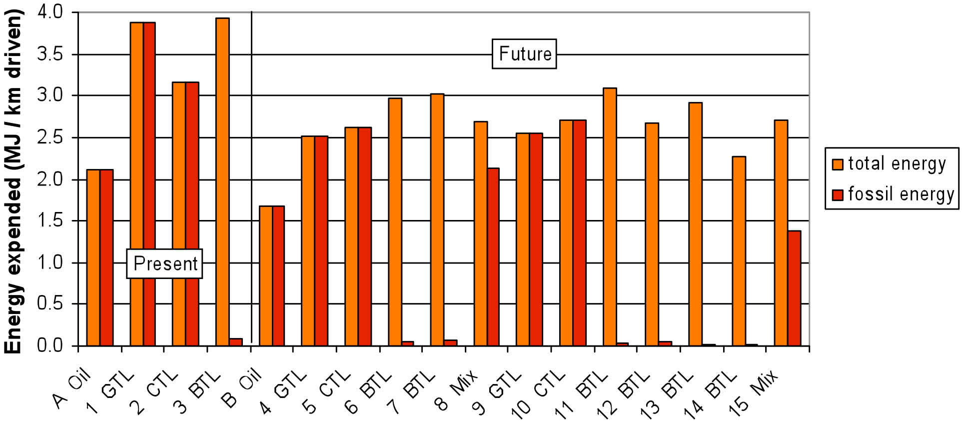

Figure 2.5: Total and fossil energy use per km driven in the selected WTW chains

The results show that total energy use will not be reduced by switching to Fischer-Tropsch diesel. A breakdown of contributions to total energy use in each chain is presented in figure 2.6.

It is observed from figure 2.6 that the most constant difference between total energy use in fossil diesel chains and FT diesel chains stems from losses in the conversion plants. Of the total WTW energy, just under 50% (for CTL- and BTL-based chains) to a maximum of 87% (for crude oil chains) is used in the vehicle.

Fossil energy is used in biomass chains for transport and farming, but this is a minor share of the total energy consumption and less than the energy use in the reference chains. The worst case pure biomass-based chain uses around 5% of the fossil energy of the most optimal fossil-based chain, not taking uncertainty in the data into account. In the best case for biomass, the fossil energy requirement (FER) is around 1% of that of a coal-based chain.

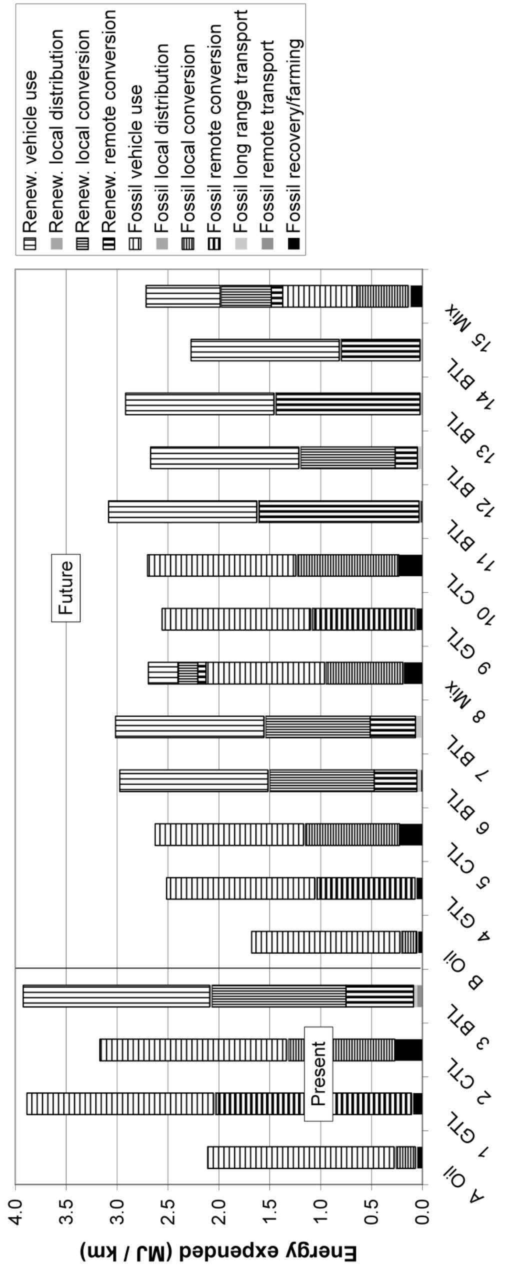

Figure 2.6: Breakdown of total energy expended per km driven for each selected WTW chain

2.4.2 Well to wheel cost

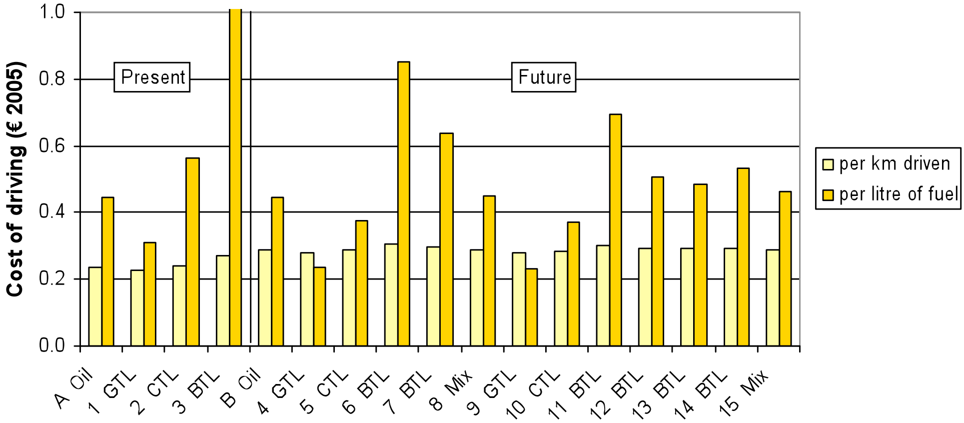

Figure 2.7: Costs per km driven and per litre for each selected WTW chain

The median fuel cost for FT and fossil diesel chains is around 0.02 €/km. Important in this respect is that 77%-96% of the total costs per km can be attributed to the vehicle, which somewhat levels out the differences between the various fuel production methods. To facilitate a comparison between the well-to-tank parts of the chain, a breakdown of the cost per litre of fuel is given in figure 2.8.

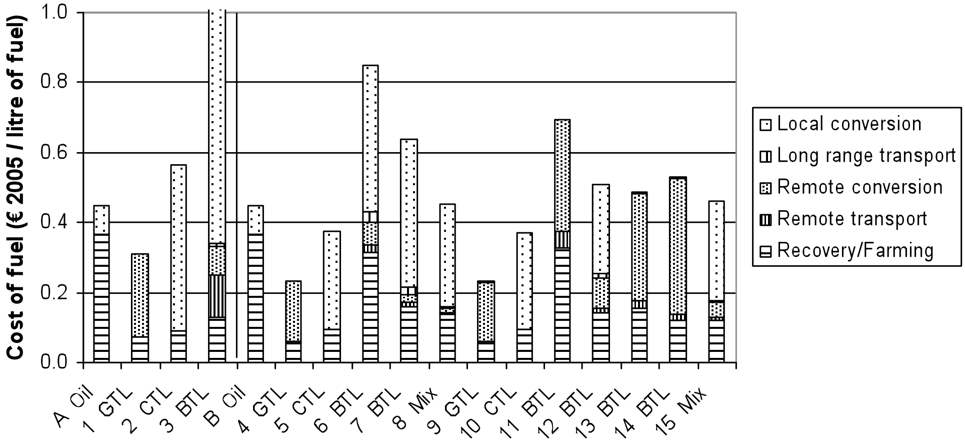

Figure 2.8: Breakdown of fuel cost per litre in individual chain links in WTT chains

With feedstock and transport costs as assumed, diesel from crude oil could be delivered at around 0.45 €/litre. FT diesel costs may range from just over half that number (using low feed prices and high efficiency conversion plants) to almost twice as much (using inefficient biomass-based processes).

Using natural gas at a cost equivalent to production prices (1.07 €/GJ$_{LHV}$, see section 2.3.2.1) would make GTL the cheapest option in the medium and long term (due to electricity revenue). The corresponding break-even (vs. fossil diesel) oil price is found to be 33 $/bbl, which would account for the enthusiasm with which oil companies are investing in GTL plants in recent years.

At the assumed fossil fuel prices and biomass feedstock prices (2.5 €/GJ$_{LHV}$ for Eastern Europe and 4.9 €/GJ$_{LHV}$ for Latin America) BTL is more expensive than all other FT options. The break-even oil price for BTL is above 65 $/bbl. The break-even oil price for CTL is found to be 52 $/bbl and mixed biomass-with-coal chains will end up somewhere in this range. Break-even oil prices between 45 $/bbl and 70 $/bbl were presented for CTL and XTL plants by Williams et al. [171].

The results indicate that FT diesel will be competitive when made from very cheap feedstocks or when oil prices stay above 80 $/bbl. The most constant difference between the costs of fossil diesel and FT diesel stems from the cost of conversion plants. The FT plants are consistently (much) more expensive per unit of fuel than oil refineries, a condition that is obviated by lower feedstock costs only if feedstocks are extremely cheap (because more feedstock is needed with feed-to-fuel efficiency around 50%).

2.4.3 Well to wheel greenhouse gas emissions

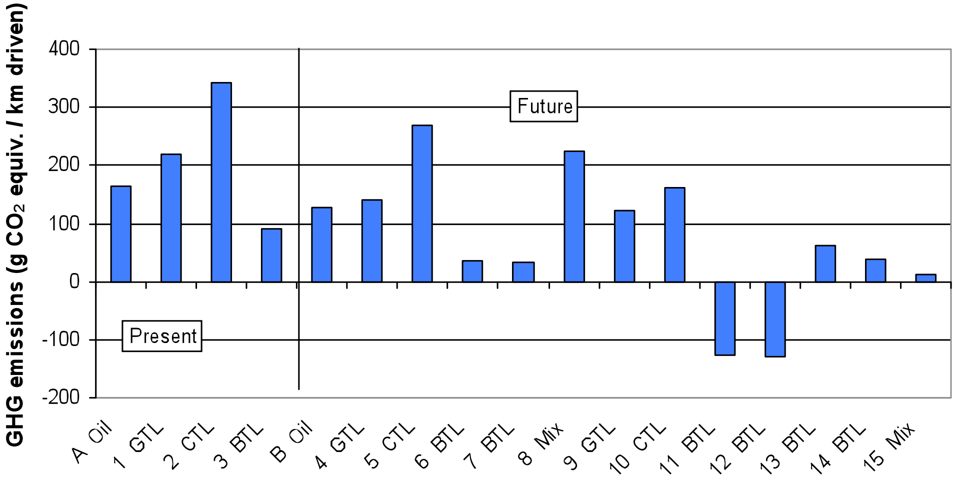

Figure 2.9: GHG emissions per km driven for each selected WTW chain

Figure 2.9 demonstrates that the use of CTL and GTL fuels will not necessarily reduce GHG emissions. In the case of CTL without CCS, GHG emissions would increase by 110% over those from fossil diesel chains. Even with CCS, emissions from CTL chains are found to be 25% higher, owing mostly to GHG emissions from mining, and are similar to emissions from synthetic crude oil (SCO) [67]. Without CCS, even GTL is found to cause up to 10% higher GHG emissions than fossil diesel. In the future, highly efficient conversion plants with CCS could give GTL a slight advantage over and oil-derived fuels (compare reference path B with FT path 9), reducing emissions by 5% vs. fossil diesel, though this reduction is largely due to GHG credited from electricity exports.

The GHG emissions from BTL chains all appear to be much lower than those of fossil diesel, many reducing GHG emissions by around 75% (assuming here that biomass feedstock is produced in a GHG neutral way). If CCS is combined with BTL, a net reduction of atmospheric CO2 is achieved, making for climate-positive driving. This effect can be used to compensate for the emissions of fossil feedstocks: when using a mix of 54% biomass and 46% coal in our advanced XTL plant, total chain emissions are zero. When mixing either BTL-CCS chain with fossil diesel, the required share of BTL would be 50%.

2.4.4 Supply chain issues

Figure 2.10 shows the difference between profiles for energy and costs to supply biomass to FT plants (field-to-gate). In all cases, conversion to an intermediate (pellets or TOPS) causes by far the most energy loss, but the biomass feedstock is the most costly element. Costs and energy expended for collecting the biomass are important only in chain 3, where long distances must be covered by truck to collect forestry residues. Long range transport has a minor role in both energy and cost even when intermediates need to be shipped over 12 000 km.

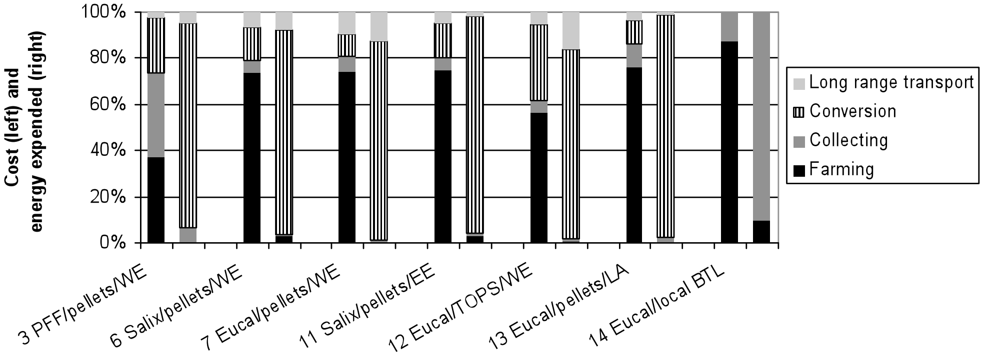

Figure 2.10: Shares of total cost and energy expenditure of biomass supply chains up to the factory gate

Despite its minor role in total costs and emissions, the long range transport of Fischer-Tropsch feedstocks could have a large impact on logistical centres because the volume of FT feedstock that must be processed upstream is much larger than the volume of oil required for the same amount of fuel. Compared to fossil diesel, about 2.9 times the volume of feedstock is needed to produce CTL. For BTL from TOPs, this is 3.4 times and for BTL from wood pellets, the volume rises to 6.1 times the volume of crude oil. Replacing fossil diesel with FT diesel could therefore require an extension of port facilities. GTL and BTL chains that convert to FT in the region of origin would require extensions to port facilities only in their respective regions.

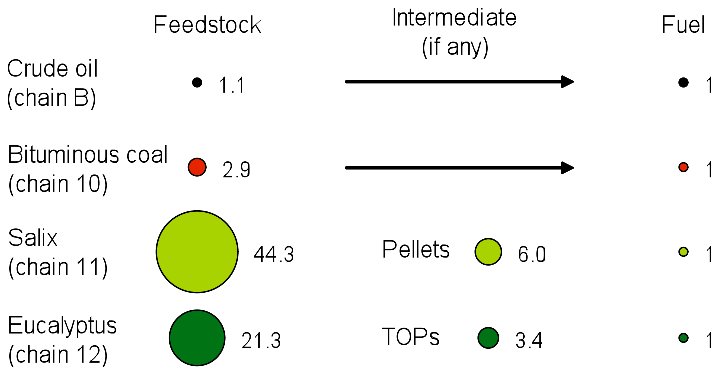

Figure 2.11: Relative transported volumes of raw feedstocks and intermediates

It is also evident that the collection of raw biomass will require a large logistical operation. Using available point sources of agricultural residues can save cost and energy.

2.4.5 Sensitivity

To determine which parameters have a significant effect on the results, sensitivity analysis was done for changes in feedstock costs, price of primary diesel and heavy fuel oil for transportation, FT α, oil and electricity price, CO_2 credit price and discount rate. Effects of carbon leakage, caused by methods of obtaining biomass that have significant emissions of GHG as well as sequestration effects, are also investigated. Ranges for oil, gas and coal price variations were obtained from the World Energy Outlook 2006 and 2007 [2, 3]. The sensitivity for transport fuel cost and FT α was found to be negligible. Indicative results are presented in figure 2.12.

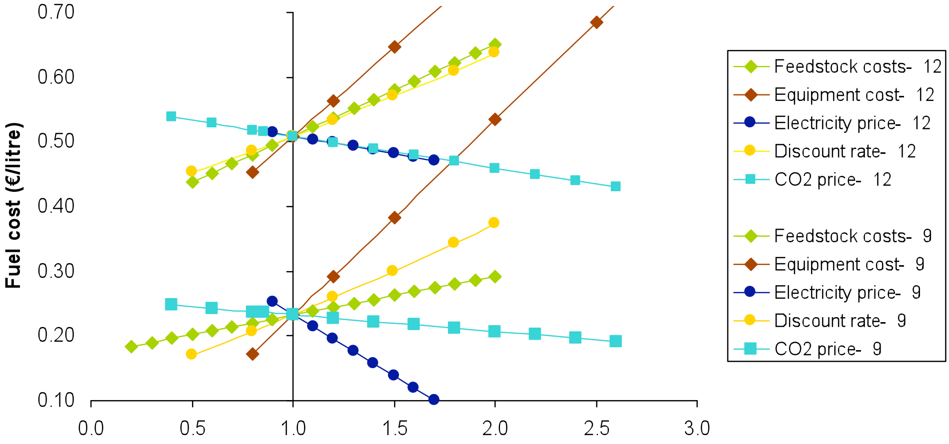

Figure 2.12a: Sensitivity of FT diesel cost of GTL CCS (9) and BTL LA TOPs CCS (12) chains

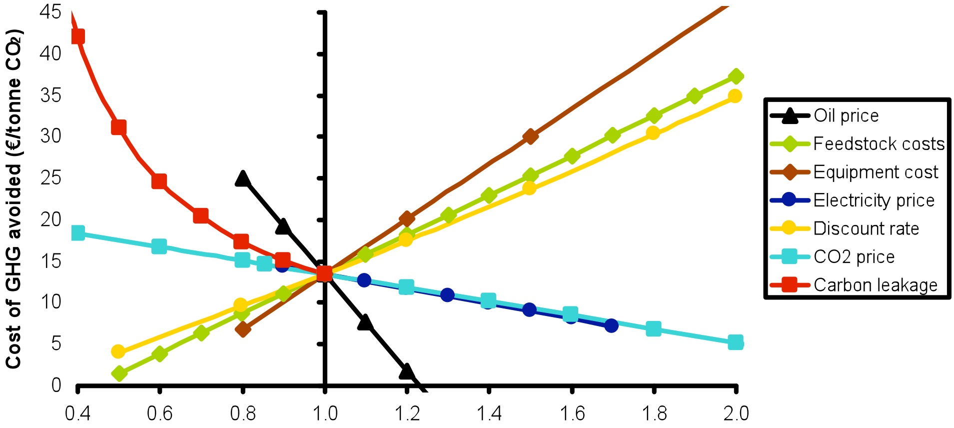

Figure 2.12b: Sensitivity of cost of avoided GHG emissions of the LA BTL TOPs CCS (12) chain

The cost of fuel and the cost of avoided GHG emissions are most sensitive to equipment costs. We estimate equipment costs to range between -20% and +200% or more, which highlights the influence of this factor. At the same time, viability of FT diesel strongly depends on the volatile price of the oil it is to replace (see figure 2.13).

For BTL, the biomass feedstock cost is an influential determinant of FT diesel cost. For most chains, doubling or halving the feedstock cost would entail a rise or fall of fuel costs by 20-40%. The difference between 4.9 €/GJ$_{LHV}$ base price for salix and 1.9 €/GJ$_{LHV}$ base price for eucalyptus shows that such variations are easily possible. Supply curves made in the VIEWLS project of the European Commission indicate that the marginal cost of feedstock from Eastern Europe could range between approximately 2-20 €/GJ$_{LHV}$, depending on the quantities required [122].

In case of non-trivial carbon leakage, the GHG benefits of BTL quickly disappear. The biomass-based chains without CCS produce more GHG emissions than fossil diesel chains when around 20%-25% of the sequestration by plants is negated. The chains with CCS reduce GHG emissions compared to fossil diesel chains when up to 70% of the carbon sequestration from plants is lost.

Using a 10% discount rate for FT plants in the baseline analysis is something of a compromise. For government policy, a 5% rate is often proposed, while a discount rate of 20% or higher would more accurately reflect the preference for a short payback time in the oil industry [179]. The effect of a 20% discount rate for most chains is an increase of the cost of FT diesel by 13-18 €ct/litre and the effect of a 5% discount rate is a decrease of 5-8 €ct/litre.

The effect of variation in electricity prices on FT diesel cost is small: a decrease of at most 4 €ct/litre for an increase to 55 €/MWh, except for the GTL chains (having more co-generation) which show a decrease of up to 15 €ct/litre.

The cost of FT diesel is not very sensitive to the CO_2 price. When comparing no CO_2 credits to a base CO_2 credit price of 14 €/tonne, fuel costs are reduced by 1 to 3 €ct/litre (this includes additional expenses for transportation and storage). If CO_2 price doubles, the cost of BTL diesel would drop by another 3-6 €ct/litre or around 10%.

2.5 Discussion

In this section, our result are compared to results from other authors, and several issues are brought forward that emerged during the preceding analysis.

2.5.1 Comparison of FT plants to literature

When compared to data from literature, the efficiency of the FT plants listed in table 2.6 is in the 50%-55% range accounted for by Bakhtiari [106]. Our conversion costs are in the same range and our fuel-to-feed efficiency is somewhat higher than what other authors have found. Results from some well-known studies are listed in table 2.11 for comparison.

At 650 to 850 €/$KW_{th\ input}$, the plants calculated here are substantially cheaper than earlier estimates for small scale biomass-fed power plants (see for example [182]. At the same time it is quite difficult to compare conversion plants from literature sources because of the diversity in configurations, assumptions and technologies used. Moreover, not all studies include detailed cost analysis (see for example [183]).

Source	**Fuel cost (€/GJ)**[1]	**GHG emitted (g CO2/MJ)**	**Feed to fuel efficiency**	**Configuration**
Oil baseline	16	88	91%	baseline refinery
GTL, as in chain 9	8	84	39%	2000 MW, catalytic POx reformer, with CCS
CTL, as in chain 10	13	110	52%	2000 MW, Shell EF, with CCS
CTL, Williams *et al.* 2006	12	29	33%[2]	C-FT-C: CTL, entrained flow gasifier, with CCS
CTL, Gray & Tomlinson, 2001	7	90	HHV: 56%	Tailgas Less CO2: CTL, unknown gasifier, with CCS in FT tail gas, uses iron-based FT catalyst
BTL, as in chain 6	29	25	44%	400 MW, Carbo-V, pellet intermediates shipped to WE, no CCS
BTL, as in chain 11	24	-87	48%	2000 MW, Carbo-V, pellet intermediates converted in EE, with CCS
BTL, as in chain 12	17	-88	46%	2000 MW, Carbo-V, TOPs intermediates shipped to WE, with CCS
BTL, as in chain 14	18	27	52%	300 MW, BFB gasifier, raw biomasss converted at CGP, no CCS
BTL, Küpers *et al* 2002	41	79	not listed	BIG-FiT: CFB gasifier, no CCS
BTL, Tijmensen *et al.* 2002	16 → 11 (long term)	n/a	44%-49%	BTL, 367 MW_{th} fluidized bed gasifier, no CCS
BTL, Hamelinck *et al.* 2003	15	n/a	46%	BTL, 400 $MW_{th,HHV}$ fluidized bed gasifier, dry gas cleaning, 60 bar FT, no CCS
BTL, Hamelinck *et al.* 2003	16	n/a	45%	BTL, 400 $MW_{th,HHV}$ fluidized bed gasifier, wet gas cleaning, 60 bar FT, with CCS
XTL, as in chain 8	15	155	50%	uses 20% biomass, seperate Shell EF gasifier using coal, and Carbo-V gasifier using pellets, no CCS
XTL, as in chain 15	16	9	49%	uses 50% biomass, single Shell EF gasifier using coal and TOPs intermediaries, with CCS
Williams *et al.* 2006	10	24	32%[2]	C/B-FT-CoC: uses 28% biomass, XTL, separate EF gasifier using coal and FB gasifier using switchgrass, with CCS

[1] Includes feedstock, not adjusted for inflation. [2] Both Williams' plants have a large electricity co-generation share: 430 MW_e and 460 MW_e, respectively for a 1032 MW FT plant. This choice leads to a lower feed-to-fuel efficiency.
Sources for comparison: [171, 180, 181, 146, 99]

Table 2.11: Comparison with FT plant characteristics from literature

2.5.2 Comparison of well to wheel alternatives with literature

A comparison of selected WTW chain results with other studies[20] can be found in table 2.12.

Fuel production technology[1]	Source	Total energy (MJ/100km)[2]	Fossil energy (MJ/100km)[2]	GHG Emissions (gCO2eq/km)[2]	Fossil energy requirement	Cost of GHG avoided (€/tonne CO2eq)
Conventional diesel (COD1)	Edwards et al, 2006	205-219	205-219	158-170	100%	n/a, baseline case
Conventional diesel	Hendriks, 2005	180-300	180-300	132-219	100%	n/a, baseline case
Biodiesel, methyl esters (ROFA1/2, SOFA1/2)	Edwards et al, 2006	292-313	161-233	28-79	65%	not listed
Biodiesel, ethyl esters (ROFE1/2, SOFE1/2)	Edwards et al, 2006	276-296	167-237	27-78	71%	not listed
BTL, ex farmed wood (WFSD1)	Edwards et al, 2006	374-426	6-18	13-26	3%	188
BTL, ex EE salix (chain 6 WTT)	this study	374	7	46	2%	194
BTL, ex LA eucal. (chain 7 WTT)	this study	379	9	41	2%	92
CTL (KOSD1)	Edwards et al, 2006	340-382	340-382	346-392	100%	n/a, +125% emissions
CTL, no CCS (chain 5 WTT)	this study	330	330	341	100%	n/a, +108% emissions
CTL, with CCS (KOSD1C)	Edwards et al, 2006	356-399	356-399	187-222	100%	n/a, +24% emissions
CTL, with CCS (chain 10 WTT)	this study	340	340	203	100%	n/a, +24% emissions
GTL	Hendriks, 2005	240-480	240-480	152-285	100%	n/a, +18% emissions
GTL, by sea (GRSD2)	Edwards et al, 2006	294-324	294-324	172-188	100%	n/a, +9% emissions
GTL, no CCS (chain 4 WTT)	this study	316	316	179	100%	n/a, +9% emissions
GTL (GRSD2C)	Edwards et al, 2006	308-339	308-339	150-165	100%	not listed
GTL, with CCS (chain 9 WTT)	this study	322	322	156	100%	-1367
XTL, ex coal and TOPs, with CCS (chain 20 WTT)	this study	341	173	18	51%	12
SCO, various extraction methods[3]	Everts, 2008	251-306	251-306	183-249	100%	n/a, +19% emissions
SCO, surface mining	Charpentier et al., 2009	n/a	n/a	176-211	100%	n/a, +18% emissions
SCO, in-situ extraction		n/a	n/a	190-215	100%	n/a, +24% emissions

[1] The codes in parenthesis are the exact path identifiers used in the source. [2] The vehicle was a 2002 diesel (DICI) in this study and in Edwards et al. and from a collection of sources in Hendriks et al. [3] Synthetic crude oil (SCO) extracted by open pit mining, CHOP, Shell IGP, THAI or SAGD-cokes method. Otherwise same as reference chain. Sources for comparison: [24, 45, 184, 67]

Table 2.12: Comparison of selected WTW chains with chains from literature on energy use, GHG emissions and cost of GHG avoided.

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[20] Most WTW studies use U.S. driving cycles, which are similar but not fully compatible with the NEDC.

Our results are quite similar to the results obtained by Edwards et al. [45], with the exception of the GHG emissions for biomass, which is probably caused by different assumptions in accounting for these emissions.

We found a fossil energy requirement of BTL in the long term to be 1% to 3%, almost all of which is oil-based. This percentage is lower than the FER of sugarcane ethanol from Brazil of around 10%, [185]. It also contrasts to the FER of US corn-based ethanol production, which is said to be in the range of 20%-100% [ibid, 186].

2.5.3 Uncertainty

The results presented in this chapter are based on publicly available data. These data were extrapolated where necessary and feasible. It should be noted that significant uncertainties surround many of the numbers involved. Important sources of uncertainty are listed in table 2.13. A 'low' impact does not lead to significant changes in our conclusions. A 'medium' impact denotes something that is noticeable in cost or in GHG emissions but makes a given WTW chain only moderately less favourable (around 4 €ct/l difference for diesel costs), but the general conclusions of the previous sections still hold. A 'high' impact has the potential to invalidate major conclusions about that particular chain. Most of the causes of uncertainty are independent of each other and the effects stack rather than mitigate each other. The uncertainties also appear to have non-Gaussian, flat (possibly uniform) distributions.

Cause (type of uncertainty)	Magnitude	Impact
Variations in the upstream emissions and energy requirement of feedstock production and supply (unknowable - case specific)	±2%-±9% [45] >25% [24]	Medium (high if above 10% or so)
Variations in feedstock properties because production methods of biomass and coal vary, as do their compositions (variability)	±3% [74, 187]	Medium, affects efficiency
Carbon losses from soil after changing land use to biomass cultivation from (abandoned) grass land (unknowable - case specific)	0 to 17 years worth of sequestration [45, 130]	High, could halve GHG reductions from biomass use
Losses of biomass during storage (lack of data)	3% per month of storage [74]	Medium, more feedstock needed
Variations in feedstock and by-product (electricity, CO_2) prices (unknowable - future development)	±20% to ±40% for feedstock, ±10% for CO_2	High, affects viability
Differences in the actual logistical situation of real plants	Unknown	Probably medium
Variation in the conversion performance of plant components such as gasifiers (lack of data)	±3% [148] or -10% to 0 % [102] for gasifiers	Medium, also depends on good practice
Alternative methods of calculating costs (methodology)	0% to +250%	High, can be reduced
Alternative methods of allocating by-products and electricity (methodology)	0% to +50% of CO_2 emissions and cost	High, can be reduced
Uncertainties in cost estimates for conversion plants, and their components (lack of data)	±40% [99, 45] to +200% [188]	High

Cause (type of uncertainty)	Magnitude	Impact
Pluriformity in vehicles and driving behaviour of motorists that actually use the diesel (variability)	-50% to +200% [189, 190]	Low, applies to all chains
Uncertainties in cost estimates for vehicles (unknowable - future development)	-12% to +14% [191, 45]	Low, applies to all chains

Table 2.13: Sources and magnitude of uncertainty in the data and impact on results

Other authors [24, 45] have reported ranges of uncertainty of the same order of magnitude. In addition to the uncertainties inherited from the data, we used an Excel-based model and results may differ from those reached in more detailed studies that use Aspen Plus™ engineering modelling software[21] (see, for example, [99, 102, 69]). The absolute results of this study should therefore be used with caution.

The differences in results for different WTW chains are in the same order of magnitude as several of the uncertainties listed above. Some of these uncertainties are associated with methodological choices or lack of data. Such uncertainties could be reduced with further research and by investigating concrete projects. However, it is unclear how results from actual locations, technologies and practises can be made to apply to other situations.

Some sources of uncertainty seem impossible to negate. In the real world, even two identically designed and constructed oil refineries have different efficiency and emissions profiles, due to local requirements and conditions as well as business focus (192). For instance, ambient weather conditions affect the volatility requirements of fuels, leading to product mixes shifting through the year. Substantial situational differences also exist in vehicle emissions, due to variation in driving patterns [190].

Third- and higher order energy inputs, as well as toxic emissions and land use impacts of FT diesel have not been taken into account in this study. It is recommended that research is done to determine significant impacts from these aspects on the desirability of FT diesel. The uncertainties involved in WTW chain analysis make projections inaccurate and these should therefore be used to draw qualitative conclusions only.

2.5.4 Oil price

In the period from 2004 to mid-2008, oil prices have moved between \$37 and \$139 per barrel. In the longer term, similar fluctuations may be expected [193]. Price projections for the future vary wildly: A 1999 report forecast a high price scenario of \$21 per barrel in 2005, \$28 by 2015 and \$30 by 2020 (in $\$_{1998}$) [194]. In the reference scenarios, the 2006 World Energy Outlook records

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[21] No integration between the ASU and the power island gas turbine is one example of the lack of detail that may influence our results. However, the comparison made in table 2.11 and more specific comparisons indicate that our spreadsheet model yields results that are very similar to those arrived at by using Aspen Plus.

a price of \$51 per barrel in 2005 and forecasts \$48 for 2015 and \$55 for 2030 (in $\$_{2005}$), while the 2007 WEO forecasts \$70 for 2015 and \$108 for 2030 (in $\$_{2006}$) [2, 3]. Shell Oil Co. stated production costs between \$35 and \$65 [195].

The variation in these prices suggests that simple extrapolations of oil prices based on current thinking are not reliable. Also, variations in fuel consumption and the dwindling of surplus production capacity seem to make price stability less likely [7, 8].

2.5.5 Cost of equipment

Literature sources indicated that the variation in the quoted prices for process units is ±30% to ±40% [99, 45]. In varying our system choices, we found that the choice of ASU and gasifier alone can cause a 30% change in plant cost. Furthermore, shortage of construction materials and workers can double the price in boom times (see [188]). High costs led ExxonMobil to cancel its GTL project in Qatar in 2007 in favour of an LNG project [196]. We recalculated capital costs to 2005 Euros.

Depending on circumstances that depend on economic variability rather than technological development, FT diesel could become somewhat cheaper or up to twice as expensive as in our best-guess calculations.

2.5.6 Environmental benefits of FT diesel

Fischer-Tropsch diesel, and current GTL diesel in particular, is touted as environmentally friendly (see, for instance, greencarcongress.com and Shell TV advertisements). While the current generation of GTL diesel is marketed as a clean fossil fuel, this should be clearly understood to apply to local air pollution only, as today's GTL seems to increase CO_2 emissions rather than abate them according to our analyses. The results demonstrate that even with advanced technology (including CCS at the FT plant), the use of CTL will probably increase GHG emissions. XTL and BTL may reduce CO_2 emissions, especially when combined with CCS, but further development of biomass gasification and carbon storage is required before this technology can be applied commercially.

Of particular concern with regard to the 'green' image of BTL fuels, are possible GHG emissions from (indirect) land use changes and biomass cultivation (see [45, 197, 130, 131, 133, 134]).

On the upside, any FT plant provides a stream of largely pure and storage-ready CO_2 which can be sequestered for around \$6 per tonne, if a suitable reservoir can be found near the site. Potential CCS cases with similar costs have been identified as early opportunities [198].

2.5.7 Conversion plant locations

One of the questions in selecting viable WTW chains is where to situate conversion plants. Given the high volumes of feedstock, the most efficient way of producing FT diesel seems to be to convert the feedstock to fuel as close to the source as possible. All commercial FT plants to date have been planned and built in the vicinity of feedstocks, rather than consumers. However, these were all constructed at point sources (gas fields and coal mines).

There are several reasons to put an FT plant close to the feedstock source, especially in case of a BTL (and/or CTL) chain:

- Because the volume of feedstock transported decreases as one moves down the chains, fewer logistical facilities are needed to handle the total chain. Port facilities in Western Europe would not have to be expanded several times over. Consequently, the total costs should be lower.
- Creation of industrial facilities in biomass-producing regions would present opportunities for economic development in those regions.
- Investment and operational costs (land rent, labour) in biomass-producing regions will probably be lower than in Western Europe.

There are three reasons to put an FT plant close to the fuel market instead:

1. A source-located FT plant is entirely dependent on a local supply system and it requires a significant investment into a region that may be less developed or less stable region than Western Europe. However, it must be noted that large oil companies have for decades invested in large projects in troubled regions.
2. Biomass production is often seasonal (see [74, 185], and FT production at a seasonal source would require ample storage facilities. A plant near the fuel market could use biomass from sources that vary around the year.
3. In case of a further transition to a hydrogen-based economy, it is technically feasible to 'unhook' the FT synthesis train and shift the entire volume of syngas to H_2. The majority of a conversion plant investment would therefore be robust even if future developments go against the Fischer-Tropsch option. Distributing this hydrogen would be easier if the plant were located close to the consumers.

Also of importance is the FT-naphtha, a by-product of FT synthesis that could be a valuable feedstock for chemical industries. These industries are commonly located near oil refineries. Depending on how a transition is made from fossil to FT, this could be either a business opportunity or lead to capital losses. The choice of locations for FT production, together with a reduced oil consumption, can cause a geographical shift of economic activity in the fuel sector.

2.6 Summary and conclusions

We calculated carbon and energy flows in 14 models of FT plants. Representations of various gasifiers, FT synthesis units and other process units were constructed and incorporated. Based on the sizes of the various process flows, factored estimation were used to derive investment costs. The FT plants were then combined with data on coal and natural gas supply, biomass production, conversion to biomass intermediaries such as pellets or TOPS, transport costs, vehicle costs and GHG emissions to arrive at 17 complete WTW chains.

Based on technological developments described in literature, we framed assumptions for these developments until 2020. These include moving towards biomass conversion at the source, improvements in process efficiency, and the use of CCS.

Important uncertainties, to order of tens of percents, are found in the data for component costs, variability in prices of feedstocks and by-products, and the GHG impact of producing biomass. It is impossible to fix such case-specific data in ex-ante assessments, unlike methodological choices and technical data. This study is not able to reduce the ranges of the uncertainty in WTW studies (some seem to have expanded), but we catalogue the sources of uncertainty (see table 2.13). Given the extent of the uncertainties that we find and others have found, cost and GHG emission values for Fischer-Tropsch diesel should be interpreted as best-guess estimates within uniform ranges of uncertainty.

Costs of FT diesel depend in large part on feedstock prices and conversion plant efficiency. GTL is competitive with oil-based diesel in terms of cost, breaking even at an oil price equivalent of \$33/bbl. For CTL, the oil price equivalent cost is found to be \$60/bbl. For BTL, feedstock costs would have to come down or oil prices be above \$75/bbl. At the same time, fuel costs comprise only 5%-17% of the total cost of driving.

GHG emissions from FT diesel depend almost completely on the efficiency of conversion plants, the efficiency of conversion to biomass intermediates, and the feedstock used. CTL and, to a lesser extent, GTL chains without CCS are found to increase our transport-related GHG emissions. GTL with CCS is found to reduce GHG emissions by around 5% compared to fossil diesel. The net emissions from BTL can be an order of magnitude smaller and can be made negative by application of CCS.

It is possible to have net climate neutral driving by using around 50% BTL with CCS, combined with other fuels, if biomass gasification and carbon storage can be made to work on an industrial scale and the feedstock is obtained in a sustainable (climate-neutral) manner. Further reductions in GHG emissions may come from improvements in conversion plants and supply logistics, as well as reducing improving the fuel economy of cars.

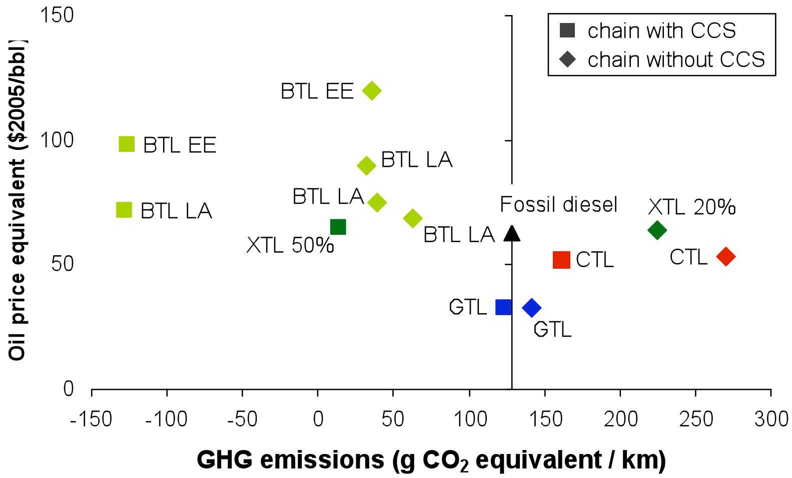

Figure 2.13: Cost of fuel in oil price equivalent vs. carbon emissions per km driven as found in this study.

Like hydrogen, Fischer-Tropsch fuels should be considered as an intermediate to put natural gas, (clean) coal or biomass into the fuel tank of an automobile. The evidence suggests that it is worth to further explore FT chains that use the latest in technology and conversion as early in the chain as possible. In practice this would mean FT plants with CCS, either in the country of origin of the feedstock, or using a more easily processed intermediate such as TOPS over biomass pellets. However, many uncertainties will remain until the actual implementation of such strategies.

“It's always easy to do the next step and it's always impossible to do two steps at a time.”

- Seymour Cray

3. Techno-economic comparison of series hybrid, fuel cell and regular cars

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3.1 Introduction

More than 90% of the transport sector is powered by fuels derived from oil. However, the consumption of these fuels is considered problematic due to costs of oil, doubts about of security of supplies [7, 6], greenhouse gas (GHG) emissions, and the emissions of air pollutants such as NO_x, PM_{10} and volatile organic compounds [12, 13].

To reduce dependence on oil in transport, the use of hydrogen and electricity in cars has been advocated for decades [30, 31, 32]. Hydrogen can be converted to electricity in a fuel cell (FC) car with high efficiency, generating no tailpipe CO_2 emissions and hardly any other pollutants [34]. However, a costly infrastructure to distribute and store hydrogen will be required [35, 36]. Hydrogen and electricity can be produced from a wide variety of energy sources; fossil, nuclear as well as renewable. Both can therefore decrease the dependence on fossil energy sources and increase energy security [39, 40]. However, costs of fuel cells and batteries remain high. Researchers give varied and uncertain appraisals of the development of the costs of alternative drivetrains [41, 42, 43, 44, 37].

Recent developments show that hybrid cars such as the Toyota Prius and Honda Civic hybrid have lower fuel consumption and thereby lower emissions than cars driven by internal combustion engines (ICE) only. Although the Prius is more expensive than a comparable ICE car, over 1 million units have been sold as of 2007 [199], showing that there is a market for alternative drivetrains. As of 2008, hybrid cars have received more and more attention. With many manufacturers selling or preparing new models, hybrid cars seem to be on the verge of mainstream adoption.

Research by Demirdoven [46] and the EU JRC [45] has shown that the performance of current FC drivetrains is comparable to the performance of a parallel hybrid drivetrain. However, the FC drivetrain has more potential for reducing emissions on the long term.

In these studies, the series hybrid drivetrain was not taken into account. In this drivetrain, the ICE is only used to generate electricity and not to power the wheels directly: only an electric motor drives the wheels. The series hybrid drivetrain can be seen both as an alternative to regular cars and parallel hybrids, as well as an intermediate stage towards fully electric or fuel cell cars: It avoids both the limited range and recharging issues of an electric car, as well as the expensive fuel cells and the lack of infrastructure for refuelling a hydrogen car. The Chevrolet Volt was announced as the first series hybrid in mass production, and is to go on sale in 2010 [85].

In this chapter, we examine the competitiveness of series hybrid compared to fuel cell, parallel hybrid, and regular cars. We use public domain data to determine efficiency, fuel consumption, total costs of ownership (TCO) and GHG emissions resulting from drivetrain choices. We investigate if series hybrid technology can make cars more efficient, particularly in view of the possibility in a series drivetrain to replace the central electric motor and transmission with electric motors built into the wheels.

Production costs of ICEs are widely available in the public domain [45, 100]. This is not the case for alternative drivetrains, but much research was performed on single components using technological learning, analogy studies and manufacturer overviews to estimate future costs [200, 201, 202]. Production costs of a series hybrid drivetrain are expected to be higher than for an ICE drivetrain, because series hybrid drivetrains have larger electric motors and components that are not yet mass-produced.

Operating costs of ICE drivetrains are known in detail [101, 203, 45], but there is little data available in the public domain on costs of operating alternative drivetrains and their influence on the total cost of ownership of a car.

We therefore aim to answer the following three questions in this chapter:

> *What are the costs and fuel consumption of electric drivetrains, powered by fuel cells or as a series hybrid?*
> *What are the TCO and well-to-wheel GHG emissions of using a fuel cell or series hybrid car, in the short and medium term?*
> *Depending on driving habits, which among the ICE, FC, and hybrid cars would attain the lowest total cost of driving?*

We describe our research methods in section 3.2, and derive costs and fuel consumption for components in section 3.3. We define fifteen vehicle configurations, and derive their costs and well-to-wheel emissions in section 3.4. We derive TCO, also depending on driving habits in section 3.5. Finally, we discuss our results and uncertainties in section 3.6. Conclusions are drawn in section 3.7.

3.2 Methods

3.2.1 Drivetrains

The drivetrain consists of parts that contribute to the conversion of fuel in the tank into kinetic energy in the wheels. Figure 3.1 shows a diagram of different drivetrains.

Reference diesel drivetrain

The reference car is a compact 5-seater, the most widely used car class in NL that includes the VW Golf, Ford Focus, Renault Megane, Toyota Corolla and Opel Astra [45, 204]. We use a reference drivetrain with properties similar to the diesel Golf drivetrain (see figure 3.1a).

Hybrid drivetrain

Parallel hybrid cars, such as the Civic hybrid, have an ICE and a small electric motor. The electric motor and the ICE can both deliver power to the wheels (see figure 3.1b). Fuel consumption is slightly lower than for regular ICE cars [46, 45]. Series hybrid cars use an engine-generator and a separate electric motor to power the wheels (see figure 3.1c). Mixing these designs is also possible, as done in the Prius.

The electric motor in a series hybrid car can be installed as a central motor, using a gearbox and differential like a regular car, like in the Volt. Alternatively, electric motors can be installed in the hubs of the wheels of the car, like in the Volvo C30 Recharge and Hi-Pa Drive Ford F150 concept cars and e-Traction busses and trucks. The latter drivetrain not require the use of a gearbox because the larger diameter allows wheel motors to deliver sufficient torque (see figure 3.1e).

Fuel Cell drivetrain

The FC drivetrain is very similar to the series hybrid drivetrain, but it replaces the engine-generator and conventional fuel tank with a fuel cell and hydrogen storage device (see figures 3.1d and 3.1f). We do not consider fuel cells with a fuel reformer because of the extra cost and reduction in energy efficiency introduced by a reformer (c.f. 45).

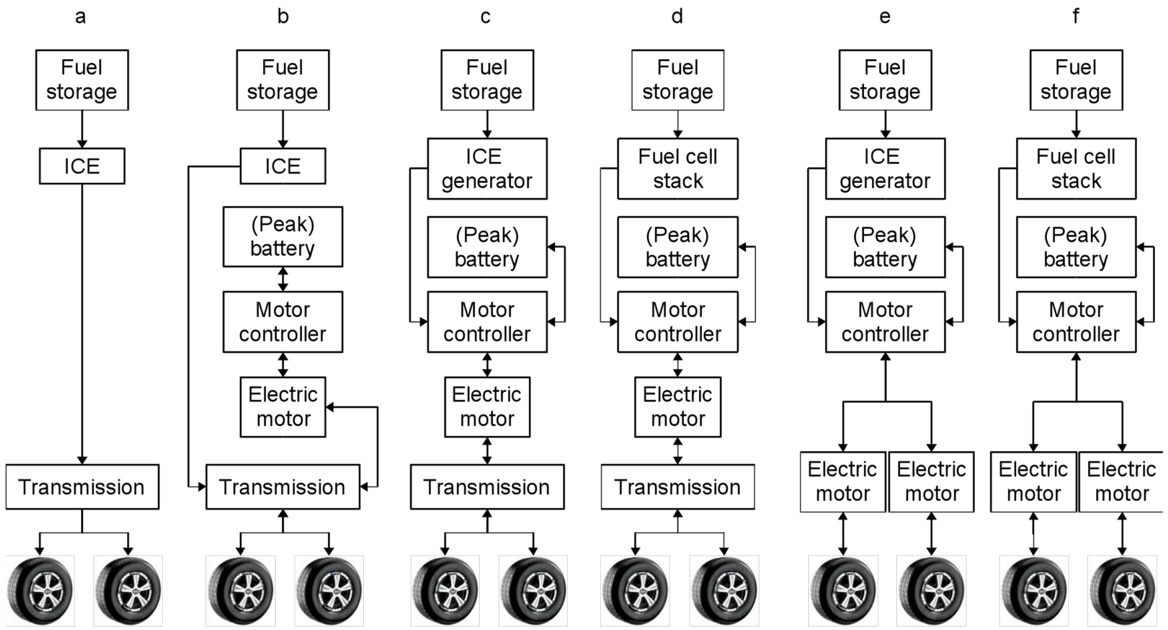


Figure 3.1: Diagram of the energy flows in six different types of drives trains; ICE drivetrain (a); Parallel hybrid drivetrain (b); Series hybrid drivetrain with central motor (c); Fuel cell drivetrain with central motor (d); Series hybrid drivetrain with wheel motors (e); Fuel cell drivetrain with wheel motors (f).

3.2.1.1 Reference car

Our reference car has a 74 kW diesel-fuelled direct injection ICE. Main characteristics of the reference car are shown in table 3.1.

Vehicle characteristics		Components	Weight (kg)	Cost (€)
Engine power (kW)	74	Vehicle platform	1016	15,725
Auxillaries power use (kW)	0.3	Diesel engine	145	4080
Torque (Nm in 1st gear, approx.)	520	Basic starter and alternator	0	300
		Gearbox	50	n/a*
Coefficient of rolling resistance	0.01	3-way catalyst	0	430
Coefficient of drag	0.32	Euro IV after-treatment	0	300
Surface area (m^2)	2.10	Diesel particulate filter	0	400
		Fuel tank	15	125
Fuel consumption (MJ/km)	1.77	Diesel 90% full tank	23	
Approximate range (km)	550			
Maintance cost (€/km)	0.043	Totals	1248	21,360

Sources: [178], 2010 DICI in [45]. *gearbox cost is included in engine cost.

Table 3.1: Characteristics of the diesel ICE reference car.

The vehicle platform is defined as everything but the drivetrain, such as chassis, suspension, doors, seats, windows, and assembly. Like Weiss et al. and the EU Joint Research Centre (JRC) [101, 45], we use the same platform for our hybrid and fuel cell configurations, exchanging only the drivetrain. The fuel consumption of the reference car is based on the New European Driving Cycle (NEDC) driving cycle.

For the TCO comparison, we also use the petrol equivalent of the reference car and a parallel hybrid car. The petrol reference car has a petrol consumption of 1.90 MJ/km and costs €19160 to purchase. For the reference parallel hybrid, we use configuration from JRC with a battery that allows for 20 km of electric driving [45]. Its purchase cost was recalculated using the battery costs for our current series hybrid cars. The parallel hybrid reference car has a petrol consumption of 1.51 MJ/km and costs €24950 to purchase.

3.2.1.2 Future developments in the reference drivetrain

Several assessments have been made of future developments of ICE efficiency. Estimates of efficiency increases until 2020 range between 7.5% [205] and 25% [206]. These fuel consumption benefits are reached through downsizing of the engine, better variable valve timing and a more efficient gearbox. Others claim that more stringent emission laws will compensate possible efficiency improvements and therefore do not expect large efficiency improvements for the ICE [45].

Improvements in baseline ICE carry over into parallel and series hybrid cars (which also use ICE), and fuel cells are also likely to improve. Because unknown but similar efficiency improvements do not essentially change the comparison between different drivetrains, we use current efficiency data for all drivetrain components.

We expect that the production costs of an ICE drivetrain of 74 kW will stay around €2600 for a petrol engine and €4300 for a diesel engine [45].

3.2.2 Drivetrain efficiency

To derive the efficiency of a series hybrid drivetrain, we use the electricity consumption of electric cars, because the motor and transmission are the same. Total energy required for driving an electric car at a constant speed can be calculated as follows:

$$P_{total} = \left(P_{tire\ friction} + P_{drag}\right) / \eta_{transmission} / \eta_{motor} + P_{auxillaries} \tag{3.1}$$

$$P_{tire\ friction} = C_{rr} \times m \times g \times v \tag{3.2}$$

$$P_{drag} = \tfrac{1}{2} \rho \times v^3 \times A \times C_d \tag{3.3}$$

in which η_{motor} = efficiency of the electric motor, $\eta_{transmission}$ = efficiency of the transmission, (axles, gearbox, differential, etc.), $P_{tire\ friction}$ = power needed to overcome rolling resistance, P_{drag} = power needed to overcome drag, C_{rr} = rolling resistance coefficient, m = mass of the vehicle (kg), g = gravitational acceleration constant (9.81 m/s^2), v = velocity of the vehicle (m/s), ρ = density of air (1.22 kg/m^3), A = frontal area of the vehicle (m^2), C_d = coefficient of drag, and $P_{auxiliaries}$ = power needed run auxiliaries (air condition, car stereo, etc.). We define the transmission efficiency as the mechanical power exerted by the wheels divided by the mechanical power generated by the motor. For a wheel motor, by definition, $\eta_{transmission}=1$.

The prime advantage of hybrid cars is that much of the kinetic energy that is lost in braking in a regular car can be recovered using regenerative braking, stored in the battery and subsequently used for acceleration. The extent of this advantage depends on the efficiency of the battery.

In a series hybrid, the total efficiency is further influenced by the η_{ICE} and $\eta_{generator}$ ($\approx\eta_{motor}$). For a series hybrid to be more efficient than a parallel hybrid, the losses due to η_{motor} and $\eta_{generator}$ that result from the engine indirectly driving the wheels, must be smaller than the benefits from resizing and balancing the load on the ICE that are possible [207].

3.2.3 Total cost of ownership

We calculate the TCO in €/year as a function of the fixed costs of the car, composed of a chassis and drivetrain, and the variable costs, composed of maintenance, repair and tires (MRT) and fuel costs.

We use analogies, expert opinions and data from literature. In the case of technological analogy, the key factors determining the price of a product are identified and compared to similar technologies [208]. Because of a lack of data, we have been largely unable to use quantitative methods such as experience curves (as described in [29, 209, 201, 210]).

3.2.3.1 Fixed costs (initial purchase)

Purchase cost of estimates of the drivetrains are based on costs and cost estimates of components from publically available literature sources. We use an annuity factor to convert the purchase cost to annual capital costs, with a commercial lifespan of 10 years [179].

For investment costs, harmonised EU-25 average consumer price indices from 1996 to 2007 [119] are used to compensate for inflation in data from years other than 2005. Costs in non-Euro currencies are converted to Euro first, using Interbank currency exchange rates averaged over the entire year [120], and corrected for inflation afterwards.

3.2.3.2 Variable costs (lifetime, maintenance, repair and tires)

The costs for maintenance, repair and tires (MRT) are expressed in €/km and are not constant. In general, an older drivetrain has higher maintenance and repair (M&R) costs than a new drivetrain. Drivetrain maintenance and repair is only a part of the total MRT cost. We use an average MRT cost of 4.3 €ct/km for the first 120 000 km for a compact European diesel car [178]. We assume that the MRT cost is the same for the remainder of the car's lifespan. Average MRT for the first 60 000km is 3.8 €ct/km for a similar petrol car and for a petrol-fuelled hybrid [178]. We assume MRT of a petrol-fuelled car is equal to 4.3 €ct/km of the diesel car for the remainder of its lifespan.

The lifespan of an ICE drivetrain can be between 192 000 km [211] and 240 000 km [212]. We assume an average lifespan of drivetrains of 200 000 km, though the drivetrain must be designed to last far beyond this average. We therefore assume a design lifespan of 300 000 km.

The NEDC is supposed to reflect an average driving pattern, and the average velocity of a car in the NEDC is 34 km/h [18]. With an average drivetrain lifespan of 200 000 km, the drivetrain must function for at least 6000 hours on average, and be designed to last up to 9000 hours.

3.2.3.3 Fuel costs

We initially assume an oil price of 80 $/bbl, close to the short term projections in the World Energy Outlook 2009 [5]. At this oil price, assuming 41.87 MJ/kg and 820 kg/m^3 for crude oil, fuel prices at the pump in the Netherlands are around 1.21 €/liter for diesel and 1.40 €/l for petrol (using [213, 214, 45]). This includes 19% value-added tax (VAT) and excise duty [215]. Untaxed, prices are 19.3 €/GJ$_{LHV}$ or 0.69 €/l for diesel and 19.9 €/GJ$_{LHV}$ or 0.64 €/l for petrol.

Electricity from the grid is not taxed as a transport fuel, but it is subject to energy taxes in NL. The exact price of electricity from the grid depends on several factors, including quantity, time of use (separate tariffs for daily and nocturnal use), network operator and the provider. We use the average of variable home-use tariffs of grid electricity in NL in early 2009 of several large utilities (EON Benelux, Elektrabel, Eneco, Essent, Nuon, RWE Nederland). This grid price is 0.10 €/kWh, including VAT but excluding additional energy taxes (c.f. [215], Dutch excise duty is 0.13 €/kWh including VAT).

There is at present neither a large fleet of hydrogen powered cars nor a large network of hydrogen filling stations. However, the co-evolution of hydrogen-fuelled cars and the infrastructure for producing the hydrogen and refuelling the cars is beyond the scope of this study. Based on Shell data, Kramer et al. [216] have estimated the costs of production and distribution of hydrogen from coal at 4.5 €/kg as of 2020, excluding VAT. This is equivalent to a price of hydrogen of 44.3 €/GJ_{LHV} including VAT. We use this as baseline price for hydrogen produced on a large scale.

Fuel costs are summarised in figure 3.2.

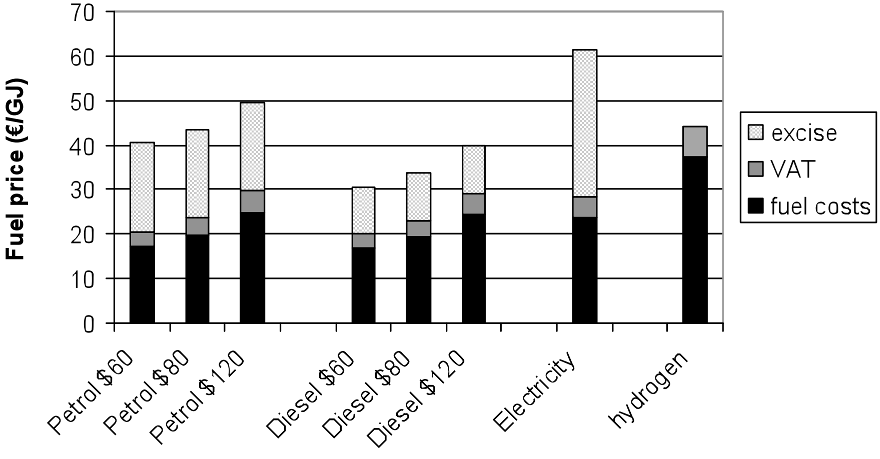


Figure 3.2: Breakdown of fuel prices into fuel costs and taxes.

3.2.4 Uncertainties

Available data are often not precise. Uncertainty in efficiency and TCO of our selected configurations is calculated as standard deviation (σ) from the indicated value. The costs of most drivetrain components depend on configurations but not on each other, and therefore have independent cost uncertainties. We therefore assume no co-variance for propagation of uncertainty in independent components and full co-variance if the cost uncertainties derive from the same underlying variable.

In cases where either an upper or a lower bound exceeded a realistic value (for instance, upper bound of a future cost > known current costs), we assumed an uncertainty of $\sigma_x = |x'_{\text{unknown}} - x_{\text{certain}}| / 2$. The same correction was applied to cases where $\sigma_x > x$ (which makes no sense for costs).

3.3 Hybrid drivetrain

3.3.1 Electric drivetrain efficiency

There are no series hybrid cars or fuel cell cars sold to consumers at this time. However, the drivetrain of a series hybrid car does not differ from a battery electric car (BEV). The only difference is that the series hybrid car has a generator to get a larger driving range and therefore the battery can be smaller.

Among electric cars used by consumers are the current Tesla Roadster, the late Toyota RAV4 EV and General Motors EV1. Plug-in conversions also exist of the Prius, by Hymotion and Energy CS, as do electrical versions of many other cars. These cars can be used to calculate the electricity consumption of a series hybrid car with a central electric motor.

The set of fuel consumption data in table 3.2 yielded a simple average consumption of 103±20 Wh/km for the whole vehicle on the SAE J1634 drive cycle. Variations are due to weight and shape of the cars, as well as the components used in the drivetrains.

Electricity consumed	**General Motors**		**Toyota**	**Enery CS**	**Hymotion**	**Tesla**
(Wh/km)	**EV1**[a]	**mid-size**[b]	**RAV4 EV**[a]	**Prius**[a]	**Prius**[a]	**Roadster**[c]
Aggregated only	96	145	131			110
Cold start						
No airconditioning				91	79	
With airconditioning				108	107	
Warm start						
No airconditioning				82	79	
With airconditioning				104	106	

Sources: [a] Idaho National Laboratory [217]. [b] General Motors [218], approximate mid-size vehicle simulation result). [c] Tesla Motors [219]. Note: We assume an AC to battery charging efficiency of 90% and a 96% battery discharge efficiency for the Prius models [220].

Table 3.2: Electricity consumption (in drive cycle) of selected electric cars.

To determine the losses in various components of the drivetrain (losses in the electric motor and transmission, air drag, tire friction, power for auxiliaries), we further examined the RAV4 EV and EV1. The resistance that the car has to overcome on a flat road is the sum of the rolling resistance and drag. The difference between the power that the motor delivers and the total resistance is the energy lost in the drivetrain.

Table 3.3 shows the mass, surface area and drag coefficient of the RAV4 EV and EV1. Both electric cars use low-friction tires, and we calculate for both value we found for C_{rr}. Furthermore, we use an efficiency of 90% for electric motor and power controller electronics module (PCE) at constant speed, a 96% battery discharge efficiency and a power consumption of 0.3 kW for auxiliaries [45, 219, 220].

	Toyota RAV4 EV	**GM EV1**
mass (kg)	1510	1347
A (m^2)	2.8	1.89
C_d	0.35	0.20
C_{rr}	0.0027 or 0.0045	0.005 or 0.008

Sources: [217, 221, 222, 223].

Table 3.3: Mass, surface area, C_d and C_{rr} for RAV4 EV and EV1.

From known electricity consumption at fixed speeds [217, 219], we calculate the drivetrain efficiency at velocities of 72 and 96 km/h (20 and 27 m/s) for the RAV4 EV and EV1, as shown in table 3.4. We find an $\eta_{\text{transmission}}$ of 0.86±0.07, which is similar to the 0.89 found in simulations by JRC [45].

For charging and discharging the battery, we use a combined efficiency of 94% [45]. We assume that half of the electricity generated by the on-board generator or fuel cell is charged and discharged through the battery, and the other half is used directly by the electric motor. For plug-in hybrids, we use efficiencies of 90% for charging the battery from the grid and 96% for discharging the battery [220].

3.3.2 Central electric motor

Almost all existing electric cars use a single motor and a simplified transmission to connect to the wheels.

Efficiency and fuel consumption

The costs of the electricity in the reference car depend on how that electricity is generated. We calculated that the central motor drivetrain with a generator or fuel cell and a battery uses 106±21 Wh/km, including charge/discharge losses. If powered by the grid, conversion losses increase this to 119±23 Wh/km.

Production costs

The central electric motor consists of three parts, the motor itself, the control electronics and a gearbox especially designed for electric motors. Deluchi et al. [212] provided equations to calculate the production costs of these three components and the development of the production costs when the production volume is increased to 20 000 and 200 000 units per year. As sales of

	Toyota RAV4 EV				General Motors EV1			
velocity (m/s)	20	20	27	27	20	20	27	27
electricity consumption (Wh/km)	293	293	440	440	177	177	234	234
Crr	0.0027	0.0045	0.0027	0.0045	0.005	0.008	0.005	0.008
rolling resistance (kW)	0.80	1.34	1.07	1.79	1.33	2.13	1.77	2.84
air resistance (kW)	4.87	4.87	11.54	11.54	1.83	1.83	4.34	4.34
total resistance (kW)	5.67	6.21	12.61	13.32	3.16	3.96	6.11	7.17
power to drivetrain (kW)	7.9	7.9	16.1	16.1	4.7	4.7	8.4	8.4
power from source (kW)	8.2	8.2	16.4	16.4	5.0	5.0	8.7	8.7
PCE + motor efficiency	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
transmission efficiency	0.80	0.88	0.87	0.92	0.75	0.94	0.80	0.94
combined drivetrain efficiency	0.72	0.79	0.78	0.83	0.68	0.85	0.72	0.85

Table 3.4: Power consumption, tire friction, drag, total resistance and drivetrain efficiency of the Toyota RAV4 EV, General Motors EV1 at 72 and 96 km/h.

hybrid cars exceeded 300 000 per year in the US alone in 2007 and 2008 [224], we use the 20 000 units/year costs as an upper bound and the 200 000 units/year costs as a lower bound. JRC also gave cost estimates for these components.

Table 3.5 shows the unit production cost estimates for electric motors. For small production volumes the fixed costs have a significant contribution to total production costs of brushless permanent magnet (BPM) motors.

Type	Fixed (€)	Variable (€/kWe)	Fixed (kg)	Variable (kg/kWe)
AC induction motor[a]	-	13.0	5	1
BPM motor >20K[a]	107	17.0	5	1
BPM motor >200k[a]	-	15.1	5	1
generic electric motor[b]	-	8.0	-	0.7

Sources: [a] Delucchi et al. [212]. [b] JRC [45].

Table 3.5: Electric motor costs.

Table 3.6 shows the unit production cost estimates for electric motor controllers. Again, fixed costs play a bigger role when the production volume is small.

Type	Fixed (€)	Variable (€/kWe)
AC induction controller >20k[a]	1205	8.6
AC induction controller >200k[a]	376	9.2
BPM controller >20k[a]	964	5.8
BPM controller >200k[a]	316	8.3
generic controller[b]	-	19.0

Sources: [a] Delucchi et al. [212]. [b] JRC [45].

Table 3.6: Electric motor controller costs.

The gearbox for a series hybrid is simpler and lighter than a regular gearbox. A single-speed gearbox for a 200 kWe motor in an electric sports car weighs only 45 kg [225]. Table 3.7 shows unit costs of less powerful transmissions.

Type	Fixed (€)	Variable (€/kWe)	Fixed (kg)	Variable (kg/kWe)
gearbox & differential >20k[a]	971	19.3	-	0.4
gearbox & differential >200k[a]	565	11.3	-	0.4
hybrid drive adaptations[b]	2630	-	30	-

Sources: [a] Delucchi et al. [212]. [b] JRC [45].

Table 3.7: Transmission costs.

Table 3.8 lists total production costs for a 74 kW_e central electric motor, calculated by adding the average of production costs of the three different components.

	Cost (€)	Weight (kg)
74kW electric motor	1000 ± 281	74 ± 12
Controller	1324 ± 355	-
Gearbox	2144 ± 652	30
Total	4467 ± 1288	104 ± 12

Table 3.8: Breakdown of the production costs and weight for an electric drivetrain with a 74kW central electric motor.

Lifetime, maintenance & repair

As electric motors have fewer moving parts and face less temperature stress than an ICE, we expect the lifespan to exceed 6000 hours. While electric motors are simpler in construction than ICE, dealerships currently lack experience in maintaining them. The M&R estimations diverge from 15% higher to 50% lower than an ICE car [212]. To be conservative and for the sake of simplicity, we assume the MRT costs are the same as those of the reference diesel car.

3.3.3 Wheel electric motor

A wheel motor is an electric motor built inside a wheel. The design was first used in a Lohner-Porsche of 1902. In most permanent magnet motors, the housing of the electromotor remains stationary and the centre spins inside it. In a wheel motor this is reversed: The rotor of the electric motor is built inside the rim and the stator is placed in the hub of the wheel. The stator is fitted with electromagnets and the rotor with permanent magnets. The maximum torque that can be generated depends on the diameter of the rim. A wheel motor drivetrain is more efficient than an ICE or a central electric motor, because no losses occur in the gearbox and differential.

Our wheel motor has power output similar to an existing e-Traction design, TheWheel SM 450 [226]. The wheel motor delivers a maximum torque of 400 Nm and is installed in pairs for a total of 800 Nm. Maximum power output is 29 kW per wheel motor, for a total of 58 kW per pair.

Efficiency and fuel consumption

Because wheel motor cars do not need a gearbox, differential or other parts of a conventional transmission, the wheel motor car does not suffer losses in the transmission. We determined the transmission efficiency in the central motor drivetrain to be 0.86±0.07 (in section 3.3.1). Corrected for lack of transmission losses, the electricity consumption of a wheel motor car with a 90% efficient electric motor is 89±19 Wh/km on an SAE J1634 drive cycle. This is 7%-21% lower than a central motor car.

A 58 kW motor for the wheel motor drivetrain provides less than the 74 kW output of the reference car, but its performance should be at least equivalent, as the reference ICE produces around 55 kW at the wheels (after transmission losses) with less torque.

Production costs

Wheels with a motor in the hub have a higher weight than normal wheels, so a specific sub-frame is installed that supports the wheel motor and its suspension. Some extra parts are also needed to produce a wheel motor drivetrain such as cables, software and special mounting parts. These are grouped under auxiliaries.

At present, production costs for a 58 kW wheel motor set for a 5-seater compact car is €17245 [227]. A breakdown of the production costs is shown in Table 3.9.

A wheel motor differs from a common permanent magnet motor only in size and shape. Therefore, we assume that at 100 000 sets, the costs of producing a wheel motor are the same as producing a normal permanent magnet motor (see section 3.3.2). We assume that the auxiliaries and the sub-frame continue to have the same share of production costs as the electric motor and controller.

	Single set (€)		100 sets (€)	>100k sets/year (€)
TheWheel SM 450	11714	68%	6488	810 ± 228
Auxilliaries	1228	7%	680	166 ± 47
Sub-frame	2156	13%	1194	292 ± 82
Controller	2147	12%	1189	1066 ± 61
Total	17245		9551	2335 ± 362

Table 3.9: Production costs of wheel motors, for a single set of two motors, 100 sets [227] and extrapolated to >200k motor/year production volume.

Lifetime, maintenance and repair

M&R of wheel motor drivetrains is difficult to estimate. There are a handful of wheel motor cars on the road today. The wheel itself is the only moving part in a wheel motor, which should reduce M&R costs compared to central motor cars with a transmission, but the motor is subject to vibrations that would be dampened by the car's suspension in a central motor configuration which could increase wear. As with central electric motors, it is expected that M&R costs will decline when there is more experience with a wheel motor. As with central motor drivetrains, we assume that MRT costs are the same as those of reference car.

3.3.4 Downscaling the electricity generation device

One benefit of the series hybrid drivetrain is the possibility of downscaling the electricity generation device, compared to the engine of the reference ICE drivetrain. The maximum power that the reference car generates is 74 kW, used at maximum acceleration or at very high velocity of the car (>160 km/h). In a central motor series hybrid, the electric motor also has a maximum power of 74 kW.

However, the maximum power is only used in short periods of acceleration and for driving faster than is legally allowed in most places. In hybrid cars, a battery complements the generator for peak loads. Therefore, the generator only needs to deliver the electricity to sustain maximum cruising speed, around 120 km/h.

The amount of electricity needed to drive a car at a constant velocity of 120 km/hr is the sum of rolling resistance, drag, transmission losses and motor losses of the car (see section 3.3.1). The sum of rolling resistance and drag for the reference car at a constant velocity of 120 km/hr is around 20 kW, but increases rapidly with higher speed due to drag (see Table 3.10). Including losses in the transmission, the load in a central motor hybrid at 120 km/h is around 30kW.

Speed (km/h)	**50**	**80**	**100**	**120**	**140**
rolling resistance (kW)	1.8	2.9	3.6	4.3	5.0
air resistance (kW)	1.1	4.5	8.8	15.2	24.2
total resistance (kW)	2.9	7.4	12.4	19.5	29.2
transmission efficiency	0.86	0.86	0.86	0.86	0.86
power to drivetrain (kW)	3.3	8.5	14.3	22.6	33.8
PCE + motor efficiency	0.90	0.90	0.90	0.90	0.90
auxillaries draw (kW)	0.3	0.3	0.3	0.3	0.3
power from source (kW)	4.0	9.8	16.2	25.4	37.8
combined drivetrain efficiency	0.78	0.78	0.78	0.78	0.78
electricity consumption (Wh/km)	80	122	162	212	270
σ in power from source (kW)	0.31	0.79	1.32	2.09	3.12
σ in power to drivetrain (kW)	0.28	0.71	1.19	1.88	2.81

Note: Using reference car characteristics (C_{rr}=0.01, mass=1306 kg, C_d=0.321, A=2.1 m^2). Electricity consumption does not include charge/discharge or AC conversion losses.

Table 3.10: Hybrid drivetrain energy requirements at various speeds.

General Motors use a 53 kW engine-generator in their Volt series hybrid. To have similar reserve capacity, and allow sustained speeds of over 140 km/h, we use a 53 kW engine-generator for the central motor hybrid. The engine-generator can be downscaled further to 46 kW for the wheel motor hybrid, because the wheel motor drivetrain does not suffer efficiency losses in the transmission.

3.3.5 Diesel generator

A diesel engine-generator is a diesel powered ICE that drives an electricity generator. The electricity that is generated is fed to the motor controller that distributes electricity either to the battery or to the motor directly.

An engine-generator with batteries can be operated at higher efficiency than an engine that drives the wheels of a car directly, because the engine load and speed can be kept such that the engine runs constantly at or near maximum efficiency while the battery provides power for sudden variations in power demand.

Efficiency and fuel consumption

The efficiency of an engine-generator depends on the load at which it is operated. The generator has an efficiency of 90%-95%, so most of the energy losses in an engine-generator are in the diesel ICE. Maximum efficiency of the ICE is approximately 40% [228]. Accounting for start-up or operations at lower than maximum efficiency, we assume an overall efficiency of 33% [227, 229].

An efficiency improvement in the ICE can have a large effect on diesel engine-generator efficiency. For consistency however, we assume the same net status quo development as with the diesel engine in a reference drivetrain.

Fuel consumption depends on how much electricity an electric car uses. One litre of diesel contains 36 MJ and generates 3.3 kWh_e.

Production costs

At present, a 42 kW diesel engine-generator costs € 3143 and this technology is quite mature [226]. If we use the electric motor costs of the previous section and component breakdown from JRC, the ICE in the generator has a cost of €1500 + 25 €/kW_e. We add €125 for a fuel tank and €730 for exhaust gas treatment to the cost of the engine-generator [45].

Using this data, and assuming the uncertainty in costs is in the electric motor only, we estimate a 46 kW_e diesel generator to power a wheel motor car at a cost of €4500 ± €200. We estimate a 53 kW_e diesel generator to power a central motor car at a cost of €4800 ± €200. We assume the controller is integrated with the controller of the electric motor(s) that drive(s) the wheels.

Lifetime, maintenance and repair

An engine-generator used in stationary applications has an average lifetime of 15 000 hours at full load [229], far exceeding the lifetime of the car. Over the equivalent lifetime of a car, a normal engine-generator needs little maintenance. Normal maintenance is performed every 500 hours of operation. Over the 6000-hour lifetime of the car that means approximately 11 times. Maintenance consists of changing the oil and all filters. This costs approximately €140 including labour [229]. Total M&R costs over the lifetime add up to € 1540.

An ICE that drives a car directly must be able to go from idling to maximum power in a few seconds and back. This causes large temperature differences in the ICE and puts stress on the ICE. These differences in load cause wear in an ICE. In urban traffic or traffic jams in particular, this can lead to a shorter lifetime or higher M&R costs for the ICE. An ICE that drives an electricity generator is stressed less, because the load is controlled electronically and more constant. This should lead to lower M&R costs for the ICE. However, the series hybrid drivetrain as a whole has more parts than the direct ICE drivetrain. We therefore assume that total MRT costs are equal to the diesel reference car MRT of 4.3 €ct/km.

3.3.6 Electricity storage

There are four important factors that determine the attractiveness of Electricity Storage Devices (ESDs); cost per unit (€), lifetime (h), specific power (kW/kg) and specific energy (kWh/kg).

Total weight and price of ESDs also depend on the design goals for the vehicle. For series hybrid cars, there is no universal goal. Some argue that the batteries must withstand peak load for a few seconds only to assist the engine-generator while accelerating. On the other hand, if a car has to deliver peak-load for a prolonged period of time, for instance climbing a long hill, it needs enough storage capacity to last at least until the top of the hill.

Others demand long driving ranges in battery mode so the car can be used as a plug-in hybrid and be charged from the electricity grid.

Lead-acid batteries and ultracapacitors were found to have insufficient specific energy, which would lead to excessive weight and volume for the battery pack. Many contemporary hybrid cars use nickel-metal hydride (NiMH) batteries, but future cost reductions are limited by the price of nickel [200]. Safety concerns (risk of thermal runaway) have been a major reason for using NiMH batteries in cars instead of Li-ion batteries. New materials in the latest generation of batteries have greatly reduced or eliminated that risk [230, 231]. We therefore use lithium-ion (Li-ion) batteries for storage options.

3.3.6.1 Minimum capacity requirements

The size of the battery is determined by specific power and specific energy and its purpose.

Power should be large enough to enable decent acceleration of the car. which means the battery must deliver the maximum power of the electric motor(s) in a plug-in hybrid, and at least 50% in other configurations. In case of emergency (such as a generator failure), this is enough to have the car function properly in battery-only mode for a short distance.

The capacity of the battery must be at least 1.0 kWh, to allow time for warming up of the generator or fuel cell and to provide sufficient reserves for using top speeds in emergencies. This is enough to drive 7-8 kilometres on battery only, depending on the efficiency of the drivetrain. This is similar to a Prius (NHW20 model), which has a 1.3 kWh NiMH battery pack and the Civic hybrid, which has a 0.7 kWh NiMH battery pack.

If the car is to be used as a plug-in hybrid, the size of the battery depends on the preference of the consumer. Around 80% of the trips made by cars are smaller than 50 km [232, see also 230, 218], and we therefore assume that a plug-in hybrid must be able to drive at least 50 km on the batteries. This requires a battery of 6-7 kWh, depending on the electricity consumption of the car. With that battery, 80% of trips can be driven entirely in battery mode, as can the initial part of the remaining 20% of longer trips.

A purely battery-powered electric car, without a generator for long range travel, would need a battery of 32-37 kWh to achieve a range ≥300 km.

3.3.6.2 Lifetime requirements

When a car is used as a plug-in hybrid, the battery pack must be able to withstand many deep discharges. Discharging a battery down to 20% of its capacity (80% depth of discharge (DoD)) is usually considered deep discharging. The battery pack therefore needs to be over-dimensioned by 25%, so that 80% of the battery capacity is be enough to drive 50 km. In view of recent advances in cathode and anode materials, we assume batteries can be operated between 20% and 90% charge without reducing lifespan.

The lifetime of the electric drivetrain should be at least 300 000 km. We assume that the share of trips made in battery mode translates to at most 80% of the total kilometres being driven in battery mode. Therefore the battery must last for 240 000 kilometres. The storage device is designed for a range of 50 km, so the battery pack for a plug-in hybrid must withstand up to 4800 discharge cycles.

If the battery is only used to cover peak-load, the usage will be less intensive since there is usually no need to fully discharge the battery pack. This will prolong the lifetime of the battery. NiMH battery packs used in hybrid taxis are reported to have lasted over 350 000 km [233].

3.3.6.3 Li-ion batteries

Many experts consider Li-ion batteries the most preferred battery for hybrid cars, especially for plug-in hybrid cars because of their high specific energy. Li-ion batteries have found their way to commercialization in small consumer electronics and are now being introduced in hybrid electric cars.

The technical potential for Li-ion is enormous. In laboratory experiments, Li-ion batteries have shown to be capable of many thousands of deep discharge cycles. They have a specific power of 2000 W/kg and a specific energy as high as 400 Wh/kg [231]. However, the battery must be able to withstand rapid cycling in a hybrid car, and for market introduction it is important that production costs are low.

Production costs

We found several examples of state-of-the-art battery technology. Assembling cells into a battery pack reduces the specific energy and capacity by 10%-15% [234]. The properties of these batteries are listed in Table 3.11.

Manufacturer	Name	Sp. energy (Wh/kg)	Sp. power (W/kg)	Pack cost (€/kWh)	Cycle life
Valence[a]	UEV-18XP	90	1200	1000	2000
A123 Systems[b]	26650 (cell)	110	3000	1400	2000
Altairnano[c]	Nanosafe (cell)	90	3000	1600	10000

Sources: [a] [235, 84]. [b] [230, 83]. [c] [231, 236].

Table 3.11: Approximate properties of modern Li-ion batteries.

Unlike NiMH batteries, Li-ion batteries do not contain scarce materials [237, 238]. For the coming decade however, it is expected that the biggest challenge will be to develop safe and low-cost Li-ion batteries with a calendar life of at least 10 years. Therefore, it is not expected that there will be a large decreases in price for the coming decade.

We assume that the Li-ion battery will cost approximately 800 €/kWh, have a specific energy of 110 Wh/kg and a specific power of 3000 W/kg. This is significantly more expensive and heavy than the cost of 140 €/kWh and specific energy of 150 Wh/kg that the US Advanced Battery Consortium set as the minimum requirement for all-electric cars [239].

Lifetime

Calendar life is an important factor for Li-ion batteries. The electrodes and the electrolyte can wear rapidly thereby reducing battery performance and capacity, especially when fully charged. At present Li-ion batteries have a calendar life of around 5 years [200].

Just like for NiMH batteries, life can be extended to hundreds of thousands cycles at low DoD [230]. Because experiments have shown that state of the art Li-ion batteries can withstand 4000 [200] to 9000 [231] deep discharge cycles, it is expected that lifespan will increase to at least 5000 cycles in the coming decade. We therefore ignore the possibility that a battery pack may have to be replaced over the lifetime of a car.

3.3.6.4 Series hybrid battery packs

Table 3.12 shows the properties of our battery packs, calculated using the vehicle configuration in table 3.13 (section 3.3.4). For the current technology series hybrids, high specific power (see table 3.11) allows for the smallest, and therefore the cheapest batteries. For the plug-in hybrid, specific power is not a limiting factor and the cheapest unit per kWh (see table 3.11) is used. Plug-in hybrids also include a charger at a cost of €482 [212].

Drivetrain			Min. range (km)	Capacity (kWh)	Cost (€)	Weight (kg)
Central motor	hybrid	current	8	1.1	1,737	12
Wheel motor	hybrid	current	8	1.1	1,467	10
Central motor	plug-in	current	50	7.4	7,546 ± 1374	83 ± 16
Wheel motor	plug-in	current	50	6.4	6,585 ± 1291	72 ± 15
Central motor	hybrid	future	9	1.4	1,085	12
Wheel motor	hybrid	future	8	1.1	851	10
Central motor	plug-in	future	50	7.4	6,379 ± 1147	67 ± 13
Wheel motor	plug-in	future	50	6.4	5,577 ± 1077	58 ± 12

Table 3.12: Properties of the four ESDs now and in the future, as assumed in this study.

The biggest challenge for batteries in the coming decade is to reduce production costs without reducing specific capacity.

3.3.7 Fuel cell

There is a small market for mobile fuel cells, mostly Proton Exchange Membrane (PEM) cells [201, 240]. BMW, Ford, Toyota and Honda have been the most active producers, building small runs of demonstration fuel cell cars [51].

Efficiency and fuel consumption

A fuel cell has a theoretical maximum conversion efficiency of 83% [241]. In practice, fuel cell efficiency is generally lower. Efficiency depends on the workload of the fuel cell. Efficiency is highest in low- to midrange loads, and lower than 50% only at loads smaller than 10% and above 80% [45, 241, 242]. Therefore, we assume that the fuel cell works with a constant efficiency of 55% during a driving cycle.

In a PEM fuel cell with 55% efficiency, one kilogram of hydrogen containing 120.1 MJ generates 18.5 kWh.

Production costs

The production costs of the fuel cell are currently the most important hurdle for large-scale introduction. The most expensive parts of the fuel cell are platinum, which is used as a catalyst, the bipolar plates and the proton exchange membrane.

At present the production costs of the fuel cell are between 1000 €/kW and 1800 €/kW [201, 202, 240, 243]. Many assessments have been made on how the production costs of the fuel cell will develop. The conclusions vary between 27 to 35 €kWe [41] 38 €/kWe or more [201], 50 €/kWe [244, 245], 294 €/kWh [246] and 50 to 450 €/kWe [247]. Assumptions have a strong influence: Tsuchiya & Kobayashi ranged between 12 and 120 €/kW [201] in 2020 after 5 million units are produced. With lower production volumes, costs could remain much higher.

We assume the current cost to be 1200±200 €/kW. Based on the sources above, we assume long term production costs to be 110±49 €/kW, contingent on large production volumes. This is roughly equal to the cost of diesel generators and a reduction of over 90% of the current costs.

Lifetime, maintenance and repair

Under ideal circumstances current PEM fuel cells are capable of operating for 20 000 hours. Putting a fuel cell through many start/stop cycles has no significant negative influence on the lifetime [240]. However, dirty air from a city, hydrogen that is not clean or operating at full-load for prolonged periods can reduce the lifespan of a fuel cell. If the voltage that the fuel cell delivers is 10% lower than the voltage in the beginning of the life, the fuel cell is considered worn [240]. The minimum lifetime of a fuel cell under full load is approximately 2000 hours. We assume that the fuel cell uses clean hydrogen and rarely operates at full load, extending the lifetime of the fuel cell to that of the car (9000 hours, section 3.2.2).

3.3.8 Hydrogen storage

The energy density of hydrogen under atmospheric pressure at room temperature is very low at 0.0108 MJ/liter, compared to 36 MJ/liter for diesel. This necessitates special storage methods. The only viable storage option at this moment is compressed gaseous hydrogen (CGH_2) [248, 37]. This situation is expected to remain into the near future [37]. A full tank is 4.2 kg for a central motor car and 3.6 for a wheel motor car , with storage pressure between 35 and 70 MPa. JRC estimates the price of such a tank to reach 575 €/kgH_2 and to weigh 56 kg [45].

3.4 Cars

We constructed 15 vehicle configurations using our data: 3 reference cars, 6 current series configurations and 6 future configurations. The requirements are the same for current and future configurations, and difference is in the vehicle costs. Our configurations are summarised in Table 3.13.

Vehicle configuration	Abbreviation	Motor power	Generator / fuel cell power	Minimum battery required
ICE diesel reference car		74 kW	n/a	n/a
ICE petrol reference car		77 kW	n/a	n/a
Petrol-fuelled parallel hybrid		62 kW + 30 kW_e	n/a	2.9 kWh (20km)
Central motor series hybrid	SHEV CM	74 kW_e	53 kW_e	37 kW (50%)
Wheel motor series hybrid	SHEV WM	2 x 29 kW_e	39 kW_e	29 kW (50%)
Central motor plug-in hybrid	PHEV CM	74 kW_e	53 kW_e	7.7 kWh (50km)
Wheel motor plug-in hybrid	PHEV WM	2 x 29 kW_e	39 kW_e	5.1 kWh (50km)
Central motor fuel cell car	FCEV CM	74 kW_e	53 kW_e	37 kW (50%)
Wheel motor fuel cell car	FCEV WM	2 x 29 kW_e	39 kW_e	29 kW (50%)

Note: In brackets with minimum battery required is the marginal capacity requirement (see section 3.3.6.1).

Table 3.13: Vehicle configurations investigated in this study.

We compare these configurations to each other and the reference diesel and petrol cars, as well as a petrol-fuelled parallel hybrid.

3.4.1 Fuel consumption and CO_2 emissions

Table 3.14 shows the tank-to-wheel (TTW) and well-to-wheel (WTW) fuel consumption of our vehicle configurations. The results are dominated by the efficiency of the on-board energy converters: 33% for the diesel generator, 55% for the fuel cell, and 86% for the battery charger (from the grid). The WTW uncertainties include uncertainty in marginal oil refining (20% for diesel, 25% for petrol) [45], electricity generation at an assumed 44%±5% efficiency and 86% grid efficiency [220], and differences between various ways of hydrogen production [249, 45, 250].

Vehicle configuration	Fuel	Fuel consumption (MJ/km)	Range (km) on 36 MJ	Primary energy used (MJ/km)
Reference diesel	diesel	1.77	20	2.00 ± 0.4
Reference petrol	petrol	1.90	19	2.19 ± 0.55
Parallel hybrid	petrol	1.51	24	1.74 ± 0.44
SHEV central motor	diesel	1.16 ± 0.23	31 ± 6	1.31 ± 0.37
SHEV wheel motor	diesel	1.00 ± 0.21	36 ± 8	1.16 ± 0.34
PHEV central motor	grid electricity	0.43 ± 0.08	83 ± 16	1.13 ± 0.26
PHEV wheel motor	grid electricity	0.37 ± 0.08	97 ± 20	0.98 ± 0.24
FCEV central motor	hydrogen	0.70 ± 0.14	52 ± 10	1.04 ± 0.21
FCEV wheel motor	hydrogen	0.60 ± 0.13	60 ± 13	0.90 ± 0.2

Note: Plug-in hybrids have the same fuel consumption as regular series hybrids when driving on diesel.

Table 3.14: TTW fuel consumption, range on 36 MJ (equivalent of 1 litre of diesel) in the tank or battery, and WTW energy consumption.

Our calculations show a reduction in fuel consumption of 44% for a wheel motor series hybrid compared to the reference diesel car. Our only known empirical comparison is from an wheel motor city bus that achieved a certified reduction of 62%-69% when compared to an equivalent regular diesel bus in a SORT 2 driving cycle that mimics light urban traffic [251, 252, 253].

Table 3.15 shows the emissions of greenhouse gasses from our vehicle configurations. The GHG emissions depend on the emissions of the car (TTW) and the emissions made in producing the required diesel, petrol, hydrogen or electricity (well-to-tank - WTT). We used TTW emission factors of 73.2 gCO_2/MJ diesel and 73.3 gCO_2/MJ petrol and WTT emission factors of 14±3 $gCO_{2\ \mathrm{equivalent}}$/MJ diesel and 12±3 $gCO_{2\ \mathrm{equivalent}}$/MJ petrol [45]. For hydrogen and electricity, there are no TTW emissions, and WTT emissions vary by the source. WTT emissions are assumed to be 0 if generated from solar or wind power, and up to 467±59 gCO_2/kWh for electricity and 158 g/MJ H_2 if generated from coal without carbon capture and storage (CCS) [based on 250]. Emissions from electricity assume the same electric utilities used to calculate electricity price, fuelled with around 20% coal and 45% natural gas, corrected for grid losses.

Vehicle configuration	Fuel	TTW emissions (g/km)	WTT emissions (g/km)	total emissions (g/km)
Reference diesel	diesel	131	25 ± 5	156 ± 5
Reference petrol	petrol	140	22 ± 6	163 ± 6
Parallel hybrid	petrol	112	18 ± 4	129 ± 4
SHEV central motor	diesel	87 ± 17	16 ± 5	103 ± 20
SHEV wheel motor	diesel	75 ± 16	14 ± 4	89 ± 19
PHEV central motor	grid electricity		0 to 69	0 to 69
PHEV wheel motor	grid electricity		0 to 60	0 to 60
FCEV central motor	hydrogen		0 to 131	0 to 131
FCEV wheel motor	hydrogen		0 to 115	0 to 115

Note: Total emissions may also be sharply reduced by other means, such as sustainable biofuels.

Table 3.15: Greenhouse gas emissions from our vehicle configurations in g CO_2 equivalent / km.

The series hybrid cars generate less CO_2 than the reference cars: well to wheel, the diesel series hybrid produces less than 60% of the CO_2 of the reference diesel car. The plug-in hybrid using electricity has lower CO_2 emissions than any of the diesel-fuelled cars: around 69 g/km for a central motor and around 60 g/km for a wheel motor configuration.

The production of the fuel and/or electricity has as much influence on transport emissions as the efficiency of the drivetrain. However, calculating the impact of alternatives, such as sustainable biofuels and CCS, requires a context that is beyond the scope of this study.

3.4.2 Production costs

Table 3.16 and Figure 3.3 show the total production costs per component and the total production costs of the car. Total production costs are the lowest for ICE drivetrains. Current production costs of fuel cell stacks are an order of magnitude higher than those of competing drivetrains.

Vehicle configuration	Platform	Electrical drive	ICE / generator / FC	Battery	Total (€)
Reference diesel	15725	0	5635	0	21360
Reference petrol	15435	0	3725	0	19160
Parallel hybrid	15435	3662	2983	2826 ± 0	24906 ± 0
SHEV CM now	15725	4375 ± 747	4823 ± 211	1737	26659 ± 776
SHEV WM now	15725	9551	4546 ± 188	1467	31289 ± 188
SHEV CM future	15725	4375 ± 747	4823 ± 211	1085	26008 ± 776
SHEV WM future	15725	2335 ± 724	4546 ± 188	851	23456 ± 748
PHEV CM now	15725	4375 ± 747	4823 ± 211	7546 ± 1374	32469 ± 1578
PHEV WM now	15725	9551	4546 ± 188	6585 ± 1291	36407 ± 1304
PHEV CM future	15725	4375 ± 747	4823 ± 211	6379 ± 1147	31302 ± 1385
PHEV WM future	15725	2335 ± 724	4546 ± 188	5577 ± 1077	28183 ± 1312
FCEV CM now	15725	4375 ± 747	66015 ± 10600	1737 ± 132	87852 ± 10627
FCEV WM now	15725	9551	57296 ± 9200	1467 ± 204	84039 ± 9202
FCEV CM future	15725	4375 ± 747	8245 ± 2588	1085	29430 ± 2694
FCEV WM future	15725	2335 ± 724	7156 ± 2246	851 ± 119	26066 ± 2363

Note: Uncertainty depends on the assumptions about conversion efficiency and motor cost.

Table 3.16: Vehicle production costs (in € including VAT).

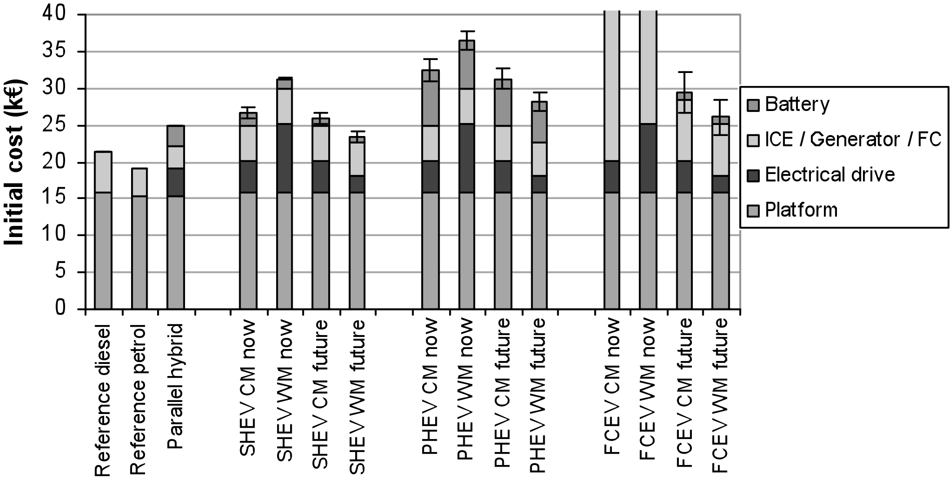


Figure 3.3: Vehicle production costs (including VAT). Error bars indicate uncertainty in total production costs, given the assumptions about conversion efficiency, and motor cost.

The production costs of any of the hybrid cars will remain higher than the cost of an ICE car, because of the additional components (mostly electric motors).

3.5 What does it cost to drive?

3.5.1 Variable costs

Table 3.17 shows the variable costs of driving our vehicle configurations, with fuel prices including VAT but no excise duty. Because we assumed no net efficiency gains in the drivetrains and stable fuel prices, the current and future models have the same results. The total variable costs for plug-in hybrids are calculated with driving 80% on electricity and 20% on diesel.

Vehicle configuration	MRT	Diesel / petrol	Electricity (grid)	Hydrogen	Total (€/km)
Reference diesel	0.043	0.041			0.084
Reference petrol	0.041	0.044			0.085
Parallel hybrid	0.041	0.035			0.076
SHEV central motor	0.043	0.027 ± 0.005			0.070 ± 0.005
SHEV wheel motor	0.043	0.023 ± 0.005			0.066 ± 0.005
PHEV central motor	0.043	0.027 ± 0.005	0.012 ± 0.002		0.058 ± 0.003
PHEV wheel motor	0.043	0.023 ± 0.005	0.011 ± 0.002		0.056 ± 0.003
FCEV central motor	0.043			0.031 ± 0.006	0.074 ± 0.006
FCEV wheel motor	0.043			0.027 ± 0.006	0.070 ± 0.006

Note: Uncertainty derives from the assumptions on efficiency.

Table 3.17: Variable costs (including VAT).

The variable costs for the wheel motor drivetrains are lower than those for the central motor drivetrain, whether electricity is generated by a fuel cell, by a diesel generator or drawn from the grid. Variable costs of the ICE powered by petrol are the highest. The fuel cell car has the highest variable cost among the configurations with fully electric drivetrains.

3.5.2 Total cost of ownership

We calculate the TCO assuming the cars are driven 20 000 km per year, using a 10-year depreciation period and a 5% social discount rate. Table 3.18 and figure 3.4 shows the TCO of our configurations with VAT only.

Vehicle configuration	Annualised purchase	MRT	Diesel / petrol / H2	Electricity	TCO (€/yr, VAT only)
Reference diesel	2766	866	813	0	4445
Reference petrol	2481	834	899	0	4214
Parallel hybrid	3225 ± 0	832	713	0	4770 ± 0
SHEV CM now	3453 ± 100	866	534 ± 104	0	4852 ± 145
SHEV WM now	4052 ± 24	866	462 ± 98	0	5379 ± 101
SHEV CM future	3368 ± 100	866	534 ± 104	0	4768 ± 145
SHEV WM future	3038 ± 97	866	462 ± 98	0	4365 ± 138
PHEV CM now	4205 ± 204	866	107 ± 21	195 ± 38	5372 ± 213
PHEV WM now	4715 ± 169	866	92 ± 20	168 ± 36	5841 ± 178
PHEV CM future	4054 ± 179	866	107 ± 21	195 ± 38	5221 ± 189
PHEV WM future	3650 ± 170	866	92 ± 20	168 ± 36	4776 ± 179
FCEV CM now	11377 ± 1376	866	617 ± 120	0	12860 ± 1381
FCEV WM now	10883 ± 1192	866	533 ± 113	0	12282 ± 1197
FCEV CM future	3811 ± 349	866	617 ± 120	0	5294 ± 369
FCEV WM future	3376 ± 306	866	533 ± 113	0	4775 ± 326

Table 3.18: Total cost of ownership (TCO, €/year) breakdown of our model configurations using a 5% social discount rate and VAT only, driving 20 000 km/year and depreciating over 10 years.

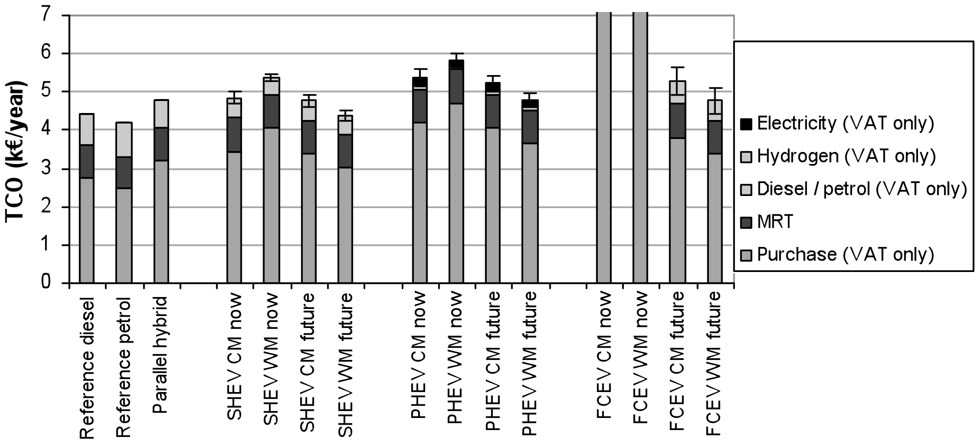


Figure 3.4: Total cost of ownership (TCO, k€/year) breakdown of our model configurations using a 5% social discount rate and VAT only, driving 20 000 km/year and depreciating over 10 years.

These results are dominated by the cost of purchasing the car, which are 60%-90% of the TCO. The TCO of all of our hybrid configurations are higher than those of the reference cars, with the sole exception of the future wheel motor series hybrid. There we may conclude that the current generation of hybrid cars cannot compete strictly on costs with regular diesel or petrol cars without additional support.

3.5.3 Tax incentives

From the perspective of motorists, the financial attractiveness of hybrid cars is influenced by tax incentives, as well as a higher implicit discount rate [179]. Many countries have tax incentives for low-emission cars and tax situations are country-specific. We use a 10% consumer discount rate, which is closer to consumptive credit loan interest rates, and the Dutch tax context as an example. In the Netherlands, three forms of tax affect TCO of a car:

- Fuel excise duty, an additional 0.38 €/l on diesel, 0.69 €/l on petrol and 0.1085 €/kWh on electricity in 2009 (excluding VAT) [215].
- Tax on light duty cars and motorcycles (BPM in Dutch), which is 45.2% of the car price, modified for the type of engine and fuel consumption in 7 categories. BPM is further reduced for hybrid cars, and plug-in hybrids and hydrogen-fuelled cars are exempt entirely. BPM is a one-time payment.
- Road tax, depending on the type of fuel and weight of the car. Road tax is reduced by half for diesel-fuelled cars with TTW emissions of less than 95 gCO_2/km. Road tax is paid at regular time intervals.

Figure 3.5 shows that the Dutch tax context is advantageous to our series hybrid configurations and future fuel cell cars.

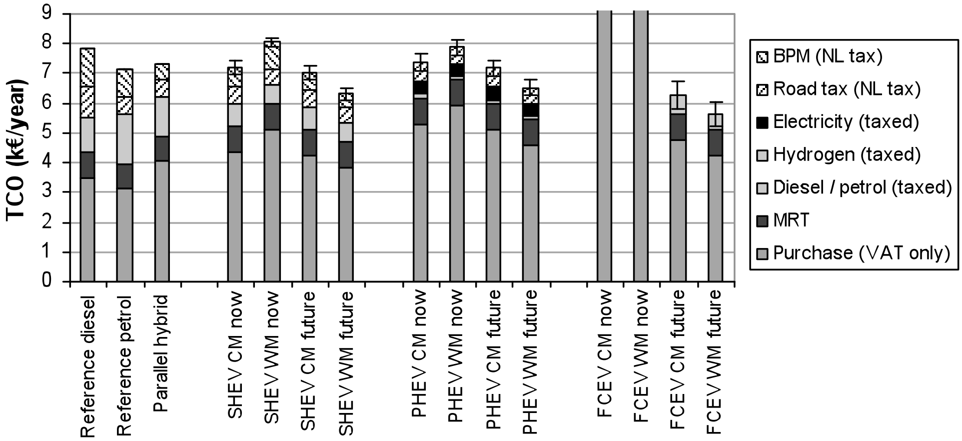


Figure 3.5: Total cost of ownership (TCO, k€/year) of our model configurations with a 10% consumer discount rate in the Dutch tax context.

Mass produced parallel hybrid cars, and series and plug-in hybrid cars with a central motor have equal or lower TCO than the reference diesel car in the current Dutch tax context. TCO of current central motor hybrid cars is slightly higher.

While future fuel cell cars have the lowest TCO in the current tax context, it should not be taken for granted that this situation will be reached, as the current fuel cell cars have much higher TCO and the reduction in the cost of fuel cells depends on large-scale production. Some in the car industry do not expect large scale penetration of fuel cell cars until 2035 [38]. Furthermore, the tax incentives for stimulating fuel efficient cars may change as hybrid and/or fuel cell cars break into mainstream use.

Using a 33% discount rate and 15 year lifespan [254], the purchasing cost of the vehicle completely dominates the TCO ranking and the difference made by taxes and fuel costs fall within the uncertainty margins.

3.5.4 Who can benefit from the series hybrid car?

We showed that a series hybrid car can be operated at the lowest costs with (existing) supporting incentives. However, without such measures, the lowest TCO is found for cars with low variable costs, i.e. hybrids and plug-in cars. Variable costs depend on the distance driven in a year and, for plug-in hybrids, the share of electricity that is used instead of diesel.

When we plot the TCO for different configurations as a function of distance and electricity share in total fuel, and project the intersects in a flat plane, we obtain isopleth curves which show at which driving habits it is cheaper to switch to another configuration (break-even points).

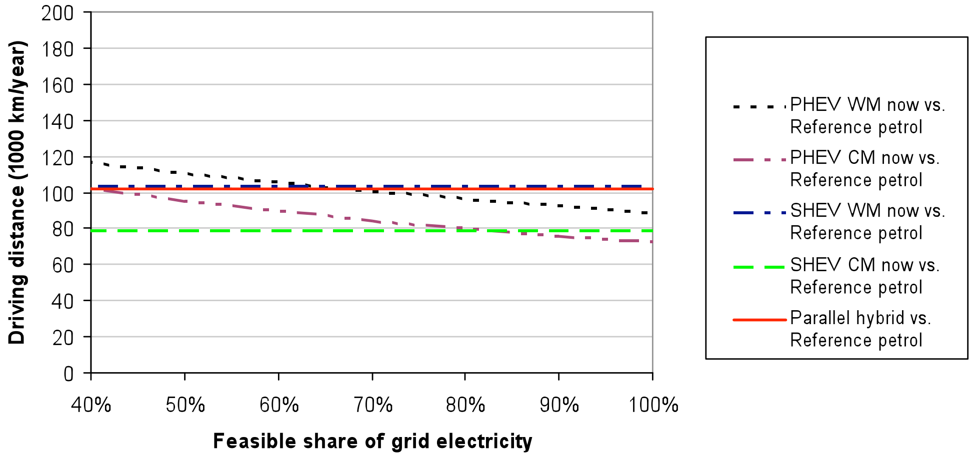


Figure 3.6: Lowest TCO isopleths for current generation central motor configurations and reference cars, using a 10% consumer discount rate.

Figure 3.6 shows that the current series hybrid, though more expensive to purchase, becomes more attractive than a petrol car at 79 000 ± 9800 km per year. That large distance is due to the lower MRT costs of a petrol car, which partially offsets the lower fuel costs of the series hybrid. The difference in TCO between the central motor and wheel motor hybrid cars at this distance is less than 500 €/yr, even with current production costs for wheel motors. At less than 60 000 km per year, there is no significant difference in TCO of the central motor series hybrid and parallel hybrid cars. Diesel cars, the traditional choice for those who drive more than 20 000 km per year, are found to be more expensive than a petrol car at small distances, and more expensive than a series hybrid at higher distances.

The plug-in configuration becomes more attractive than the SHEV at a >80% share of electricity and large distances, which could be mutually incompatible in the real world. However, the TCO differences between a PHEV and SHEV are fairly small and the uncertain zone around these isopleths fills the whole graph. The wheel motor PHEV also benefits less from lower fuel costs than the central motor configuration because the overall fuel consumption of the wheel motor configuration is smaller.

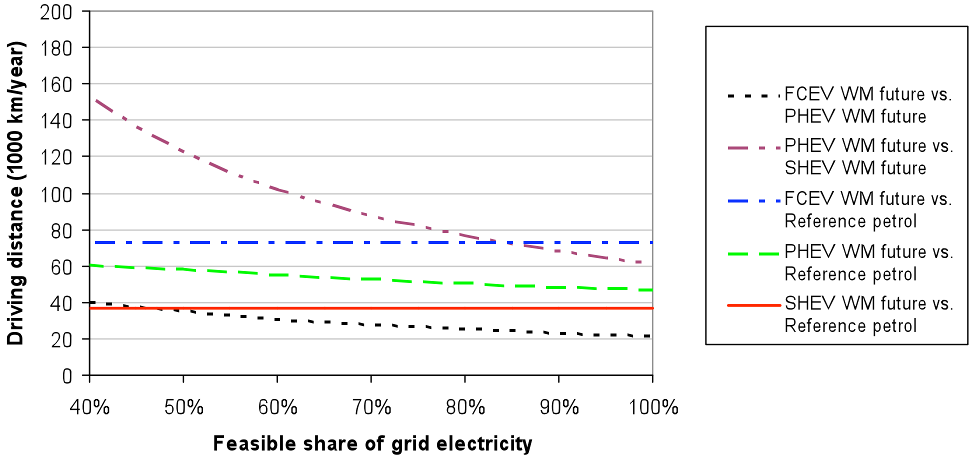


Figure 3.7: Lowest TCO isopleths for future hybrid and fuel cell configurations and petrol reference car.

Figure 3.7 shows that for future generations of wheel motor series hybrids, the petrol car remains attractive for those who drive fewer than 37 000 ± 3500 km/year. If our projections on cost developments hold, plug-in hybrids and fuel cell cars will be cheaper than either petrol or diesel cars when driving more than 70 000-84 000 km/year, but the series hybrid has lower TCO than the fuel cell car at any relevant distance. Again, the plug-in configuration only becomes attractive at high shares of electricity and large distances.

Our findings suggest that resources be devoted to further development and commercial introduction of wheel motors and to promote the use of hybrid cars among groups such as taxi drivers and others who drive high distances.

3.6 Discussion

3.6.1 Drivetrain efficiency

With regards to the fuel consumption, our calculations for the electric drivetrain depend on very few measurements of very different existing cars, and our transmission efficiency result of ~0.86 treats the transmission as a black box.

We also assumed 33% engine-generator efficiency, and 90% efficient electric motors, which is generally true only for constant speeds. Average electric motor efficiency can drop to 84% in parallel hybrid configurations, where a small electric motor is used almost exclusively for acceleration [45].

We also treat fuel consumption results from the SAE J1634 drive cycle (used for electric cars, and to derive our platform fuel consumption) as equivalent to those achieved with the NEDC (used for the reference cars). Furthermore, we assume that average real-world driving conditions are properly represented by the NEDC and SAE J1634 drive cycles. A driver who drives at more constant speeds and makes fewer stops will benefit less from a hybrid car. Driving patterns have particularly strong impact on the benefits of a series hybrid compared to an ICE car and to fuel consumption in general.

These limitations explain why our central motor series hybrid configurations have lower average fuel consumption than a parallel hybrid, while other authors assert fuel consumption should be similar [207, 255]. However, even if the central motor series hybrid is not an improvement on the parallel hybrid, wheel motors reduce fuel consumption significantly by removing the transmission.

Our medium term calculations do not include potential further efficiency improvements to drivetrains. However, total fuel consumption is 4%-19% of TCO, and the effect of efficiency gains on TCO is therefore similar to the variations in oil prices and smaller than that of (implicit) consumer discount rates.

3.6.2 Weight

We did not correct fuel consumption for extra weight. For cars without regenerative braking, fuel consumption increases by some 3%-8% for every 10% increase in car weight [98], due to increased rolling resistance. For our series hybrids, weight increases were not included in the fuel consumption calculations. Figure 3.8 shows that the weight increase for a central motor series hybrid is less than 5%, while the wheel motor hybrid is slightly lighter than the reference diesel car.

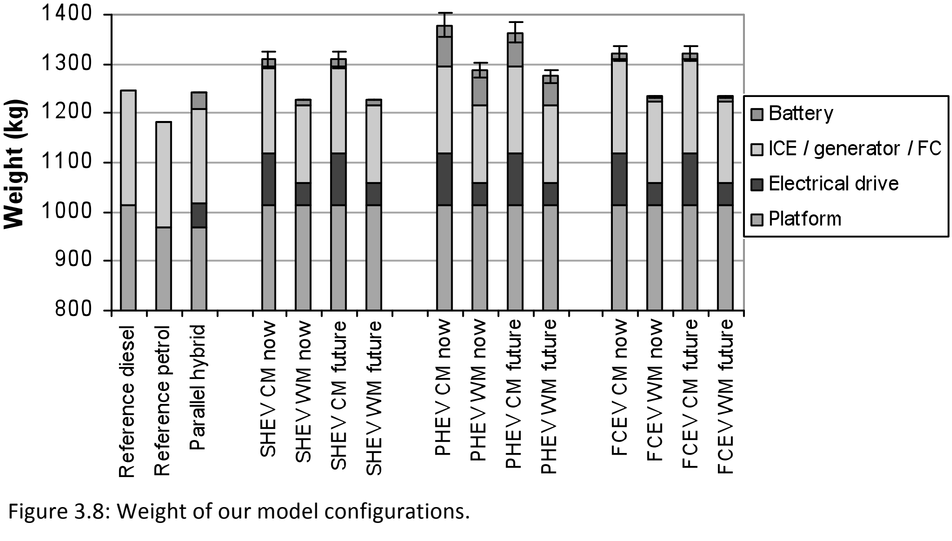
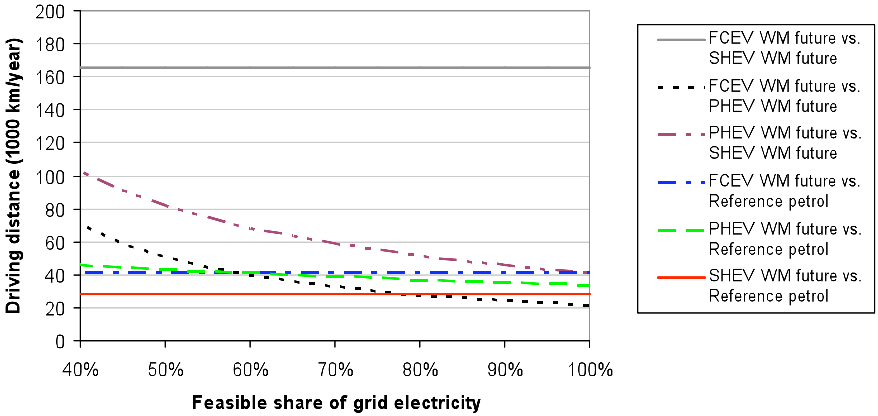


Figure 3.8: Weight of our model configurations.

3.6.3 Prices of fuel

The prices of diesel and petrol are volatile. Therefore, they can have substantial influence on the TCO. To illustrate this, we increase the price of oil to 120 \$/bbl, without raising the price of electricity or hydrogen, plug-in hybrids and fuel cell cars would essentially have the same TCO as series hybrids (uncertainty ranges overlap), as shown in figure 3.9. This situation is unlikely because prices of electricity and hydrogen do not move independently from oil prices, and because alternatives to diesel and petrol such as heavy crude and second generation biofuels become competitive when oil prices exceed 75 \$/bbl [250].



Note: Assumes that 80% of car trips are <50 km and could be driven on electricity in a plug-in hybrid.

Figure 3.9: Lowest TCO isopleths for current generation central motor configurations and reference cars with oil at 120 \$/bbl.

Lower hydrogen prices make fuel cell cars more competitive. We found estimates of costs (not commercial prices at the pump) of production and distribution of 15-36 €/GJ [100, 249, and combining 37, 256, 250]. With fuel cell production cost of 110 €/kW, hydrogen would need to cost less than 20 €/GJ for the future fuel cell car to have a lower TCO than future series hybrids. However, current fuel cell cars cannot compete commercially even if hydrogen is provided free of charge.

The influence of driving on grid electricity on TCO is limited. The added costs for batteries in a plug-in hybrid were only compensated at high shares of electricity and high driving distance. The competitiveness of plug-in hybrids (and, by extension, electric cars) therefore mainly depends on the price of batteries.

Imposing a CO_2 tax on cars and/or fuels may also shift competitiveness. There are many ways of producing alternatives to diesel and petrol (including biofuels) as well as electricity and hydrogen, with strongly divergent GHG emissions. Because the vehicle configuration is in no way linked to the way of producing the fuel, calculating the impact of CO_2 taxes on GHG emissions from cars requires a context that is beyond the scope of this study.

3.6.4 Vehicle costs and maintenance

We found the cost of batteries would have to drop to below 300 €/kWh for the plug-in hybrid to have the same TCO (at 80% electric driving) as a regular series hybrid. This is a smaller cost reduction than estimated for fuel cells. An all-electric car with a 250km range would almost the same TCO as a plug-in hybrid at a battery production cost of 200 €/kWh. Our incremental costs for PHEV are similar to those found in other studies that use similar assumptions on battery cost [257, 258].

Cycle life of batteries has tripled (or better) in recent years, and we have assumed that the same will apply to calendar life. However, it is unclear if calendar life of state-of-the-art batteries will last the 10 year lifespan of a car. If this is not the case, the TCO must be increased by a discounted €900-€1800 somewhere in the life of the vehicle. The same applies to fuel cells, with replacement costs upwards of €5100.

The uncertainties in the cost of fuel cell drivetrains are substantial, and the case can be made [42, 46] that current high prices and lack of refuelling infrastructure will not allow sufficient units to be sold to reach mass production. In this case, the final cost of fuel cells will remain higher than the 110 €/kW$_e$ we assumed.

The same is true in principle for wheel motors, but the TCO of a wheel motor hybrid is relatively much closer to that of a central motor hybrid, so initial cost should not be a major barrier.

Although we find substantial uncertainties regarding the production costs of the different components of drivetrains (see table 3.16 in section 3.4.2), their influence, except for the fuel cell, on the TCO is limited (see table 3.18 in section 3.5.2). The vehicle platform, MRT, fuel, and taxes all have more influence on TCO.

For a lack of experience, maintenance, repair and tires costs for series hybrids and fuel fell cars, both with central motor and wheel motors, are unclear. Because drivetrain maintenance is only a part of the total MRT costs, we expect the differences to be small. Available data shows that MRT costs of existing commercial hybrid cars are equal or slightly lower than those of non-hybrid versions or similarly sized models for the same manufacturer [178]. However, our TCO comparison is quite sensitive to maintenance costs: for every MRT cost increase of 0.1 €ct/km (20 €/year), the break-even distance of the series hybrids and fuel cell car increases by 2000-5000 km/year.

3.6.5 Availability of data

We observe substantial uncertainty ranges in component costs and fuel consumption, caused by a shortage of freely available data on the production costs of car parts, and a lack of comparable data about fuel consumption. Our data on the production costs of wheel motors are based on the data from a single small producer.

With regard to the costs of electric motors and batteries, we assume that commercial interests keep producers from publishing transparent prices. The only way to improve the quality of this data would likely bar free publication.

3.7 Summary and conclusions

We investigated the fuel consumption and costs of four diesel-fuelled series hybrid, four plug-in hybrid and four fuel cell car configurations and compared these to three reference cars.

Results indicate that series hybrid cars may reduce fuel consumption by 34%-47% compared to reference petrol and diesel cars and reduce WTW GHG emissions to 89-103 g CO_2/km using regular diesel. Series hybrid cars with wheel motors have lower weight and 7%-21% lower fuel consumption than series hybrid cars with central electric motors. However, series hybrid cars currently cost €5000-€10 000 more than ICE cars.

The higher purchase cost of hybrid cars means they are financially interesting for taxi drivers and others who drive more than 80 000 km per year. For these groups, the current generation of series hybrid would the most attractive option, even without tax incentives. Including the Dutch tax incentives, the TCO of a parallel or series hybrid is currently lower than that of a diesel car even when driving around 20 000 km per year.

The TCO of a wheel motor series hybrid car is currently higher than one with a central motor, but the difference is less than 500 €/yr at driving distances where the series hybrid is preferred over a petrol car. In the future, wheel motors are projected to be the cheapest and most efficient drivetrain. The possibility to use wheel motors is the main benefit of a series drivetrain.

The fuel cell car is currently uncompetitive by a large margin. If, despite their current financial unattractiveness for use in cars, the production of fuel cells would increase so that the costs come down by 90%, series hybrids would still have slightly lower total cost of ownership. Plug-in hybrids are competitive only when driving large distances on electricity and/or if cost of batteries come down substantially. Plug-in hybrids may reduce WTW GHG emissions to 60-69 g CO_2/km, assuming emissions for generating electricity of around 467 gCO_2/kWh.

We recommend benchmarking fuel consumption using a standardised vehicle platform and a single representative drive cycle to clarify the differences in efficiency between transmission attached to ICE and electric drivetrain, and between central motor and wheel motors. If this cannot be done using real engines, the results can be simulated using engine maps for the ICE and electric motors.

“Everything is simpler than you think and at the same time more complex than you imagine.”

- Johann Wolfgang von Goethe

4. Energy use, cost and CO_2 emissions of electric cars

This chapter is to be published as: van Vliet OPR, Brouwer AS, Kuramochi T, van den Broek M, Faaij APC. *Energy use, cost and CO_2 emissions of electric cars*.

4.1 Introduction

Worldwide, more than 90% of the transport sector is powered by fuels derived from oil. However, the consumption of diesel and petrol is considered problematic due to costs of oil, doubts about of security of oil supplies [7, 6], greenhouse gas (GHG) emissions, and the emissions of air pollutants such as NO_x, PM_{10} and volatile organic compounds [12, 13].

To reduce dependence on oil in the transport sector, alternatives like biofuels and more efficiency (hybrid) cars are used in increasing volume and numbers [259, 199]. The cost and potential emission benefits of biofuels and hybrid vehicles have been pointed out in numerous studies (c.f. 8, 45, 46, 260, 75, 40, 250, 261, 262). For example, costs of sugar cane ethanol are already competitive with traditional fuels, and second generation ethanol can become so in the near future. In addition, using biofuels reduces emissions of GHG when produced sustainably, and also reduces emissions of other air pollutants. Fuel consumption and therefore emissions from efficient hybrid cars are lower than those from traditional cars. Drawbacks of these alternatives concern the uncertainty about the available supply of sustainable biofuels, the currently higher costs of hybrid vehicles, and the remaining tailpipe emissions of GHGs and air pollutants.

Electric driving is also considered a promising alternative and has been advocated for decades [263, 47, 32]. It does not cause any tailpipe emissions but may cause emissions of GHGs and other air pollutants, depending on the mix of electricity sources used. Three basic designs for electric driving can be distinguished: The first is a series-parallel hybrid car, which has an internal combustion engine (ICE) and an electric motor that are both connected to the wheels and supplement each other when needed (see [264]). The second is a plug-in series hybrid vehicle (PHEV), which has a small battery for trips up to approximately 50 km and a generator using an ICE to provide power for long range driving. The third is a fully battery powered electric vehicle (BPEV), which has a large battery for longer trips (200-300 km). The series-parallel car has been in use for over a decade and is not considered in detail in this study. PHEV and BPEV are currently introduced into the market: major car manufacturers all over the world are working on new models [265, 85, 266, 267, 268]. Electric utilities and governments in various countries support the emergence of this market (e.g. [269]).

The additional costs of plug-in hybrid and fully electric cars compared to regular ICE cars largely depend on the high costs of batteries [261, 270, 255]. With current battery costs in the order of €1000/kWh, plug-in cars with a battery-powered range of 50 km or more (which requires a battery of ±7 kWh) are prohibitively expensive. However, to determine the total cost of owning and driving an EV in the short term and to determine prospects on longer term, requirements for additional electricity generation and distribution, and technological improvements and cost reductions should be taken into account [271, 44, 272].

It has been projected that an electric vehicle increases the electricity consumption of a household in an industrialised country by 50% [273]. Introducing a large number of electric vehicles therefore introduces new challenges, like building infrastructure for charging, improving the electricity distribution grid, and taking care of legal and privacy issues regarding coordinated 'smart' charging systems. The extent of these challenges is strongly determined by the timing and pattern of charging EVs [33, 274].

We wish to determine whether large scale use of EV is or can become feasible from a techno-economic perspective, and if so, under what conditions. We therefore examine efficiency and costs of current and future EV, as well as their impact on electricity demand and infrastructure for generation and distribution, and thereby on GHG emissions. Energy used and emissions from manufacture of EV are left outside the scope of this study (c.f. [275]).

Earlier studies have addressed some of these issues separately. Some important well-to-wheel (WTW) studies do not include PHEV and BPEV cars [45, 100, 203]. Campanari et al. and Silva et al. focussed on efficiency of EV using current technology and did not take uncertainty in various chain aspects into account [220, 255]. Van Vliet et al. and Shiau et al. included sensitivity analysis on various factors affecting EV performance, including battery cost and vehicle weight, but did not take charging patterns into account [261, 270].

Earlier studies have also only partially addressed how increased electricity demand could be catered for. A study for Sweden assumed that only renewable energy sources are used for electricity generation [276]. A study for Germany used inflexible charging scenarios, not taking options for coordinated charging into account to smooth demand [33]. Studies for the US assumed that the capacity factors of power generation sources will remain the same with high numbers of EVs [274], or just evaluate how many cars the current grid can support [277]. Other studies did not take into account the load pattern of existing demand [47, 278].

We therefore examine the feasibility of electric driving taking into account not only drivetrain choices, but also driving patterns, changes in the electricity mix, charging patterns, and energy losses in relevant parts of the WTW chain. There are three main aspects to this analysis:

Determine the effect of EV charging patterns on household and total electricity demand.
Derive GHG emissions and costs of charging of EVs in the 2015 Dutch context and beyond.
Compare GHG emissions and costs of PHEV and BPEV with those of regular cars.

We briefly discuss methods in section 4.2, present data used in section 4.3, present results in section 4.4, discuss the applicability of our results in section 4.5 and give a summary and conclusion of our findings in section 4.6.

4.2 Methods

The car class we focus on is the compact 5-seater. It includes the Volkswagen Golf, Ford Focus, Renault Megane, Toyota Corolla and Opel Astra. We compare EV configurations to a regular petrol car, diesel car, parallel hybrid car and SHEV. Vehicle configurations are composed using the methodology and data described in Van Vliet et al. [261].

In order to compare vehicles, we use the same platform for all vehicle configurations and only exchange the drivetrain as is also done in Weiss et al., the EU Joint Research Centre (JRC) and Van Vliet et al. [101, 45, 261]. The vehicle platform is defined as a vehicle without the drivetrain and includes the chassis, suspension, wheels, doors, seats, windows, and assembly. This platform weighs 1016 kg, costs €15700, and is powered by a 74kW ICE or equivalent [45]. The drivetrain consists of the engine and the transmission connecting it to the wheels. An EV can be designed with a single central motor connected to the wheel via a transmission like in a regular ICE car, or with electric motors built into the rims of the wheel [261].

Series hybrid vehicles (SHEV) and BPEV represent opposite ends of an electric drivetrain spectrum. The SHEV uses an ICE exclusively to power the electric motor, the BPEV uses a battery. A series drivetrain PHEV is somewhere within this spectrum. It uses a battery for short range driving, and switches to ICE-generated electricity when the battery is depleted.

Total WTW energy consumption in an EV (E_{total}) is expressed in MJ/km determined as follows:

$$E_{total} = E_{resistance} / \eta_{transmission} / \eta_{motor} / \eta_{fuel\ supply} \tag{4.1}$$

where $E_{resistance}$ is the mechanical energy required to move the car against resistance from inertia, wind and tire friction. Losses accumulate through the WTW chain, where $\eta_{transmission}$ is the transmission efficiency, η_{motor} is the efficiency of the electric motor or ICE motor, and $\eta_{fuel\ supply}$ is the fuel supply efficiency. For a wheel motor, by definition, $\eta_{\mathrm{transmission}} = 1$.

Fuel supply efficiency depends on whether the EV is powered by an ICE or electric motor. The well-to-tank (WTT) efficiency (η_{WTT}) is determined as follows for liquid fuels and electricity:

$$\eta_{liquid\ fuel} = \eta_{distribution} \times \eta_{fuel\ plant} \times \eta_{resoure\ extraction} \tag{4.2}$$

$$\eta_{electricity} = \eta_{charging} \times \eta_{grid} \times \eta_{power\ plant} \times \eta_{resource\ extraction} \tag{4.3}$$

Where $\eta_{distribution}$ is the energy used for driving distribution trucks and filling stations, $\eta_{fuel\,plant}$ is most commonly the efficiency of an oil refinery, $\eta_{resource\ extraction}$ is the efficiency of mining or farming of energy resources, $\eta_{charging}$ is efficiency of charging and discharging the battery, and η_{grid} is the efficiency of the electricity distribution grid. If solar power or wind is used, $\eta_{resource\ extraction} = 1$.

The source of electricity used for charging EVs depends on the available power capacity and existing demand pattern of households, offices, industry, and public services (such as street lighting). We determine the total costs, marginal costs, and emissions of electricity at 15-minute intervals by matching dispatch of electricity generation options to the demand pattern. The demand pattern uses household or national demand and includes additional load for EV charging, depending on the EV used and the EV penetration rate.

Electricity generation capacity is ranked in a merit order on the basis of variable costs and types of units. We determine the supply mix by employing plants that are progressively higher in the merit order until demand is satiated. Combined heat and power (CHP) plants co-produce heat that must be delivered and are therefore given precedence. Base load is preferably provided by nuclear and coal-fired plants that provide constant supply with relatively low operating costs. Wind and solar power produce electricity with low operating costs but their production is not entirely predictable or controllable. Fluctuations in demand and intermittent supply are accommodated by the use of peak-load capacity like natural gas-fired turbines and hydropower that can be quickly switched on or off. All power plants have limits on availability (due to maintenance and unplanned outages), so we include capacity factors for calculating average supply.

Total cost of ownership (TCO) of a car is the sum of the annualised fixed (purchasing) costs of the car, variable costs composed of maintenance, repair and tires (MRT), and fuel or electricity costs, for a standard distance driven per year. The purchasing costs of the car consist of the platform, and any applicable combination of ICE, transmission, battery, and electric generator and motor(s).

For a PHEV to be a cost-effective alternative, reductions in fuel consumption and fuel cost must outweigh the added weight and cost of having both a battery and an ICE on board. We do not include country-specific taxes on car purchase, car ownership (road tax) and fuel, but we include 19% VAT, as is common to the EU.

Uncertainty in efficiency and TCO of our selected car configurations is calculated as standard deviation (σ) from the indicated value. We account for uncertainty about electric motor efficiency and transmission efficiency. These lead to uncertainty in fuel consumption and in the minimum battery capacity required to allow 50 or 250 km range. We also account for uncertainty in emissions of fuel production and the cost of batteries and electric motors. We address the uncertainty in specific cost (€/kWh) of batteries and the share of km driven on electricity in PHEV through sensitivity analysis. We do not examine uncertainty in driving cycles. We assume no co-variance for propagation of uncertainty in independent conversion steps and full co-variance if the cost uncertainties derive from the same underlying variable.

4.3 Data

Our dataset for vehicles is not nation specific. However, for country-dependent factors such as electricity demand, electricity generation capacity, and transport demand, we use data for the Netherlands. Where available, we also include data for the entire EU and compare with other countries to widen the validity of our analysis.

4.3.1 Reference cars and drivetrains

All reference car configurations except the regular diesel car use petrol engines, because the purchase cost of petrol engines is some €1500 lower than of diesel engines [45]. We assume that petrol engine-generators in SHEVs and PHEVs have the same efficiency relative to diesel generators as petrol engines relative to diesel engines in regular cars (see [45]). We also assume a shift from current central motor (CM) drivetrains to wheel motor (WM) drivetrains from 2015 onwards because higher efficiency of wheel motor drivetrains allows for smaller and cheaper engines and battery packs.

For costs of petrol and diesel, we assume an oil price of 80 $/bbl, close to the short term projections in the World Energy Outlook 2009 [5]. At this oil price, assuming 41.87 $\mathrm{MJ_{LHV}}$/kg and 820 kg/$\mathrm{m^3}$ for crude oil, fuel prices at the pump in the Netherlands are around 1.21 €/liter for diesel and 1.40 €/l for petrol (using [213, 214, 45]). This includes 19% value-added tax (VAT) and excise duty [215]. Untaxed, prices are 19.3 €/GJ or 0.69 €/l for diesel and 19.9 €/GJ or 0.64 €/l for petrol.

We assume that the same electric motors are used to propel SHEVs, PHEVs or BPEVs and electricity consumed per kilometre is therefore the same for both types of cars, as long as the car weight is similar. Based on work by Van Vliet et al. [261], we use an EV drivetrain with a single 74kW central motor (CM) that consumes 103±20 Wh/km from 2010 and one with two 29kW wheel motors (WM) that consumes 89±19 Wh/km from 2015. In hybrid car configurations, these are powered by a petrol-fuelled engine-generator that produces 53 kWe for a CM drivetrain and 46 kWe for a WM drivetrain with an efficiency of 31%.

TCO is calculated using a 5% social or 10% consumer discount rate, 10 year depreciation period, including VAT but excluding excise duties. For initial TCO calculations we use average annual distance driven in The Netherlands of approximately 14 000 km/car/year [279, 280, 16].

4.3.2 Plug-in hybrid and battery powered electric cars

Building on the SHEV drivetrains, we assume PHEVs with an electric range of 50 km and BPEVs with a range of 250 km, again using the methodology and data described in Van Vliet et al. [261].

The efficiency to charge the battery from the grid varies between 89% and 96% in literature, and battery cycle efficiency (combined charge and discharge) varies between 85% and >95% [45, 220, 281, 282, 283, 284, 285]. For EV, we use efficiencies of 90% for charging the battery and 96% for discharging the battery [220]. To account for speed fluctuations that cause some of the electricity from the ICE generator in a SHEV or PHEV (when not driving on grid electricity) to go through the battery, we use a combined efficiency of 97% for transfer of electricity between generator and electric motor (based on [45], as described in [261]).

We use Li-ion batteries with a cost of 960 €/kWh in 2010, and we assume this reduces to 800 €/kWh around 2015, and to 400 €/kWh in the more distant future [84]. These costs are much higher than the minimum target for long term commercialisation of 150 $/kWh set by the U.S. Advanced Battery Consortium [239]. The Li-ion batteries we use have a specific energy of 86 Wh/kg, and we assume this increases to 110 Wh/kg around 2015 and to 150 Wh/kg in the more distant future [235, 220]. We use a depth of discharge of 70% [261]. We assume a battery pack last for the lifetime of the vehicle, but explore the sensitivity of TCO to a mid-life replacement in section 4.5.

Our vehicle platform includes structural reinforcement to support heavy batteries. This increases platform weight by 48 kg compared to a petrol car (based on [45]). However, advances in specific energy of batteries and the exact reinforcement required can vary [270]. We therefore assume an uncertainty of 50% in total future battery weight including reinforcements.

Increased vehicle weight increases fuel consumption. For cars without regenerative braking, fuel consumption increases by some 3%-8% for every 10% increase in car weight [98], due to increased inertial mass and rolling resistance. With regenerative braking, this reduces to approximately 1%-5% for every 100 kg increase in car weight [270, 220].

To calculate the increase in fuel consumption, we compare the weight of our PHEV and BPEV configurations with that of our SHEV configurations (CM to CM, WM to WM) and apply a fuel consumption penalty of 3%±2% for every 100 kg of extra weight.

4.3.3 Projections for uptake of electric driving

The amount of electricity used by electric cars depends on the vehicle kilometres travelled in electric cars, which in turn is proportional to the number of PHEVs and BPEVs on the road and, in case of PHEV, the share of electricity in total fuel used. Currently, ICE cars have ~99% market share. Table 1 summarises projections of penetration rates of electric vehicles in 2030 from recent studies.

Estimate	Region	Institute	Source
9% of sales are PHEVs	OECD	IEA	[86]
21% PHEV and 7% BPEV in 450 ppm scenario	OECD	IEA	[5]
30% of distance by car powered by electricity, mainly in PHEVs (range 5%-38%).	EU	ECN	[286]
6% BAU market share of electrical vehicles and 12% in "carbon constraint case"	EU	European Commission	[287]
3% BAU market share of electrical vehicles	EU	European Commission	[288]
Electric vehicles comprise 24% of the light duty vehicle fleet	USA	Berkeley	[289]
2% of light duty vehicles sales is a PHEV	USA	EIA	[290]
20% of distance by car powered by electricity in 2030 and 50% of car sales is a PHEV.	USA	EPRI	[291]
Around 27% of the total fleet will consist of PHEVs.	USA	U.S. National Renewable Energy Laboratory	[292]
40% of all light duty vehicles will be PHEVs by 2030.	USA	Argonne National Laboratories	[292]
PHEVs make up between 10% and 30% of the vehicle fleet.	Japan	MIT	[293]
80% of the car fleet consist of PHEVs	Japan	University of Tokyo	[294]

Table 4.1: Projections of the penetration rate of electric vehicles In the EU, US, and Japan in 2030.

Two trends emerge from table 4.1: PHEVs are projected to be the main electric car type, and the penetration levels do not seem to be very different for different regions. The only exception is a study by the University of Tokyo that forecasts a penetration rate of 80% of PHEV. To assess the impact of different EV penetration levels, two values will be used in our calculations: a low estimate of 6% and a high estimate of 30%.

Total electricity demand for EVs also depends on the number of EVs in use. The number of cars on the road in the Netherlands is projected to rise from 7.2 million cars in 2006-2008 to around 8.1 million in 2015 and around 9 million in 2030 [279, 16].

Cars are driven 38 km per day on average in Britain and The Netherlands, and 52 km per day in the USA [280, 295, 296, 297, 298]. This average is not projected to change significantly [16, 299]. We assume this is true for everyday use, and does not include irregular trips (holiday travel by car, etc.). For Britain and The Netherlands, this results in electricity demand of approximately 4.8 kWh/day per CM EV and 4.0 kWh/day per WM EV.

The share of trips smaller than 50 km ranges between 60% and 80% [232, 300, see also 230, 218]. We initially assume that on an annual basis, PHEV are driven 30% on petrol and 70% on electricity (see also [301, 302]). We analyse the impact on TCO of different assumptions of annual distances driven and shares of electricity use in PHEVs in section 4.4.4.

4.3.4 Electric vehicle charging

Three different charging setups are currently used in the USA (see table 4.2). Type 1 resemble a regular socket dedicated to charging EVs. Type 2 chargers are also available to all residential customers, but require the installation of special equipment [303]. Type 3 are installed at locations where many vehicles need charging quickly, reducing the recharge time to under 10 minutes. In the EU and Japan, the IEC standard 68851 is in development [304]. This standard allows for normal charging with single phase or three-phase electricity. The equipment is installed in the vehicle and is designed for a maximum load of 40 kW. Fast charging up to 250 kW could become available with fixed chargers.

We use a cost of € 480 for the charger, which is included in the car purchase cost [212]. Assessing the cost of different chargers in detail (while charging standards are still in development) is outside the scope of this study.

Table 4.2 shows that PHEV with a 50 km electric range can easily be charged overnight (19:00 to 7:00) with any charging equipment. For driving further in BPEV, an IEC68851 or USA type 2 charger should be used to ensure a fully charged car in the morning.

Electricity demand Household level	Charger type	Power (kW)	2010 / central motor		2015 / wheel motors	
			km/hour	hours to charge	km/hour	hours to charge
United States	Type 1	1.4	12	4.31	14	3.73
52 km/day	Type 2	3.3	28	1.88	32	1.63
	Type 3	60	502	0.10	581	0.09
European Union	1-phase	3.5	29	1.30	34	1.12
38 km/day	3-phase	10	84	0.45	97	0.39
	maximum	40	335	0.11	388	0.10

Table 4.2: Charger types, power per type, vehicle kilometres that can be charged per hour, and hours needed to fully charge an EV battery that provides 50km range. Sources: [305, 304, 261]

Charging loads add to the existing demand for electricity. Literature suggests a number of charging patterns, as shown in table 4.3 [306, 274, 33].

Charging pattern	Description
Uncoordinated	EV owners charge their vehicles when they come home until fully charged. No coordination takes place. The peak EV-demand will exacerbate daily peak demand. Both the business as usual and worst case scenario.
Delayed	Comparable to the uncoordinated scenario, with the difference that charging starts in the end of the evening. This will shift the peak EV-demand so that it does not coincide with the daily peak demand. Also, charging will be cheaper at the night-rate for electricity
Off-peak	Charging takes place during the night when the overall electricity demand is low and generation is mostly base load. Local utilities can control charging to employ the electricity generation capacity optimally. The advantage for owners is that electricity is cheap during the night.

Charging pattern	Description
Continuous	Uncoordinated scenario in which vehicle owners charge their vehicles whenever possible. Charging takes place at, for example, home and work throughout the day. Continuous charging results in better charged batteries, which enables more trips to be electricity powered. It also requires an ubiquitous charging infrastructure.

Table 4.3: Charging scenarios from literature

We examine the uncoordinated and off-peak patterns, as these represent the worst case and best case scenarios. We assume the car is charged in one session per 24-hour period. The uncoordinated charging pattern is defined as normal-distributed around 19:30 in the evening with a standard deviation of 3 hours. The off-peak pattern depends on the demand pattern, and is defined by fitting a straight demand line between 22:00 and 7:00 so that the total electricity delivered is equal to the total required existing and charging demand.

For consumers, we assume two price levels, depending on the time of day. We use average of household 3-year fixed and variable prices from several large Dutch utilities in spring 2010 (EON Benelux, Electrabel, Eneco, Essent, Nuon, RWE Nederland, see websites). From 7:00 to 23:00, the price is 102 €/MWh, and from 23:00 to 7:00 the price is 64 €/MWh. Flat rate prices were 83 €/MWh, all excluding the 129 €/MWh Dutch energy tax but including VAT [215].

4.3.5 Household and overall electricity demand

Electricity demand of a set of 2000 households in an urban environment in the year 2003 is simulated using the SEPATH generator[22]. Since the generator cannot simulate spring and autumn conditions, the average of the summer and winter simulation are used for these seasons. We assume that this demand pattern is representative for all households.

Average household electricity consumption was 3350 kWh/yr in the year 2000 [309]. Based on projections for autonomous increase in this demand ranging between 0.5% and 1.5% per year [310, 309, 311, 288], we assume an increase of 1.1% per year for households. Consequently, electricity consumption per household is calculated at 3600 in 2007 and 3900 kWh/yr in 2015. We scale the 2003 household pattern from the SEPATH generator to match the total national household electricity demand in 2007 (see figure 4.2), 2010 and 2015.

The total number of Dutch households is projected to rise from 7.19 million households in 2007 to 8.5 million households [312, 313]. For sake of simplicity, we assume one car per household.

Figure 4.2 also shows the daily pattern of the total Dutch electricity demand per season, based on the average of the years 2006-2008, as obtained from TenneT [314]. Projections for autonomous

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[22] SEPATH is a fully validated pattern generator that simulates the present day electricity demand of households over a 24-hour period. It was developed by KEMA and IVAM [307, 308].

national electricity demand increases range between 1.1% and 2.4% per year [311, 288], and we assume an increase of 1.5% per year.

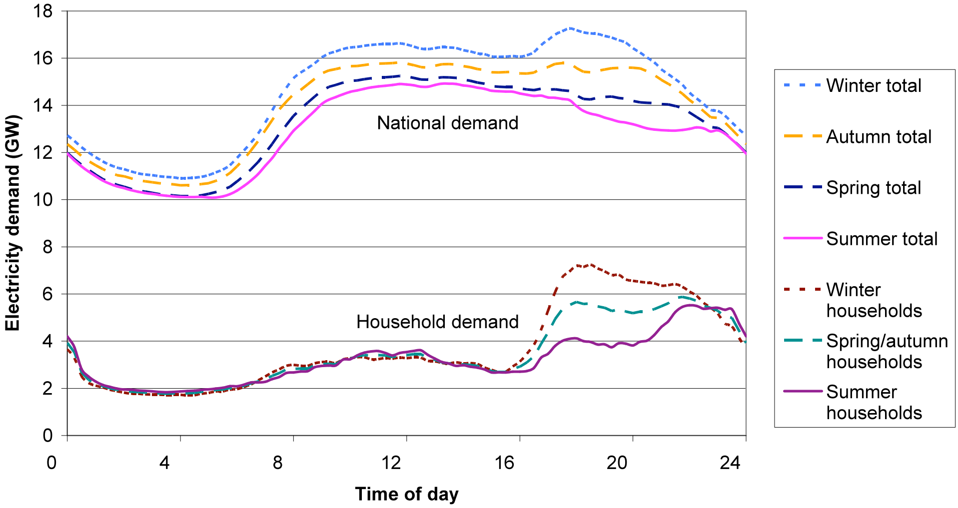


Figure 4.2: Average total 2006-2008 national and total 2007 household electricity demand patterns for the Netherlands.

National demand follows household demand in night and evening, but daytime demand is clearly increased by electricity consumption in the workplace. Both the highest peak demand (winter time evening 17:00 to 20:00) and off-peak (night from 23:00 to 7:00) intervals are caused by dynamics in household demand. However, as demand from households is projected to rise more slowly than overall demand, the influence of households on this pattern will diminish.

4.3.6 Electricity supply

We use the Dutch vintage electricity generation capacity for our supply calculations. For constructing cost and emission supply curves it is assumed that the electricity generation mix of the Netherlands will not change substantially in the near future. Plans for new power plants support this, as well as the intentions of the Dutch government. Furthermore, the 20-60 year lifespan of power plants makes the generation mix rather static [315, 316, 317].

Vintage capacity	CO_2 emissions	Variable costs	Capacity	Generation capacity installed			
Technology merit order	(tonne/MWh)	(€/MWh)	factor	2005	2010	2015	2030
Preferred capacity*	mixed, not relevant		included	3858	3910	3621	1217
PC super critical new	0.85	16	0.89	0	0	3600	3600
PC super critical	0.89	16	0.89	1230	1230	1230	1230
PC sub critical	1.00	18	0.89	2690	2690	2690	2045
Integrated coal gasification	1.03	19	0.87	253	253	253	253
NGCC new	0.43	62	0.89	0	2098	5869	5869
NGCC	0.48	69	0.89	4809	3782	3718	2961
Gas-fired power plant	0.61	88	0.80	4527	4068	2643	0
CHP gas engine	0.61	89	0.46	1794	2517	1810	0
Gas turbine peaking plant	0.70	103	0.25	239	0	0	0

Note: *Preferred capacity in the merit order consists of nuclear power, gas turbine district heating, PV, onshore and offshore wind, and most varieties of CHP. Abbreviations: PC: pulverised coal-fired; NGCC: natural gas combined cycle; CHP: combined heat and power. Source: [318]

Table 4.4: Electricity generation capacity in the Netherlands in 2005, 2010, 2015 and remaining 2015 vintage in 2030, in order of merit.

Table 4.4 shows existing and projected vintage electricity generation capacity, taken from Van den Broek et al. [318]. For 2015, this assumes three currently planned pulverised coal-fired power plants with a total capacity of 3.4 GW and several NGCC plants with a total capacity of 5.9GW are built.

Merit order is based on variable operating and maintenance (O&M) and fuel costs, except for nuclear, wind, PV and CHP (except gas engine CHP), which are always used when available. We do not take a CO_2 price into account when determining the merit order.

For 2030, only the plants that remain from the 2015 vintage are included, to show the inertia in the composition of the generation capacity. New capacity will be needed to meet demand after 2015, but projections regarding the type of plants built after 2015 are beyond the scope of this chapter. If GHG emissions from electricity generation are to be reduced, we can expect an increasing role for electricity generation using renewable resources like biomass and wind, and for the use of carbon capture and storage (c.f. [319, 320]).

From 2000-2009, grid losses have accounted for 3.8% of electricity produced in the Netherlands [321]. The Dutch grid is relatively efficient, compared to the whole EU where losses were reduced from 8.7% in 1996 to 7.2% in 2007 [322]. We adjusted variable costs and GHG emissions of delivered electricity and available electricity for losses in the Dutch grid. We include the difference between Dutch and EU grids in our uncertainty calculations.

As we assume no additional capacity is built for charging EV, there are no additional capital costs. The costs for charging EV at a specific hour in a year are determined by the variable O&M and fuel costs of the marginal available generation plants.

To calculate emissions and variable costs, we use emissions factors from JRC and price projections from the World Energy Outlook 2009 [45, 5]. For coal, emissions are 108.4 kg $CO_{2\,eq}$/GJ, including emissions from mining and transport, and price is 1.8 €/GJ around 2010 and 2.0 €/GJ in 2015. For natural gas, emissions are 69.5 kg $CO_{2\,eq}$/GJ, including recovery and 4000km pipeline transport, and price is 9.2 €/GJ around 2010 and 10 €/GJ in 2015.

4.4 Results

4.4.1 Plug-in hybrid and battery powered car configurations

Table 4.5 shows the battery-related aspects of our SHEV and EV configurations. The increase in fuel consumption due to weight (3%±2% per 100 kg extra weight) ranges up to 14% compared to reference SHEV. Table 4.6 shows component costs and total purchasing costs of our reference cars, SHEV and EV configurations.

Vehicle configuration	Battery (kWh)	Battery weight (kg)	Car weight (kg)	Range on full battery (km)	Electricity consumption (Wh/km)
SHEV CM 2010	1.1	10	1310 ± 20	8 ± 1	petrol only
SHEV WM future	1.5	10 ± 0	1220 ± 0	11 ± 2	petrol only
PHEV CM 2010	7.4	80 ± 20	1380 ± 20	50 ± 7	122 ± 27
PHEV WM future	6.4	40 ± 20	1250 ± 20	50 ± 7	104 ± 23
BPEV CM 2010	36.9	410 ± 80	1530 ± 80	250 ± 34	127 ± 35
BPEV CM 2015	36.9	340 ± 180	1450 ± 180	250 ± 34	124 ± 32
BPEV WM 2015	31.8	290 ± 160	1350 ± 160	250 ± 37	107 ± 29
BPEV WM future	31.8	210 ± 120	1270 ± 120	250 ± 37	104 ± 25

Table 4.5: Battery capacity, battery weight, total car weight, range (+σ) on full battery, and TTW electricity consumption (including correction for weight) of EV configurations investigated in this study.

Vehicle configuration	Platform	Electrical drive	ICE / generator	Battery	Total (€)
Regular diesel	15730	0	5640	0	21360
Regular petrol	15440	0	3730	0	19160
Parallel hybrid	15440	3660	2980	2830 ± 0*	24910 ± 0
SHEV CM 2010	15730	4380 ± 750	3020 ± 210	1740	24860 ± 780
SHEV WM future	15730	2330 ± 720	2730 ± 190	580	21370 ± 750
PHEV CM 2010	15730	4380 ± 750	3020 ± 210	7550 ± 1370	30670 ± 1580
PHEV WM future	15730	2330 ± 720	2730 ± 190	3030 ± 540	23820 ± 920
BPEV CM 2010	15730	4380 ± 750	0	35800 ± 6870	55900 ± 6910
BPEV CM 2015	15730	4380 ± 750	0	29970 ± 5730	50070 ± 5780
BPEV WM 2015	15730	2330 ± 720	0	25960 ± 5390	44020 ± 5440
BPEV WM future	15730	2330 ± 720	0	13220 ± 2690	31280 ± 2790

*The parallel hybrid car has a 2.9 kWh battery.

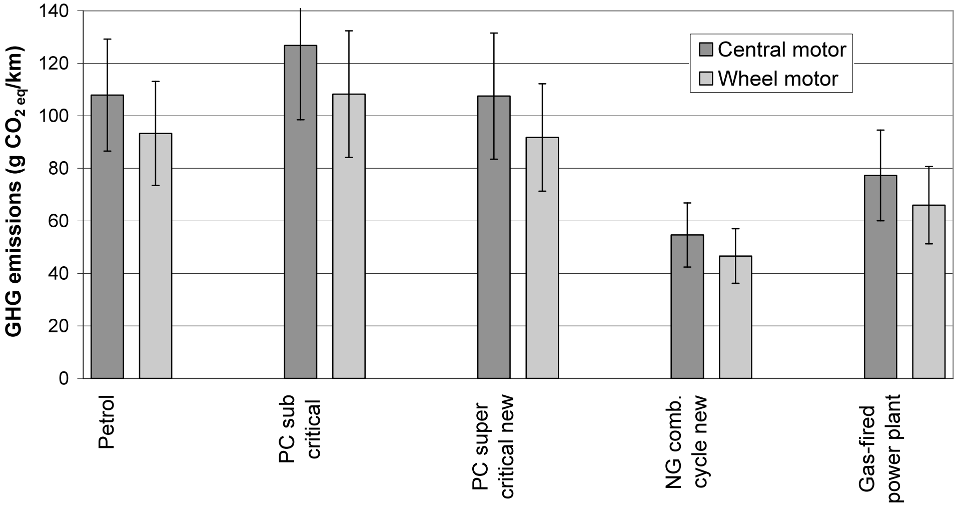
Table 4.6: Component costs and total car purchasing cost of car configurations investigated in this study.

Vehicle configuration	Fuel	WTT emissions (g/km)	TTW emissions (g/km)	total emissions (g/km)
Regular diesel	diesel	25 ± 5	131	156 ± 5
Regular petrol	petrol	22 ± 6	140	163 ± 6
Parallel hybrid	petrol	18 ± 4	112	129 ± 4
SHEV central motor	petrol	15 ± 4	93 ± 18	108 ± 21
SHEV wheel motor	petrol	13 ± 4	81 ± 17	93 ± 20
PHEV CM 2010	electricity / petrol*	3 to 116	29 ± 6	25 to 151
PHEV WM future	electricity / petrol*	2 to 99	24 ± 5	22 to 129
BPEV CM 2010	electricity	0 to 166	0	0 to 166
BPEV CM 2015	electricity	0 to 163	0	0 to 163
BPEV WM 2015	electricity	0 to 139	0	0 to 139
BPEV WM future	electricity	0 to 136	0	0 to 136

*PHEV emissions use 70% electricity and 30% petrol.

Table 4.7: WTT, tank-to-wheel (TTW) and total WTW emissions from reference drivetrains in gram CO_2 equivalent / km.

Table 4.7 shows GHG emissions of our car configurations, using petrol, diesel and electricity produced by wind or PC sub-critical power plants. Figure 4.3 shows GHG emissions from electric driving in 2015 PHEV with CM and WM configurations using fossil fuels, calculated from drivetrain electricity consumption, conversion efficiency of petrol and power plants, grid losses, and relevant emission factors. We find that EVs charged using electricity from coal do not have significantly different GHG emissions from driving in regular cars. EV charged with electricity from NG may reduce emissions to as low as 47 g/km. These emissions results are similar to those found by other authors (e.g. [33], relative emissions pattern based on USA vehicles repeated in [281, 220]).



Note: PC: Pulverised coal, NG: natural gas.

Figure 4.3: GHG emissions from driving (g $CO_{2\,eq}$/km) on petrol and on electricity from fossil energy resources in CM and WM 2015 PHEV configurations.

The variation in GHG emissions of electric driving is considerable, and depends more than anything else on the mix of electricity sources used for charging. GHG emissions from electricity from a modern coal-fired power plant cause emissions that are approximately equal to those when driving the same PHEV on petrol.

4.4.2 Additional electricity demand from cars

Matching supply to demand, electricity generation capacity in the Netherlands in 2010 is sufficient to allow for uncontrolled charging with 6% penetration of EV. Projected generation capacity for 2015 is sufficient for uncontrolled charging up to 30% penetration of EV.

At a national level in the Netherlands in 2015 using a CM 2015 BPEV, we project EV charging to increase total demand by 3% at a 30% penetration rate of EV, as shown in table 4.8. However, the charging scenario makes a strong difference: Uncoordinated, the minimum load does not change but peak load increases by 7%. No additional peak load occurs if a wheel motor drivetrain used. With off-peak charging, the minimum load increases by 20% but the peak does not increase at all, resulting in an increased and more stable base load, and no need for additional investment for driving. Figure 4.4 shows the resulting demand patterns on a national level.

Figure 4.5 shows the resulting demand patterns on a household level. This pattern is even more pronounced at household level, where additional demand would be 35%, but peak increase for uncoordinated charging would be 54% and base load increase for coordinated charging would be 47%. The peak increase for household demand using coordinated charging would be around 7%. Though the increased peak demand from uncontrolled charging is nationally within projected 2015 peak generation capacity, the increase in peak household demand indicates that distribution infrastructure may locally need strengthening if the penetration rate of EV becomes significant. Further research into the effects of EV charging on local (district or street level) infrastructure may therefore be needed.

Daily demand	**National level, 8.1 million cars**			**Household, single car**		
Winter 2015	total GWh/day	maximum GW	minimum GW	total kWh/day	maximum kW	minimum kW
Baseline	351	17.3	10.9	14	1.11	0.26
Uncoordinated	362	18.6	10.9	18	1.70	0.27
Off-peak	362	17.3	13.1	18	1.18	0.38

Table 4.8: Electricity demand without (baseline) and with (uncoordinated & off-peak) electric driving at 30% penetration rate of CM 2015 BPEV.

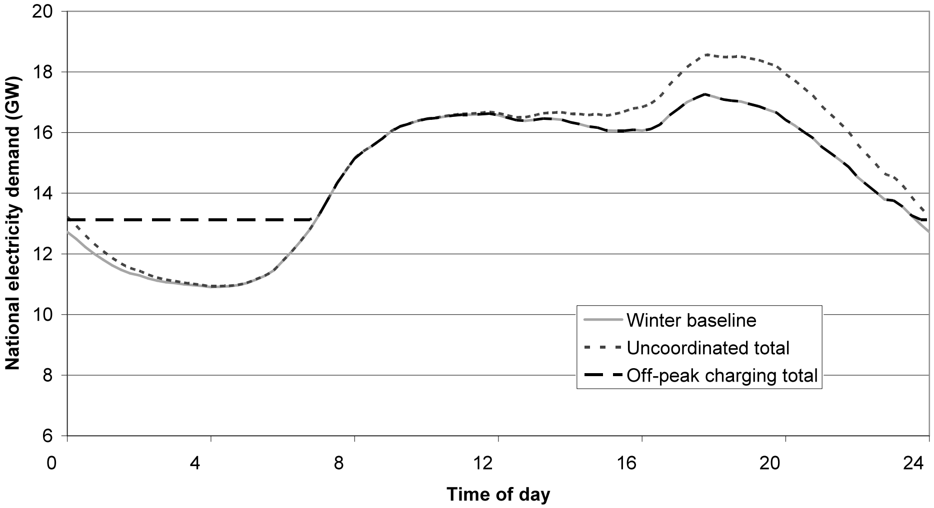


Figure 4.4: Electricity demand pattern in winter at national level with and without CM 2015 BPEV in 2015 at 30% penetration.

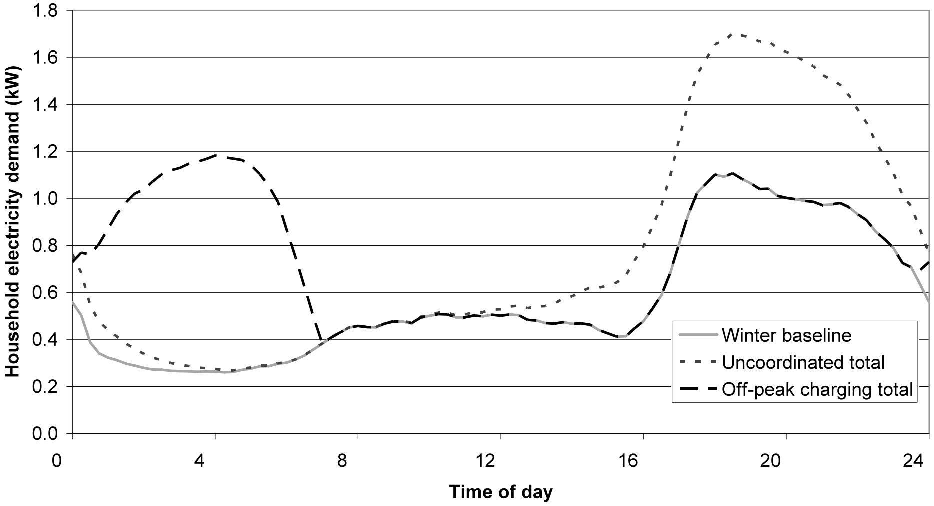


Figure 4.5: Electricity demand pattern in winter at household level with and without CM 2015 BPEV in 2015 at 30% penetration.

EV charging patterns have most impact when household demand is highest or lowest. Therefore, despite households' minority share in total demand, household demand dynamics are most relevant in determining the impact of EV on national electricity demand.

The impact of off-peak charging is different on household level than on national level, to a point where night-time demand is almost equal to peak demand without EV charging. However, as long as night / off-peak electricity prices remain significantly lower than afternoon / evening prices, this should not affect the incentive to charge off-peak.

4.4.3 GHG emissions and costs of EV charging

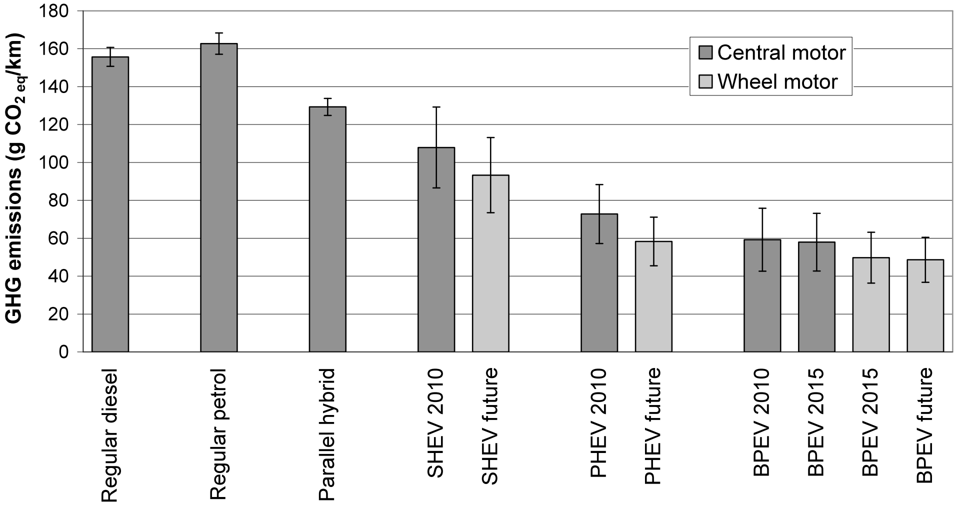
Table 4.9 shows the cost and emissions of additional electricity required for driving a PHEV or BPEV. There is no significant difference in the average cost or emissions for different levels of penetration. GHG emissions reflect that most of the electricity used for charging is generated with efficient natural gas-fired power plants (NGCC). Both without EV charging and with off-peak charging, we project that NGCC is the *de facto* marginal source at all times in all seasons in the Netherlands in 2015.

The off-peak charging pattern results in a 8% reduction in GHG emissions and 34% reduction in EV charging price at a household level compared to uncoordinated charging (excluding possible excise duties on electricity). Emissions are higher in case of uncoordinated charging because less efficient NG power plants used to supply electricity for charging. Including uncertainties in electricity consumption and variation between CM and WM cars, GHG emissions are 35-77 g/km when charging from the Dutch grid in 2015. This is a reduction of 51%-78% compared to regular cars and by 17%-73% compared to other hybrids.

Additional electricity	**National level, 8.1 million cars**			**Household, single car**	
Winter 2015	generation cost		emissions	electricity price	
	€/MWh	€/km	g CO_2/km	€/MWh	€/km
6% penetration					
Uncoordinated	70	0.009	62	97	0.012
Off-peak	65	0.008	57	64	0.008
30% penetration					
Uncoordinated	71	0.009	62	97	0.012
Off-peak	65	0.008	57	64	0.008

Table 4.9: Average costs, including VAT and excluding excise duty, and emissions of additional electricity for electric driving at 30% penetration of CM 2015 BPEV.

Figure 4.6 shows the total GHG emissions per km for our reference cars, SHEV and EV. It shows that PHEV can achieve the lion's share of the GHG reductions that are possible with EV. GHG emissions may be reduced further by reducing the CO_2 intensity of liquid fuels and electricity.



Note: Emissions for PHEV use 70% electricity and 30% petrol.

Figure 4.6: GHG emissions from driving ($gCO_{2\ eq}$/km) car configurations investigated in this study.

Using the electricity costs from table 4.9, we arrive at the variable cost of driving shown in table 4.10:

Vehicle configuration	MRT	Petrol	Electricity (grid)	Total (€/km)
PHEV central motor	0.043	0.029 ± 0.007	0.008 ± 0.003	0.057 ± 0.004
PHEV wheel motor	0.043	0.025 ± 0.006	0.007 ± 0.002	0.055 ± 0.003
BPEV central motor	0.043		0.008 ± 0.003	0.049 ± 0.003
BPEV wheel motor	0.043		0.007 ± 0.002	0.048 ± 0.002

Note: Total variable costs for PHEV use 70% electricity and 30% petrol.

Table 4.10: Variable cost of CM electric driving (€/km) at 30% penetration in winter using off-peak charging.

Electricity costs a third of diesel or petrol per km, but the variable costs are still largely determined by maintenance, repair and tires (MRT). The variability introduced by charging patterns is 8%-9%.

4.4.4 Total cost of EV ownership

Table 4.11 shows the TCO of PHEV and BPEV. TCO is dominated by purchasing cost of the vehicle, rendering the effect of fuel costs and charging patterns negligible. Figure 4.7 compares TCO of reference cars, SHEV, PHEV and BPEV.

Vehicle configuration	Annualised purchase	MRT	Diesel / petrol	Electricity	TCO (€/yr, VAT only)
Regular diesel	2770	610	570	0	3940
Regular petrol	2480	570	630	0	3690
Parallel hybrid	3230 ± 0	570	500	0	4300 ± 0
SHEV CM 2010	3220 ± 100	610	400 ± 80	0	4230 ± 130
SHEV WM future	2770 ± 100	610	350 ± 70	0	3720 ± 120
PHEV CM 2010	3970 ± 200	610	120 ± 30	80 ± 24	4780 ± 210
PHEV WM future	3090 ± 120	610	110 ± 20	60 ± 21	3860 ± 130
BPEV CM 2010	7240 ± 890	610	0	110 ± 41	7960 ± 900
BPEV CM 2015	6480 ± 750	610	0	110 ± 38	7200 ± 750
BPEV WM 2015	5700 ± 700	610	0	100 ± 34	6400 ± 700
BPEV WM future	4050 ± 360	610	0	90 ± 31	4750 ± 360

Table 4.11: Total cost of ownership (TCO, €/year) breakdown for car configurations investigated in this study using a 5% social discount rate, VAT only, driving 14 000 km/year and depreciating over 10 years.

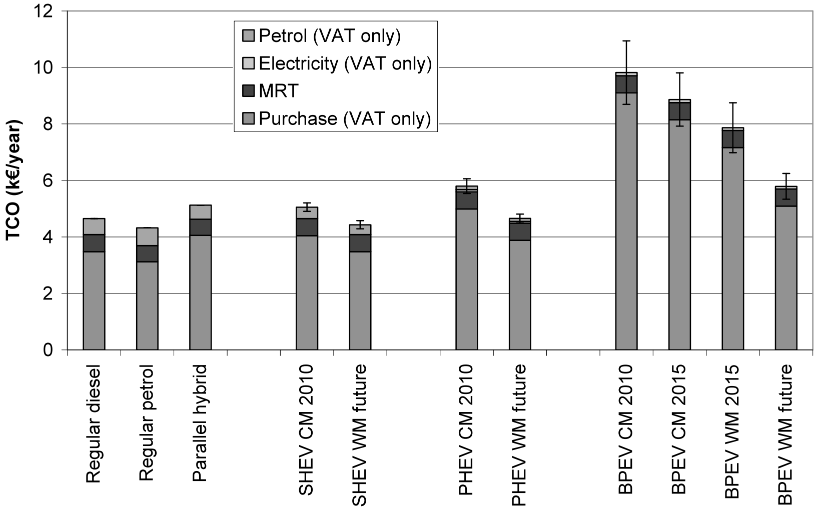
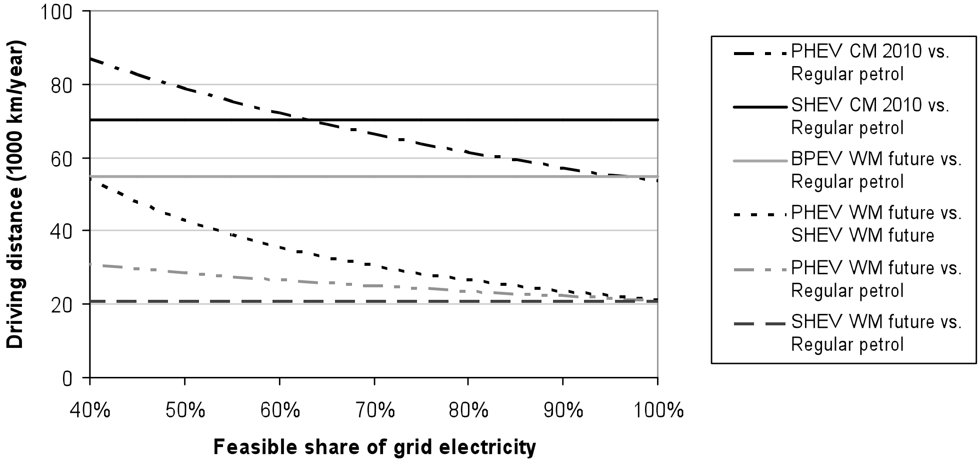


Figure 4.7: Total cost of ownership (TCO, k€/year) breakdown of our car configurations using a 10% consumer discount rate and VAT only, driving 14 000 km/year and depreciating over 10 years.

BPEV are at least 800 €/year more expensive than the reference cars or any of the alternatives, even at a battery cost of €400/kWh. By contrast, the future wheel motor PHEV is not more expensive than any alternative but the current regular petrol car and the future WM SHEV.

However, PHEV TCO in table 4.11 depends on driving on 70% electricity and on the relative impact of variable costs. We therefore examine the sensitivity of TCO comparisons to driving distance and share of electrically-fuelled km driven (assuming that these shares are feasible).

When we plot the TCO for different configurations as a function of driving distance and feasible share of electrically fuelled km driven, and project the intersects in a flat plane, we obtain isopleth curves which show at which driving habits it is cheaper to switch to another configuration (break-even points). Figure 4.8 shows the isopleths curves for our PHEV and BPEV configurations and reference cars.



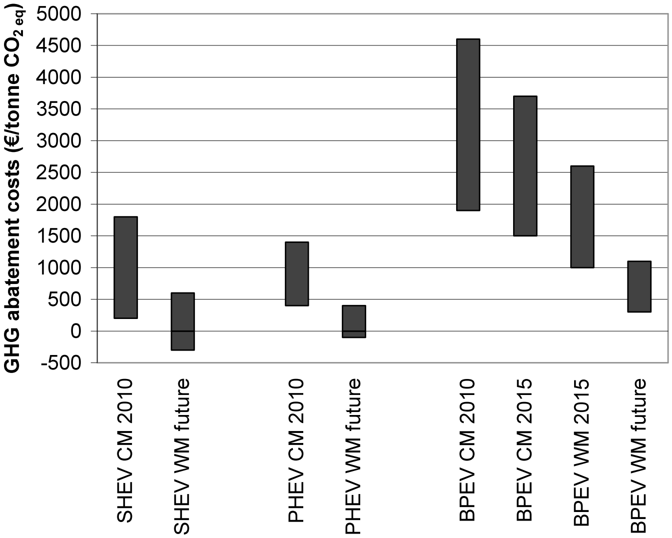
Note: For every line, the configuration listed first in the legend has lowest cost above the isopleth line, and the configuration listed second has lowest cost below the line.

Figure 4.8: Lowest TCO isopleths for SHEV, PHEV, BPEV and reference cars, using VAT only and a 10% consumer discount rate.

Figure 4.8 shows that low share of electric driving reduces competitiveness of PHEV, but that a motorist who drives long distances (e.g. 40 000 km per year) with access to recharging away from home may still benefit from a future PHEV.

Increasing the oil price from 80$/bbl to 120 $/bbl does not change the relative positions of the lines in figure 4.8, but reduces the driving distance for all isopleths by one-third. For example, at 120 $/bbl, current CM SHEV have lower TCO than regular petrol cars at a driving distance of more than 54 000 km/year. TCO cost for SHEV are increased by approximately 100 €/yr compared to table 4.11.

Using results from tables 4.7, 4.9 and 4.11 we calculate the approximate GHG abatement costs for our car configurations, as shown in figure 4.9. Results indicate the future SHEV and PHEV may be competitive with other options for GHG emissions reductions, but current EV technology and BPEV are not.



Note: Range in abatement costs is caused by uncertainty in EV costs, GHG emissions and by comparing to both petrol and diesel cars.

Figure 4.9: GHG abatement costs (€/tonne CO_2 equivalent) for EV configurations investigated in this study compared to regular diesel and petrol cars, in the Dutch electricity supply context, using a 5% social discount rate and VAT only, driving 14 000 km/year and depreciating over 10 years.

4.5 Discussion

4.5.1 Effect on electricity generation infrastructure

Electric driving is potentially an extra source of revenue for utilities. If charging is done off-peak, a 30% penetration rate causes an increase of 3% in total electricity demand. This can be met without additional investments in electricity generation plants. Electrification of the entire car fleet would result in an increase of around 10% in total electricity demand, which can still be met with existing generation capacity, without higher peak loads at a national level and with 7% higher peak loads at the household and district level using a CM EV or no higher peak load using a WM EV.

However, if EV charging is uncoordinated and there are no incentives to charge off-peak, the peak load would increase substantially, as described in section 4.4.2. This increase of peak load is much more pronounced on the household level than on the national level (compare figure 4.4 and 5). Furthermore, there is not much incentive (other than lower off-peak rates) to adopt coordinated charging on the household level, because the impact of charging patterns on total household costs is relatively small, while this incentive is much stronger for utilities and grid operators. Consequently, if EVs will be concentrated in certain districts or even streets, uncoordinated charging may quickly cause the local distribution grid to be overloaded.

The household demand pattern resulting from off-peak charging (see figure 4.5) has implications for CHP installations, as the combined pattern resembles that of household heat demand in a country like the Netherlands (see [323]). District and micro-CHP would become more viable with increased penetration of electric vehicles. We therefore recommend further investigation of combining CHP with EV charging.

The longevity of the existing generation capacity precludes rapid changes in the GHG emissions profile of EV. In the Dutch context, 68% of 2015 capacity is projected to still be in use in 2030 (see table 4.4). In the medium term, GHG emissions from EV driving are relatively fixed. There is therefore neither a risk of EV electricity being entirely supplied from coal, nor a possibility to supply all of it from renewables.

This limits the GHG emissions reductions that may be achieved through EV. However, the emissions profile may change, for example, if stringent GHG reduction policies cause existing electricity generation capacity to be retired early or retrofitted for co-firing of biomass and/or carbon capture and storage (see also [320]). Alternatively, complementary means of reducing transport emissions may be used, such as sustainable biofuels.

4.5.2 Uncertainty in energy use

Table 4.5 shows that the weight increase for future WM vehicle configurations is less than 5% compared to the reference cars (as in [261]). However, central motor PHEV and BPEV shows up to 17% increase weight, leading to significantly increased electricity consumption. This increase would be even more significant in larger size cars (mid-size sedans up to SUV) and in case battery-powered range were increased beyond 50 km for PHEV and 250 km for BPEV. Significant uncertainties exist in the GHG emissions from electric driving, which depend to a large extent on energy efficiency of the drivetrain (in addition to electricity source). We arrive at an uncertainty in emissions of around 22%.

However, additional minor uncertainties could arise from variability in charger efficiency and battery cycle efficiency. In the context of current Dutch electricity generation capacity in the short term, any additional electricity is likely to be generated from natural gas, and therefore does not significantly alter the overall GHG emissions profile. However, GHG emissions would rise more in supply contexts where the marginal electricity source causes high emissions.

Driving patterns (as represented in drive cycles) have a major impact on fuel consumption and affect electric drivetrains differently than ICE drivetrains. Further research, using comparable vehicle platforms, may shed light on the exact impact of driving patterns.

4.5.3 Battery costs

As batteries entirely account for additional weight and cost between SHEV and our PHEV and BPEV configurations, we expect some motorists may favour PHEV configurations with a battery–powered range between 20 and 50 km, or BPEV configurations with ranges between 100 and 250 km. Lower cost and weight may outweigh concerns over range for some. The PHEV is more flexible in this sense, because it also carries an ICE and the battery size determines the share of km driven on electricity, rather than restrict driving range.

We calculate that TCO of a future WM BPEV configuration with 100 km electric range is roughly equal to that of regular and hybrid cars, but less advanced BPEV configurations remain more expensive. PHEV with 20 km electric range have approximately equal cost to SHEV. Future BPEV also become competitive if cost of batteries can be reduced to 150 €/kWh, but this implies an 85% reduction in cost compared to current batteries.

The battery cost reductions we use are based on policy targets and not on a comprehensive analysis of battery technology. It is therefore uncertain if the reduction of battery costs to 150 €/kWh can be reached at all, nor if the lesser reduction to 400 €/kWh can be reached, especially in 2015. More research is needed to assess future battery costs.

Our calculations assume EV batteries last the entire lifetime of the EV. At present Li-ion batteries have a calendar life of around 5 years, which suggests that one mid-life replacement may be necessary [200]. In parallel hybrids at least, cycle life has not proven to be problematic, as batteries in hybrid taxis are reported to have lasted over 350 000 km [233]. If a mid-life battery replacement is needed, discounted TCO of PHEV increase by 1640-1940 €/yr or 33%-35% compared to the results in table 4.11. TCO increase for BPEV would be 60% to 94%. This reinforces our conclusion that BPEV are economically uncompetitive.

4.5.4 Generalising our findings

As lifestyles, working hours and household technology are fairly similar across industrialised nations and households, demand patterns without EV charging should be fairly consistent, except for higher use of air conditioners in the daytime in warmer climates. We therefore expect our findings on the impact of charging patterns on demand to be applicable to industrialised countries.

Conversely, our results for marginal supply and emissions are based on the Dutch supply and demand. Generation capacity varies strongly between countries, with wide ranges in the use of coal, nuclear, hydro and natural gas. Our calculation for cost of charging and GHG emissions are therefore circumstantial. More generally, increased base load due to electric driving could lead to increased use of coal-fired electricity with high GHG emissions. However, unless a majority of a country's electricity generation capacity will reach the end of it's lifespan in the next decade, GHG emissions profiles of EV may to remain close to current values.

Our TCO calculations use technology assumptions that are not nation-specific. Our finding that charging patterns have negligible impact on TCO is widely applicable. However, we assume no specific tax context, whereas taxation can strongly influence the relative TCO of car alternatives. For example, the Dutch tax context is advantageous to PHEV and BPEV configurations as EV buyers are currently exempt from a 45% purchasing tax, pay half of the annual road tax and pay lower fuel taxes because of lower fuel consumption (see [261]).

4.6 Summary and conclusions

We examined efficiency and costs of current and future EV, as well as the impact from charging EV on electricity demand and infrastructure for generation and distribution, and thereby on GHG emissions.

Uncoordinated charging would increase national peak load by 7% at 30% penetration rate of EV and household peak load by 54%, which may exceed the capacity of existing electricity distribution infrastructure. At 30% penetration of EV, off-peak charging would result in a 20% higher, more stable base load and no additional peak load at the national level and up to 7% higher peak load at the household level. Therefore, if off-peak charging is successfully introduced, electric driving need not strain infrastructure, even in case of 100% switch to electric vehicles.

WTW GHG emissions from electric driving depend most on the fuel type (coal or natural gas) used in the generation of electricity for charging, and range between 0 g/km (using renewables) and 155 g/km (using electricity from an old coal-based plant). Based on the generation capacity projected for the Netherlands in 2015, additional electricity for EV charging would largely be generated using natural gas, emitting 35-77 $gCO_{2\,eq}$/km. In the Dutch context, emissions vary little with charging patterns, and are unlikely to change much before 2030.

Emissions from EV charging are lower than emissions from regular or parallel hybrid cars, and equal to emissions from SHEV if electricity were generated from modern coal-fired plants.

We find that TCO of current EV are uncompetitive with regular cars and series hybrid cars by more than 800 €/year. TCO of future wheel motor PHEV may become competitive when batteries cost 400 €/kWh, even without tax incentives, as long as one battery pack can last for the lifespan of the vehicle. However, TCO of future BPEV is at least 25% higher than of SHEV or regular cars. This cost gap can be overcome if the cost of batteries drops to around 150 €/kWh in the future. Variations in driving cost from charging patterns have negligible influence on TCO.

GHG abatement costs using PHEV are currently 400 to 1400 €/tonne $CO_{2\,eq}$ and may come down to -100 to 300 €/tonne. Abatement cost using BPEV are currently above 1900 €/tonne and are not projected to drop below 300-800 €/tonne.

We find that EV can be integrated into the Dutch grid with few additional investments apart from coordinated chargers. Using PHEV, this need not increase the cost of driving significantly and could reduce emissions from driving by more than 70% compared to diesel and petrol cars and by more than 55% compared to other hybrids that use petrol. We therefore recommend further development of electric drivetrains and batteries for use in SHEV and PHEV.

With respect to the possible future deployment of EV, we recommend further research into combining CHP with EV charging, effects of EV charging on local electricity distribution grids, cost developments of batteries and chargers, and the effect of driving patterns and different vehicle classes on EV fuel consumption. We also recommend integrating WTW analysis with analysis of energy and GHG emissions from EV manufacturing, as well as impacts of EV on non-GHG emissions, and investigating the possible role of EV in conjunction with other car alternatives, low or zero carbon fuels and green electricity in reducing GHG emissions.

“Do not deny the classical approach, simply as a reaction,
or you will have created another pattern and trapped yourself there.”

- Bruce Lee, *The Tao of Jeet Kune Do*

5. Combining hybrid cars and synthetic fuels with electricity generation and carbon capture and storage

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5.1 Introduction

Electricity and heat generation and transportation are among the largest producers of greenhouse gases (GHG) in the EU, responsible for half of total GHG emissions: 32% for energy supply and 18% for transportation [93]. While overall GHG emissions have been reduced in recent years, both the demand for and the GHG emissions from transportation have continued to grow [93, 12].

In transportation, the consumption of diesel and petrol derived from crude oil is also considered problematic because of uncertainty about cost developments, lack of security of supply [7, 8], and local and regional air pollution [12]. Solutions are sought in alternatives for both fuels and drivetrains (cars). On the fuel side, possibilities exist to switch from diesel and petrol to biofuels (ethanol, biodiesel), synthetic fuels (from biomass, coal or gas), hydrogen, or electricity. On the vehicle side, possibilities exist to reduce fuel demand by a shift to more efficient hybrid, electric or fuel cell drivetrains.

In the electricity sector, major challenges are to fulfil growing demand and simultaneously to reduce CO_2 emissions [324]. Potential solutions include enhanced use of renewable sources of electricity (e.g. wind, solar, biomass), increasing the efficiency of energy conversion and end-use, and applying carbon capture and storage (CCS) technologies. This adds another challenge of integrating these technologies into the electricity system in a way that guarantees reliability of the electricity supply.

In the existing system, the electricity/heat generation sector and transport sector are largely separated. If the alternatives mentioned above come into play, these two sectors may become more intertwined because of:

- Resource competition: Lignocellulosic biomass (wood and grasses) can be used for both synthetic fuel and power[23] production. All use of biomass competes to some degree because of land scarcity.
- Development of CCS: Both power plants and synthetic fuels plants can produce streams of CO_2 suitable for storage. Combining these streams can make development of CCS infrastructure more attractive, but also fill up available storage capacity more quickly.
- Electricity co-production: Electricity is a major by-product in the thermochemical production of synthetic fuels and can be an input or a by-product in the production of hydrogen.
- Electricity demand: Electric cars and plug-in hybrid cars directly increase the demand for electricity and may therefore increase the need for generation capacity and grid upgrades. Batteries that can be flexibly charged can allow for more baseload and intermittent electricity sources.

5.1.1 Existing research

Numerous studies have been done to explore development of the total energy system including the power and transport sectors using a computer model of national or supra-national energy systems (see e.g. UK-MARKAL model [325], Hyways project [326], Energy Technology Perspectives [86]). However, nearly all of these studies address the co-evolution of the power and transport sectors in a minimal way. Other studies, like the World Energy Outlook (WEO) 2009, address power and transportation without explicitly discussing interactions [5].

Studies that explicitly explored the interaction between the power and transport sectors still have limitations. One example is a 2006 study by the Pacific Northwest National Laboratory [277] investigating the impacts of using the existing idle (off-peak) capacity of the electric infrastructure in conjunction with the emerging plug-in hybrid electric vehicle (PHEV) technology. Their conclusion was that 73% of the light duty vehicle fleet[24] could be supported by existing electric infrastructure for a daily drive of 53 km on average. They also stated that “the mix of future power plant types and technologies may change as a result of the flatter load-duration curve favouring more base-load power plants and intermittent renewable energy resources”. However, this analysis did not project a mix of power plants in the future and, thus, did not analyse the consequences for costs or emissions resulting from this mix.

Using the UK MARKAL model coupled to a GIS, Strachan et al. [327] studied scenarios for the use of hydrogen in transportation with CCS to reduce CO_2 emissions, including the matching of

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[23] In this article, we refer to the combined electricity and heat sectors as the power sector, and electricity and heat generation as power generation.

[24] By their definition, the light duty vehicle fleet includes cars, pickup trucks, sport utility vehicles (SUVs), and vans.

energy supply and demand in time and space. Their conclusion was that spatial clustering of demand allows for essential economies of scale, and proximity of production sites to demand centres is preferable over pipelines. However, they did not investigate other options to attain comparable levels of CO_2 emissions reductions in transportation. Using the MARKAL-NL-UU model coupled to a GIS, Van den Broek et al. [328, 329] similarly examined the development of CCS in the power sector of the Netherlands. This study focused on underground storage of CO_2 from production of electricity and heat only.

Using the UK MARKAL model coupled to a macro-economic model, Strachan et al. [330] studied the macro-economic impact of 60% CO_2 emissions reduction in the UK. They found that in a baseline scenario, energy demand increases in their combined model compared to standalone MARKAL but decreases when carbon constraints are included, reflecting the option of behavioural change. The preferred options for decarbonisation appear to be the use of coal with CCS, nuclear and wind energy. However, uncertainties in the future costs and characteristics of these technologies make it is impossible to robustly project the emergence of a dominant technology. A reduction in 2050 GDP of 0.3% to 1.5% was found, with the largest reduction in GDP caused by limiting technology to what is available in 2010. This study is oriented towards electricity production, with little attention paid to the co-evolution of the power and transport sectors. Transportation is noted as shifting towards biofuels, diesel- and hybrid cars and finally to hydrogen after 2030.

Grahn et al. [331] explored co-evolution between the transportation and power sectors until 2100 using the GET model. They found largely uniform mixes of fuels and cars in the short to medium term, with continuing large shares of diesel and petrol. Only after 2040 did mixes of vehicles and fuel technologies diverge. They also found that concentrated solar power and CCS delay a transition in the transportation sector in the long term, because CO_2 emissions reductions can more easily be attained in electricity generation. However, their technology descriptions are generic. They also assume challenging cost reductions for batteries, hydrogen storage and fuel cells based on policy targets and manufacturer projections, which are an order of magnitude lower than the current costs.

Wise et al. [332] explored the effect of introducing plug-in hybrid vehicles using the Minicam model. They found that plug-in hybrid cars can reduce demand for biofuels but increase demand for CCS, and that stronger climate policy and limited availability of biofuels drive adoption of plug-in hybrid cars. However, they did not take other vehicle technologies into account.

Studies that investigate the power sector usually assume constant growth rate of the electricity demand. These projections do not include major changes in trends such as a strong increase in electricity demand from transportation. Therefore, short to medium term advantages and disadvantages of, for example, a combination of CCS, renewables, and electrified transportation has not been analysed. We address these issues in combination this chapter.

5.1.2 Approach and objectives

In this chapter, we aim to explore the co-evolution of the power and transport sectors under strict CO_2 emission reduction policies. Specifically, we addressed the following research questions:

> *What shifts in the mix of fuels, vehicles and electricity generation capacity may emerge when we need to CO_2 emissions?*
> *How may the power and transportation sectors co-evolve under CO_2 emission reduction policies?*
> *How may the use of energy resources, CO_2 emissions per sector, CO_2 abatement costs and investment required develop over time as a result of CO_2 emission reduction targets?*

To investigate these questions in detail, we focus on the energy system in the Netherlands. We expand the MARKAL model for the Netherlands, a least-cost optimisation model for the energy system, with sections on transportation fuel production, biomass resources, costs and fuel consumption of vehicles, and road transportation demand. We applied this expanded model to investigate scenario variants for power and transportation that have different levels of CO_2 caps and taxes, technology incentives and prices for oil and other primary energy sources.

5.2 MARKAL model expansion

MARKAL (acronym for MARKet ALlocation) is a tool that generates bottom-up models of the energy system. It describes the energy system in terms of energy commodities and technologies. Energy supply technologies can convert primary energy to final energy and demand side technologies can convert this further to energy services. Other basic drivers for the development of the energy system are population and economic growth, expressed in demand for final energy or energy services.

The resulting model is translated into a (mixed integer) linear programming problem. MARKAL uses a mathematical solver to minimise the total discounted cost of the energy system over time within boundary conditions. Such boundary conditions may include the speed at which installed capacity can be replaced, availability of energy resources and the allowed total CO_2 emissions. The relative costs of technologies and resources play an important role in determining the final mix of technologies and primary energy sources. The optimal mix may change over time as conditions change, new technologies become available and performance of existing technologies improves (e.g. through technological learning).

5.2.1 The MARKAL-NL-UU model

The MARKAL-NL-UU model describes various energy-intensive sectors of the economy in the Netherlands, like electricity and heat generation, and the steel and chemical industries that produce for domestic consumption and export. In the model, a wide range of energy resources and technologies is represented [316, 333, 334, 335]:

- Energy resources: coal, gas, coal, biomass, solar, wind, and nuclear.
- Energy conversion: existing conversion technologies and a diverse range of advanced technologies which could become available between 2010 and 2030.
- CO_2 capture: technologies included are post-combustion capture and pre-combustion capture of CO_2 at new power plants, and retrofit of existing and newly built (capture-ready) power plants.
- CO_2 transport and storage: infrastructure development and potential underground storage options.

We model from a country-wide public perspective using an investment discount rate of 7%, not including Dutch taxes on electricity, fuels or vehicles (c.f. [215]) or road-pricing schemes.

5.2.2 Transportation expansions

To include the transport sector, we expand the MARKAL-NL-UU model with a comprehensive set of relevant technologies, from fuel production to end-use. Our expansion excludes transportation by air or waterways, as these transportation modes are extremely internationally oriented, are not part of existing treaties on GHG emissions reductions, and have a minority share of transportation GHG emissions (around 20%, half of which is from shipping on the continental shelf) [336]. We also exclude rail traffic and two-wheeled vehicles (motor bikes) because of their small share in transportation GHG emissions (<2% combined), and heavy special vehicles (agricultural and construction equipment) because of their very diverse nature. We exclude mining or conversion to intermediates of imported energy resources because these processes take place outside our model's geographical boundaries.

For end-use in the transport sector, we use kilometre demand for cars and heavy vehicles in the Netherlands. This allows our model to optimise across combinations of investment costs for vehicles and fuel production, fuel consumption, and resource cost. Instead of modelling dozens of vehicles classes, we aggregate these into the following categories:

- Busses
- Cars
- Trucks, including semi-trailers
- Vans, including very light trucks

For cars, we assume a compact 5-seater, which is the most widely used car class in the Netherlands and includes the VW Golf, Ford Focus, Renault Megane, Toyota Corolla and Opel Astra [45, 204]. We add a variety of drivetrain technologies for cars: regular, parallel hybrid, series hybrid, plug-in hybrid, fuel cell, and battery-powered electric. For vans, we assume these are predominantly used for short distance deliveries and commercial services, in a driving pattern that is similar to cars. We add regular, parallel hybrid, series hybrid and fuel cell drivetrains for vans.

Fuel cell drivetrains are not considered a good match for long range buses and trucks due to their 2000+ km range requirement and already high efficiency of diesel drivetrains at constant speed [88]. The same arguments extend to battery-powered electric buses and trucks. We found no real-world data for hybrid trucks, only estimates in existing studies (e.g. [337]). We therefore use only regular diesel drivetrains for long range buses and trucks. However, we add a series hybrid bus configuration for urban public transport.

For transportation fuel supply, we add production technologies for the following synthetic fuels:

- Fischer-Tropsch (FT) diesel and petrol from gasified coal and/or biomass intermediates
- Methanol from gasified coal and/or biomass intermediates
- Dimethylether (DME) from gasified coal and/or biomass intermediates
- Hydrogen (H_2) from natural gas, gasified coal and/or biomass intermediates

We also add import of crude oil and successive refining to diesel and petrol, as well as import of bio-ethanol from sugar cane (from e.g. Brazil) and biodiesel (from elsewhere in Europe). These default fuels and biofuels do not interact with the electricity system, nor do they offer any potential for CCS. However, they compete with synthetic fuels, hydrogen and electric driving for market share of transportation fuels.

We exclude compressed natural gas because the CO_2 emissions resulting from this alternative do not differ markedly from driving on diesel and petrol [27]. Bio-SNG could improve this GHG balance but its cost is higher than that of natural gas and quite similar to synthetic biofuels which are easier and cheaper to distribute. Furthermore, Bio-SNG is still in demonstration phase [338]. We exclude biological conversion of biomass intermediates to ethanol in NL as a separate pathway because the efficiency and cost are similar to those for methanol [71].

5.2.3 Time and technological progress

Technology improves over time, leading to reduced costs, higher conversion efficiencies and/or lower emissions [339]. However, technological progress is not only linked to time, but also to experience with using and producing the technology. It would be preferable to link the introduction of new technology to technological learning from global production, for example by incorporating learning curves (see [29, 340, 209]).

The Netherlands however, has a tiny market for fuel production (except for natural gas) and car sales compared to the rest of the world. All key technologies for our study will develop on a global scale, largely beyond the boundaries of our national model. As the Netherlands is not representative for the rest of the world, we do not extrapolate its production developments to the entire world, endogenous technological learning can therefore not be used in our simulations. Instead, in our dataset, technologies are made available when these are projected to have passed demonstration and construction of a commercial unit, and are ready for mass production (though possibly at a price that prevents adoption). Assumptions used for technological progress in fuel conversion and car technologies are based on literature and expert judgement.

We disregard possible delays from constrained production capacity for vehicles or construction of fuel plants. In doing this we show the optimal configuration that the model arrives at, instead restraining this outcome with (somewhat arbitrary) growth constraints.

Table 5.1 shows the technological advances we use for fuel production and vehicle development in five-year periods. We include only technologies that are currently in commercial or pre-commercial pilot stage, but allow for further cost reduction of these existing technologies. For this reason, no new technologies appear after 2030, and subsequent dynamics are driven entirely by scenario parameters. We discuss the sensitivity of our results to the timing of availability of these technologies in section 5.6.

5.3 Scenario and data

Figure 5.1 shows a complete diagram of the transportation expansion of the MARKAL-NL-UU model. It presents the interaction of all energy sources, conversion technologies, fuels, and vehicles in our expansion. Tables 5.2a and 5.2b provide a legend, and the technologies are described further in the following sections. All energy data are expressed in lower heating value (LHV), and all monetary data is in €$_{2007}$ unless noted otherwise. Discount rate is set at 7% for investment costs. Lifespan for conversion plants describes the technical lifespan, as we do not use a business perspective. Net present values are used to determine economic lifespan.

Vehicles	2000	2005	2010	2015	2020	2025	2030
Diesel direct drivetrain	diesel car flexifuel		improved fuel efficiency particulate filter DME option parallel hybrid option				
Diesel series hybrid			central motor particulate filter plug-in option		wheel motor reduced battery cost		
Petrol direct drivetrain	petrol car flexifuel		improved fuel efficiency parallel hybrid option hydrogen option				
Petrol series hybrid			central motor plug-in option		wheel motor reduced battery cost		
Electric car			central motor		wheel motor reduced battery cost	further reduced battery cost	
Fuel cell car					wheel motor hydrogen option petrol/diesel reformer option methanol/DME reformer option	reduced fuel cell cost	further reduced fuel cell cost
Bus	diesel bus			series hybrid option			
Truck	diesel truck						
Van	diesel van		parallel hybrid option	series hybrid option			hydrogen fuel cell option

Fuel Production	2000	2005	2010	2015	2020	2025	2030
Diesel Petrol	from crude oil in refinery						
FT diesel FT petrol		from coal at large scale	from biomass at medium scale		from biomass at large scale with CCS		
Methanol		from coal at large scale			from biomass at large scale with CCS		
DME			from coal at large scale		from biomass at large scale with CCS		
Hydrogen	from natural gas at large scale	from coal at large scale	from natural gas at small scale		from biomass at large scale with CCS		
Ethanol	from sugar cane	reduced cost from sugar cane	from cellulosic biomass	reduced cost from cellulosic biomass			

Table 5.1: Timeline of new technological options for fuel production and vehicles in our expanded MARKAL-NL-UU model.

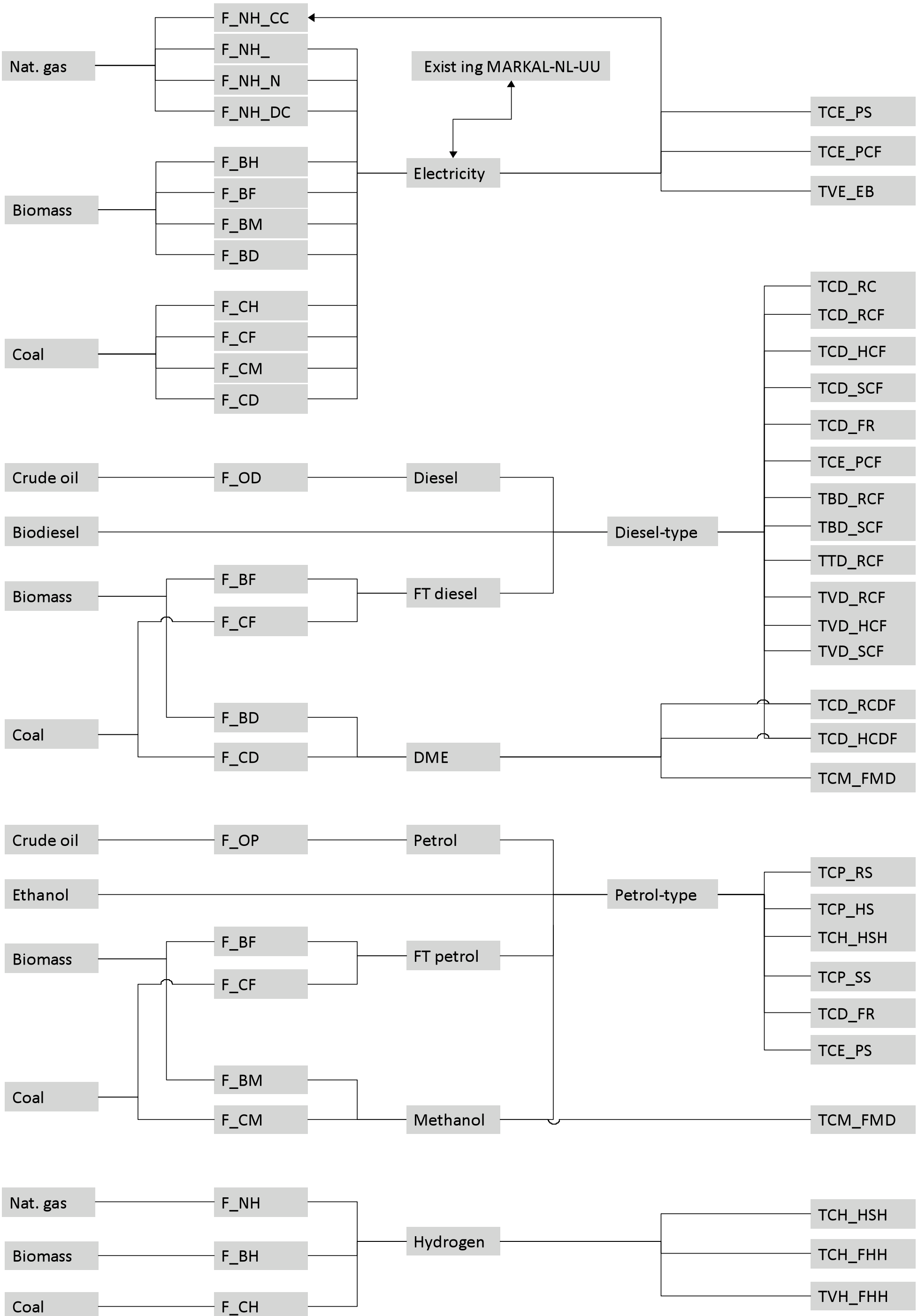
Technology family	Feedstock	Main product	Extras
F fuel	N natural gas	H hydrogen	CC centralised with capture
	B biomass	F Fischer-Tropsch	
	C coal	M methanol	DC decentralised with capture
	O crude oil (refinery)	D DME	
		P petrol	N decentralised without capture
		D diesel	

No extra indicates the conversion plant is a large, centralised facility that is not equipped to provide transport-ready captured CO_2.

Table 5.2a: Legend for fuel conversion technologies in figure 5.1.

Technology family		Primary fuel _	Drivetrain	Powerplant	Extras
T transportation	C car	D diesel-type	R regular drivetrain	C compression engine	F particulate filter
	B bus	P petrol-type	H parallel hybrid	S spark ignition engine	D extra DME tank
	T truck	H hydrogen	S series hybrid	B battery only	H (extra) hydrogen tank
	V van	E electric	P plug-in hybrid	H hydrogen fuel cell	
		M methanol	F fuel cell	M methanol reformer	
			E full electric	R Diesel/petrol reformer	

Table 5.2b: Legend for vehicle technologies in figure 5.1.



Note: Technologies distinguished only by use of CCS or years (development states of technology) are bundled if connections are identical.

Figure 5.2: Transportation technologies in our expanded MARKAL-NL-UU model.

5.3.1 Transportation demand

We use data from the Dutch statistics agency (CBS) to determine the past demand for transportation on buses, cars, trucks and vans [11]. We use other CBS data sets for the number of vehicles and total kilometres driven [341, 279, 280]. For future demand projections we use the Strong Europe[25] scenario, as defined in the Dutch 'Welvaart en Leefomgeving' study (WLO) [313, 16]. Demand data are summarised in table 5.3.

Transport demand	2000	2005	2010	2020	2030	2040*
Total distance (10^9 km/year)						
Cars	91	97	107	124	134	144
diesel	23	29	tbd	tbd	tbd	tbd
petrol	68	68	tbd	tbd	tbd	tbd
Buses	0.6	0.6	0.7	0.6	0.7	0.7
Trucks	6.8	6.8	8.0	9.0	9.7	10.3
Vans	15	18	20	20	23	27
Average distance per vehicle (10^3 km/vehicle/year)						
Cars	14	14	14	14	14	14
Buses	58	57	57	57	57	57
Trucks	48	48	47	47	47	47
Vans	22	20	21	21	21	21
Number of vehicles (10^3 vehicles)						
Cars	6343	6992	7607	8777	9504	10443
diesel	798	1069	tbd	tbd	tbd	tbd
petrol	5545	5922	tbd	tbd	tbd	tbd
Buses	11	11	12	11	11	12
Trucks	140	142	171	193	206	219
Vans	696	893	945	950	1101	1252
CO_2 emissions (10^6 kg/year)						
Cars	17338	18234	tbd	tbd	tbd	tbd
Buses	576	572	tbd	tbd	tbd	tbd
Trucks	6079	6179	tbd	tbd	tbd	tbd
Vans	3819	4662	tbd	tbd	tbd	tbd

Note: Based on the Strong Europe scenario [16]. CO_2 emissions from the Dutch National Statistics Agency (CBS) [11]. * WLO projects transportation growth of 30% of passengerkm and 40% of freightkm by 2040 vs 2002. Extrapolations arrived at a 42% growth in passengerkm and 39.4% growth in freightkm by 2030. With cars on the road projected to rise to 9.7 million, we reconcile by assuming a 2% decline in average distance per car. tbd: to be determined.

Table 5.3: Distance driven and number of vehicles on the road from 2005 to 2040

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[25] The Strong Europe scenario is characterised by high population growth, immigration mostly by family migrants, successful European integration, international trade coupled with environmental regulations, effective international environmental and climate policy, and solid public services

Designation	Characteristics	Available from year	Purchase & VAT (k€/vehicle)	Fuel consumption and emissions (fuel: km driven/GJ_{fuel})	
Regular cars					
TCP_RS_02	Regular petrol car	2002	20	petrol-type: 447	
TCP_RS_10	Regular petrol car	2010	21	petrol-type: 526	
TCD_RC_02	Regular diesel car	2002	22	diesel-type: 546	
TCD_RCF_10	with particulate filter (DPF)	2010	23	diesel-type: 566	
TCD_RCDF10	with DME tank and DPF	2010	24	diesel-type: 566	DME: 566
Hybrid cars					
TCD_HCF_10	Parallel hybrid	2010	29	diesel-type: 687	
TCD_HCDF10	Parallel hybrid with DME tank	2010	30	diesel-type: 687	DME: 687
TCP_HS_10	Parallel hybrid	2010	26	petrol-type: 663	
TCH_HSH_10	Parallel hybrid with hydrogen	2010	32	H2 CG: 673	petrol-type: 606
TCD_SCF_10	Series hybrid: central motor	2010	28	diesel-type: 862	
TCD_SCF_20	Series hybrid: wheel motor	2020	25	diesel-type: 997	
TCP_SS_10	Series hybrid: central motor	2010	26	petrol-type: 801	
TCP_SS_20	Series hybrid: wheel motor	2020	23	petrol-type: 927	
Fuel cell cars					
TCM_FMD_20	Fuel cell and methanol/DME	2020	86	methanol: 1269	DME: 1269
TCM_FMD_25	Fuel cell and methanol/DME	2025	59	methanol: 1269	DME: 1269
TCM_FMD_30	Fuel cell and methanol/DME	2030	33	methanol: 1269	DME: 1269
TCD_FR_20	Fuel cell and diesel/petrol	2020	86	diesel-type: 1148	petrol-type: 1148
TCD_FR_25	Fuel cell and diesel/petrol	2025	59	diesel-type: 1148	petrol-type: 1148
TCD_FR_30	Fuel cell and diesel/petrol	2030	33	diesel-type: 1148	petrol-type: 1148
TCH_FHH_20	Fuel cell and hydrogen tank	2020	81	H2 CG: 1662	
TCH_FHH_25	Fuel cell and hydrogen tank	2025	54	H2 CG: 1662	
TCH_FHH_30	Fuel cell and hydrogen tank	2030	28	H2 CG: 1662	

Plug-in hybrid and electric cars					
TCE_PS_10	Plug-in hybrid (50 km electric)	2010	32	electricity: 2325	petrol-type: 801
TCE_PS_20	Plug-in hybrid (50 km electric)	2020	28	electricity: 2692	petrol-type: 927
TCE_PCF_10	Plug-in hybrid (50 km electric)	2010	34	electricity: 2325	diesel-type: 862
TCE_PCF_20	Plug-in hybrid (50 km electric)	2020	30	electricity: 2692	diesel-type: 997
TCE_EB_10	Full electric (250 km)	2010	59	electricity: 2325	
TCE_EB_20	Full electric (250 km)	2020	47	electricity: 2692	
TCE_EB_25	Full electric (250 km)	2025	33	electricity: 2692	
Buses					
TBD_RCF_00	Regular diesel bus	2000	196	diesel-type: 70	
TBD_SCF_15	Series hybrid: wheel motor	2015	235	diesel-type: 183	
Truck					
TTD_RCF_00	Regular diesel truck	2000	n/a	diesel-type: 80	
Vans					
TVD_RCF_00	Regular diesel van	2000	22	diesel-type: 284	
TVD_HCF_10	Parallel hybrid diesel van	2010	29	diesel-type: 344	
TVD_SCF_15	Series hybrid: central motor	2015	29	diesel-type: 432	
TVH_FHH_30	Fuel cell and hydrogen tank	2020	35	H2 CG: 720	

Note: Truck purchasing cost varies widely and is not required because only one baseline diesel option is used. Sources: [45, 261, 178, 253, 252, 341, 11, 342]

Table 5.4: Costs, fuel consumption and emissions of vehicle technologies used in our model.

For vans, the share of kilometres driven by non-diesel vehicles dropped from 9% in 2000 to 4% in 2005. For buses and trucks, diesel vehicles made up 99% or more of the total. For simplicity, we therefore limit our investigations to diesel versions of heavy vehicles.

5.3.2 Car and heavy vehicles properties

Pursuant to Weiss et al. [101] and JRC [45], we use the same platform (chassis, interior and accessories) for our regular, hybrid, electric and fuel cell car configurations, exchanging only the drivetrain. Table 5.4 shows the vehicle properties in our dataset. Cars are assumed to have a 12 year lifespan and heavy vehicles a 15 year lifespan.

Because the modifications involved are minor [325], we assume flexifuel configurations for all vehicles with an international combustion engine (ICE), enabling them to run on mixtures of fuels with comparable properties. Petrol-type fuels include regular petrol and FT petrol, which can be blended in any ratio, and bio-ethanol and methanol. We assume ethanol can be used in petrol-driven cars in blends up to 85%. The required car modifications cost approximately €200 [325] and are already included in vehicle prices. Diesel-type fuels include regular diesel and FT diesel, which can be blended in any ratio, and biodiesel, which can be blended up to 99%. We also assume a diesel particulate filter on all new diesel-fuelled cars after 2005.

We use data for traditional cars and parallel hybrid cars from JRC [45]. Dual-fuel petrol/H2 and DME/diesel-type cars include an additional pressurised fuel tank (LPG cylinder for DME, 70 MPa cylinder for H2). Maintenance, repair and tires (MRT) costs of the five compact cars models used in our study average 41 €/1000 km for petrol and 42 €/1000km for diesel versions [178, 261].

For series hybrid, fuel cell and battery powered cars, we use the methodology and data set from Van Vliet et al. [261, 342]. Fuel consumption data for these cars has an error margin of 25%. For 2020, we assume the introduction of wheel motors and a cost reduction for batteries from 1000-1600 €/kWh in 2010 to 800 €/kWh. For electric cars we assume a minimum range of 250 km and a further reduction of battery costs to 400 €/kWh in 2025.

Direct hydrogen fuel cells are around 55% efficient [45]. We assume a cost reduction for fuel cell packs from 1200 €/kWe in 2020 to 660 €/kWe in 2025 and 110 €/kWe in 2030. Fuel cell cars can also be equipped with a reformer that converts any diesel-type or petrol-type fuels to hydrogen, or converts methanol or DME to hydrogen. Including reformer losses, fuel cells are assumed to be around 38% efficient on diesel/petrol and around 42% on methanol/DME. Reformer cost is set at 150 €/kWe [45].

For busses, we assume a large bus like the Mercedes Citaro or Berkhof Ambassador. We use the certified fuel consumption data published by Mercedes-Benz and e-Traction for regular diesel buses and series hybrid buses in an urban setting [253, 252].

For regular trucks and diesel vans, we use average fuel consumption and emission factors applied by the Dutch statistics agency [341, 11]. We aggregate semi-trailers with trucks because emissions are similar [11]. We assume that driving patterns are similar as well.

For vans, we consider regular ICE, parallel hybrid, series hybrid and fuel cell configurations. We assume the same relative fuel consumption benefits for hybridisation and fuel cells as for hybrid (18% reduction for parallel, 34% for series) and fuel cell cars (61% using hydrogen). We use an average of the purchase cost of five state-of-the-art diesel vans, assuming an engine close to 90 kW. As with cars, we only vary the drivetrain to determining purchase cost of hybrid vans. For parallel hybrid vans, a 17 kW motor and 7 kWh battery are added. For series hybrids or fuel cell vans, the engine is replaced by a 90 kW motor, and a 74kW generator or direct hydrogen fuel cell stack.

5.3.3 Production and distribution of synthetic fuels

We use the methodology and data set from Van Vliet et al. [250] to construct 19 configurations of centralised conversion plants. These include five plant configurations that produce Fischer-Tropsch (FT) synthetic diesel and petrol from coal (coal-to-liquids or CTL) or biomass intermediates (BTL). The B_FT_10 plant is dimensioned at 400 MW_{th} and the other 18 configurations of centralised plants are dimensioned at $2GW_{th}$. Based on the same methodology and data, we added six plant configurations that produce hydrogen from coal, biomass intermediates or natural gas, with or without CCS. Based on additional data from Hamelinck et al. [117] and Larson et al. [69], we add four plant configurations that produce methanol and four that produce DME. The synthetic fuel plants co-produce electricity and also intrinsically provide a low-cost stream of pure CO_2 that is readily transported off-site and stored (CCS) [250].

We also include two small scale (2MW) on-site natural gas reformer configurations, using data from Sjardin et al. [249], and two oil refining technologies as described in Van Vliet et al. [250]. Table 5.5 shows the conversion plant configurations used in this study. Electricity produced or consumed, and CO_2 sent to underground storage are integrated into the existing MARKAL-NL-UU model system. Applying CCS reduces the net output of electricity because electricity is needed to compress the CO_2 for transport.

The plants are expected to have a 35 year lifespan, and to be available 8000 hours per year (91% of time). Instead of gradually reducing the cost of the synthetic fuel conversion technologies over time, we introduce sets of more advanced conversion technologies, to reflect that fuel conversion plants are part of larger logistical chains which must be introduced interdependently. For example, upstream conversion of biomass to an intermediate must be coupled with to downstream conversion of that intermediate to FT fuel.

Designation	Feedstock	Outputs (fuel: GJ$_{out}$/GJ$_{in}$)	Investment (€/kW$_{in}$)	O&M (€/kW$_{in}$/yr)	Variable (€/GJ$_{in}$)	Emissions to air (kg CO$_2$/GJ$_{in}$)	to CCS
Fischer-Tropsch							
F_CF_05	bituminous coal	FT diesel: 0.438, electricity: 0.072, FT petrol: 0.078	668	30		56	0
F_CF_20_CC	bituminous coal	FT diesel: 0.438, electricity: 0.054, FT petrol: 0.078	685	30		7	49
F_BF_10	biomass intermed.	FT diesel: 0.429, electricity: 0.064, FT petrol: 0.076	933	40		69	0
F_BF_20	biomass intermed.	FT diesel: 0.425, electricity: 0.091, FT petrol: 0.076	646	29		55	0
F_BF_20_CC	biomass intermed.	FT diesel: 0.425, electricity: 0.074, FT petrol: 0.076	662	29		7	48
Hydrogen							
F_CH_05	bituminous coal	H2: 0.705, electricity: 0.036	550	25		92	0
F_CH_20_CC	bituminous coal	H2: 0.705, electricity: 0.004	579	26		1	91
F_BH_20	biomass intermed.	H2: 0.683, electricity: 0.048	600	27		90	0
F_BH_20_CC	biomass intermed.	H2: 0.683, electricity: 0.017	628	28		1	89
F_NH_00	natural gas	H2: 0.7, electricity: 0.037	452	21		53	0
F_NH_20_CC	natural gas	H2: 0.7, electricity: 0.019	472	21		2	51
F_NH_10_N	natural gas	H2: 0.737, : 0	554	362		56	0
F_NH_10_DC	natural gas	H2: 0.728, : 0	620	378		25	33
Methanol							
F_CM_05	bituminous coal	methanol: 0.558, electricity: 0.063	600	27		54	0
F_CM_20_CC	bituminous coal	methanol: 0.558, electricity: 0.046	617	27		7	47
F_BM_20	biomass intermed.	methanol: 0.54, electricity: 0.092	546	22		53	0
F_BM_20_CC	biomass intermed.	methanol: 0.54, electricity: 0.076	546	22		7	46
DME							
F_CD_10	bituminous coal	DME: 0.572, electricity: 0.072	606	27		54	0
F_CD_20_CC	bituminous coal	DME: 0.572, electricity: 0.054	642	28		7	47
F_BD_20	biomass intermed.	DME: 0.554, electricity: 0.095	560	23		53	0
F_BD_20_CC	biomass intermed.	DME: 0.554, electricity: 0.077	570	23		7	46
Oil refining							
F_OP_00	crude oil	petrol: 0.914			2.6	7	0
F_OD_00	crude oil	diesel: 0.897			2.6	8	0

Sources: [250, 249], and additional data from [117, 69].

Table 5.5: Inputs, outputs, costs and emissions of conversion technologies used in our model.

For distribution of liquid fuels, we use the same costs and energy consumption as for diesel and petrol (c.f. [45]). We encountered costs for distribution of petrol and diesel between 1.37 €/GJ [343, 344] and around 1.70 €/GJ [345], and we settle on 1.50 €/GJ excluding VAT (also used in [117] quoting [35]). Energy consumed in distribution is 0.0034 GJ$_e$/GJ$_{fuel}$ and 0.0132

GJ_{diesel}/GJ_{fuel} [45]. For distribution of DME, we use the same costs and energy consumption of 0.01 GJ_e/GJ_{fuel} and 0.02 GJ_{diesel}/GJ_{fuel}.

For distribution of hydrogen we use a cost of 3.2 €/GJ for transport by pipeline and 3.4 €/GJ for dispensing at the fuel station [256, 37]. Energy consumed in dispensing of H_2 (mostly for compression to 70 MPa) is set at 0.07 GJ_e/GJ_{H2} [45].

5.3.4 Supply of energy resources

We use prices of fossil energy resources as described in the WEO 2009 from 2015 to 2030 [5], and keep prices constant after 2030. We use the 450 ppm WEO 2009 scenario data unless noted otherwise because stringent CO_2 restrictions (in any form) are likely to reduce demand for fossil energy sources and cause lower prices [330]. For 2010, we use a coal price of 1.8 €/GJ, a natural gas price of 5.1 €/GJ, and an oil price of 80 $/bbl.

We also include direct emissions from burning energy resources and indirect GHG emissions for extraction, processing and transportation [45]. Indirect emissions from possible land-use change are outside the scope of this study and are not included. We assume that biomass feedstock is produced meeting relevant criteria for sustainability (see [20, 346]). Table 5.6 summarises the emission factors and energy resource prices used in this study.

Energy resource		Emissions ($kgCO_{2eq}/GJ$) direct*	indirect	Price (€/GJ) 2000	2005	2010	2020	2030	2040
Biodiesel			29	22	22	22	22	22	22
Biomass intermediates			5	7.2	7.0	6.8	6.8	6.8	6.8
Coal	reference	93	15	1.1	1.8	1.9	2.4	2.5	2.5
	450 ppm	93	15	1.1	1.8	1.9	1.8	1.5	1.5
Crude oil		76	3	4.9	7.9	9.8	11.0	11.0	11.0
Ethanol	sugar cane		22	22.3	18.4	13.0	13.0	13.0	13.0
	cellulosic		22			25.6	13.3	13.3	13.3
Natural gas		56	12	2.6	4.7	5.4	7.0	7.0	7.0

Source data: [45, 347, 348], 1G ethanol [349, 350, 63], 2G ethanol: [63, 116]. *Bio-based fuels are assumed to be carbon-neutral except for inputs in processing and transport

Table 5.6: Energy resource GHG emissions and prices used in our model.

At 80 $/bbl[26], fuel prices at the pump in the Netherlands are around 1.18 €/litre for diesel and 1.37 €/l for petrol (using [213]). This is equivalent to untaxed prices of 17.4 €/GJ for diesel and

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[26] We assume 41.87 MJ/kg and 820 kg/m^3 for crude oil [45], and average exchange rates of US$/€ of 0.80 in 2005 and 2006, 0.73 in 2007, 0.68 in 2008 and 0.72 in 2009 [120].

18.0 €/GJ for petrol at the refinery gate. Petrol and diesel prices include refining and a profit margin for producers but not distribution and marketing.

Conversion costs, efficiency and emissions of refineries used in this study are shown in table 5.5. We limit the ratio between diesel and petrol production, because refineries are bound by crude oil composition and installed processing facilities. Existing production of road transportation fuel by refineries in the Netherlands shifted from 51% diesel in 2000 to 63% diesel in 2008 [351]. We assume a maximum further 20% adjustment, limiting diesel to between 40% and 76% of refinery fuel product from crude oil.

5.3.5 Supply of biodiesel, ethanol, and lignocellulosic biomass

For biodiesel, we assume imports of a fatty acid methyl ester (FAME), produced either from rapeseed (as by product for animal feed) or sunflower. Production in 2008 in the EU-27 was estimated at 331 PJ, and consumption in the Netherlands at 8.5 PJ [259]. We use a conservative median production cost from the EU-15 of approximately 22 €/GJ biodiesel [348, c.f. 352]. Feasible production is capped at 300 PJ/year for the EU [45, 348], of which 3.2% or 9.6 PJ/year is allocated to the Netherlands on the basis of EU population share. We assume no imports of biodiesel from outside the EU.

For ethanol, we assume imports from Brazil, currently the largest producer of bio-ethanol. In addition, we base ethanol cost on the fermentation of sugar cane that is produced in a fair and equitable way. Fair production is assumed to costs 37% or 5 €/GJ more than the cheapest current production method [350] and uses 1.9 $GJ_{biomass\ (cane)}/GJ_{ethanol}$ [353, 45]. For cellulosic (2nd generation) ethanol, we assume the same cost increase for sustainable production, but using 1.3 $GJ_{biomass}/GJ_{ethanol}$ [353, 116].

To be conservative, we maintain current ethanol production costs for prices [63, 262, 349]. Cost reductions seem to have slowed [63] while at the same time showing potential to decrease by a further 30% by 2020 [262]. We assume that higher future oil prices would allow producers to produce more sustainably and/or raise profit margins while keeping ethanol competitive with other fuels.

For biomass pellets, we assume either compressed wood pellets or torrified and compressed wood pellets (TOPs). These can be used to (co-)fire electricity plants or converted to transportation fuels. Processing consumes 7% to 18% of raw biomass energy [250, 129], for an average of 1.13 GJ/GJ biomass intermediate. For prices of biomass intermediates, we use a price of 7 €/GJ in 2005 (derived from [347, 354]). This price allows cost margin for sustainable production of raw biomass (c.f. [355]). We assume this price to be constant for most of our scenario variants, but also tested the impact of prices rising to 10.5 €/GJ in 2050 and prices falling to production costs of approximately 4 €/GJ [250].

Table 5.6 shows biomass resource prices and table 5.7 shows the available biomass and biodiesel used in our study.

Biomass availability (PJ/year)	**2005**	**2010**	**2020**	**2030**	**2040**
Global generic biomass	9000	27000	66000	114000	181000
Allocated to the Netherlands		122	299	517	823
Allocation to Dutch power and biofuel production	(consumed) 63	104	256	443	705
Biodiesel in Europe	(produced) 133	300	300	300	300
Biodiesel allocated to the Netherlands	(consumed) 0	10	10	10	10

Sources: [73, 356, 357, 45, 348].

Table 5.7: Biomass availability in our model (PJ/year).

Based on the global biomass potential assessment study [73], 290 EJ is assumed to be available around in 2050. This represents an intermediate level biomass potential with medium yield improvements in agricultural technology, while excluding protected and degraded areas. We based the growth of biomass potential on an the average of a development with linear growth and one with a growth rate of 8% per year, so that the global biomass available for modern bioenergy use increases from 9 EJ in 2005[27] to 290 EJ in 2050.

We allocate part of this global biomass potential to the Netherlands by the average of two principles: the egalitarian fairness principle (i.e. equal biomass supply per capita) and the sovereignty principle (i.e. current share of national energy use in global energy use). Of the biomass available for Dutch consumption, we allocate 86% to the transport and power sectors [356].

5.3.6 Electricity generation sector

In MARKAL-NL-UU, a large number of electricity generation technologies are implemented, including power plants with CCS, nuclear power plants, and renewable electricity generation technologies. The large scale power plants operated in this model are either natural gas combined cycle power plants (NGCC), pulverised coal-fired power plants with possible co-firing of biomass (PC), integrated coal (and biomass) gasification power plants (IGCC), or gas-fired combined heat and power generation plants (CHP).

Cost and performance data for the electricity generation technologies in MARKAL-NL-UU come from a wide variety of sources and are enumerated in [316, 329]. We assume that IGCC and NGCC power plants have a lifespan of 40 years, PCs 50 years, and large scale CHP units 30 years.

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[27] In addition, around 39 EJ of traditional biomass (charcoal, wood, and manure for cooking and space heating) was used [358] .

In this study, we assume that the Dutch electricity demand will increase from 110 TWh in 2005 to 175 TWh in 2050. This is in line with the electricity demand growth in the Strong Europe scenario used by the Dutch planning agencies [311].

Three other assumptions concern the deployment of a few specific power plant types and export of electricity. First, in MARKAL-NL-UU, a bound is set to phase out 450MW of existing nuclear power in 2033 [359]. Secondly, three planned pulverised coal-fired power plants with a total capacity of 3.4 GW are built before 2015. Thirdly, instead of importing electricity (i.e. 18 TWh in 2005) electricity may be exported from 2010 to 2020. From 2020, no electricity export is allowed in the model in order to keep the analysis focussed on the Dutch electricity market.

Regarding electric vehicles, the timing of recharging such vehicles may influence the required capacity of electricity generation and the distribution grid. In the MARKAL-NL-UU model, electricity production is divided into six intervals: day, evening and night, for summer and for winter. We assume that 50% of recharging takes place at night (between 23:00 and 7:00), and 50% during the rest of the day, irrespective of the season.

5.3.7 CO_2 capture, transport and storage

In MARKAL-NL-UU CO_2 capture units are implemented for industrial processes generating medium-sized quantities of pure CO_2 (e.g. hydrogen, ammonia, or ethylene oxide production units) or large quantities at a single site (e.g. steel industry, refineries, or ethylene production units). Cost and performance data of these units are described in Damen et al. [118].

The CO_2 storage reservoir inventory in our model is based on data compiled by [360, 361, 362, 363, 364]. It results in a selection of 123 CO_2 hydrocarbon fields and aquifers which are considered suitable for CO_2 storage (e.g. deeper than 800 meters, reservoir rocks with porosity more than 10%) with a total estimated CO_2 storage capacity of 1.2 $GtCO_2$ onshore and 1.1 $GtCO_2$ offshore [329][28]. Furthermore, we assume that the large aquifer in the Utsira formation in the Norwegian part of the North Sea with an estimated capacity of 42 $GtCO_2$ [366] can become available for storage of Dutch CO_2.

Based on several sources, we estimate average CO_2 storage costs for onshore and offshore storage in the hydrocarbon fields and aquifers (see table 5.8). We also distinguish between costs for CO_2 storage when facilities of the gas production activities can be re-used, and when this is not the case (i.e. if there is a gap of more than 5 years between gas production and CO_2 storage activities). Average CO_2 transport costs to onshore sinks, offshore sinks, or the Utsira formation are derived from [329], a study which specifically investigated the development of the CO_2 infrastructure (see table 5.8).

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[28] The Slochteren field in Groningen with an estimated capacity of about 7 Gt is not included in the inventory, because it is probably unavailable for CO_2 storage before 2050 [365].

CO_2 transport and storage	**investment (M€ per Mt/yr)**	**Fixed O&M (M€ per Mt/yr)**	**Lifetime (years)**	**CO_2 storage capacity (Gt)**
Transport[a]				
to fields offshore	31	0.9	40	
to fields onshore	20	0.6	40	
to the Norwegian Utsira field	42	1.5	40	
Storage[b]				
aquifers offshore	196	9.6	21	0.0
aquifers onshore	83	3.8	28	0.0
depleted gas fields offshore	32	1.4	19	1.0
depleted gas fields offshore without re-use	111	5.3	19	
depleted gas fields onshore	11	0.4	22	1.2
depleted gas fields onshore without re-use	23	1.0	22	
Norway, Utsira field, off-shore	18	0.9	25	42

[a] Van den Broek et al. [329] modelled each pipeline separately. CO_2 transport costs were assumed to be proportional to meter length and per meter diameter of the pipeline as suggested by [367, 368] and varied between 1300 and 4300 €/m_l/m_d for a specific location depending on the land-use type, and whether there was an existing hydrocarbon pipeline corridor or not. In this study, we assume pipelines with average CO_2 transport costs derived from the CO_2 infrastructure study [329]. [b] Unit cost estimates of setting up and maintaining CO_2 storage facilities (e.g. costs for site exploration and development, an offshore platform, drilling costs per meter) are based on several sources [369, 370, 371, 372, 373]. Based on these unit costs and the characteristics of the individual sinks (e.g. depth, location), we estimate average costs for the different CO_2 storage categories.

Table 5.8: CO_2 transport and storage costs used in our model

5.4 Scenario variants

Our scenario is a modified version of the Strong Europe scenario, as defined in the WLO [313, 311, 16]. Our 'No limits' scenario variant uses the WLO narrative, but has no targets for CO_2 emissions reductions. Building on our No limits variant, we prepare an additional eight scenario variants with various degrees of reduction commitments and options, as shown in table 5.9.

Variant name	**Notable properties**
1. No limits	No CO_2 emissions cap, no CO_2 transport to and storage in the Utsira field, use WEO 2009 reference prices for coal, and WEO 2009 450 ppm prices for other fossil energy sources.
2. Aggregate reduction	*No limits* + CO_2 emissions cap of 80% vs. 1990 levels in 2020, dropping to 20% in 2050, applied to the total of emissions of power generation and transportation, use WEO 2009 450 ppm prices for all fossil energy sources.
3. Sectoral reduction	*No limits* + CO_2 emissions cap of 80% vs. 1990 levels in 2020, dropping to 20% in 2050, applied separately to transportation and to power generation, use WEO 2009 450 ppm prices for all fossil energy sources.
4. 95 gCO_2/km in 2020	*Aggregate reduction* + Require average car fleet to emit ≤ 116 g CO_2 / km in 2020 and ≤ 95 g CO_2 /km from 2030, simulating regulation EC/2009/443[*].
5. Forced electric car	*Aggregate reduction* + minimum 25% market share for electric cars in 2020, rising to 90% in 2050.
6. Forced fuel cell car	*Aggregate reduction* + minimum 25% market share for fuel cell cars in 2020, rising to 90% in 2050.
7. Utsira	*Aggregate reduction* + Allow CO_2 transport to and storage in the Utsira field, giving effectively unlimited capacity for CO_2 storage.
8. Halved biomass	*Aggregate reduction* + available biomass is reduced by half over the entire model timeframe.
9. Cheaper oil	*Aggregate reduction* + price of oil reduced to 9.4 €/GJ in 2020 and 8.0 €/GJ in 2030 and later.

[*] We use a delay to account for vehicle lifespan, because the EU regulation requires that *new* cars emit ≤ 95 g CO_2/km in 2020.

Table 5.9: Nine scenario variants used in our study.

Our scenario variants focus on the transport sector, but we also examine the effect on production of electricity and heat. Table 5.10 shows some of the bounds used in our scenario variants. A cap is set on the CO_2 emissions to reduce these by 27% in 2020 and 87% in 2050 compared to 1990 level. This cap is in line with targets of 20% and 80%, because we assume that relatively more CO_2 emission reduction is realised in the CO_2 intensive industry than in other sectors (of the 27 Mt of industrial emissions, around 11-22 $MtCO_2$ may be captured and stored per year). The equivalent CO_2 emissions reduction targets are 50% in 2030 and 68% in 2040.

Our reduction scenario variants are compatible with the EU 20/20/20 strategy for 2020 [319]. The Forced electric car and fuel cell variants are meant to illustrate the effect of forcing a transition to these cars and fuels.

MARKAL bound	**1990**	**2005**	**2010**	**2020**	**2030**	**2040**
CO_2 emissions power + transport (Mtonne/year)	93	-	-	68	35	21
CO_2 emissions transport (Mtonne/year)	21	-	-	17	10	7
Average car emissions (gCO_2/km)	n/a	n/a	n/a	116	95	95
Forced share of electric / fuel cell cars	0%	0%	0%	25%	50%	75%

Table 5.10: Emissions limits and minimum vehicle shares in the Netherlands in our scenario variants.

5.5 Results

MARKAL models generate solutions with the least net present value of total system cost within the scenario bounds. Our model runs up to 2050 for purposes of optimisation, but in this chapter, we show results up to 2040. Due to high investment costs of low- or zero emission cars, a shift in fuels is the cheapest option to realise direct CO_2 emissions reductions in transportation. However, the potential for this shift is limited by energy resource constraints.

5.5.1 Energy sources

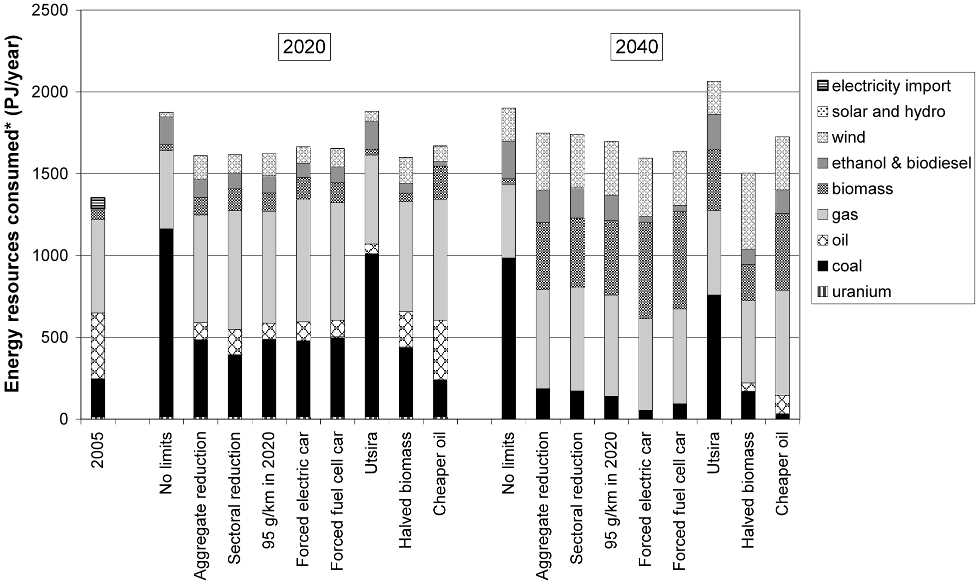
Figure 5.2 shows the combined primary energy consumption for road transport, electricity and heat generation in the Netherlands in 2020 and 2040. These sectors consume around half of the total Dutch primary energy.

The No limits variant shows almost a quintupling of coal consumption. This is caused by PC electricity generation, which more than doubles, and by crude oil-based diesel and petrol being replaced by coal-based FT fuels.

In the reduction scenario variants there is a preference for co-firing biomass in electricity plants combined with coal-based FT fuel production with CCS if sufficient CO_2 storage capacity is available (Utsira variant). If CO_2 storage capacity is limited, a combination of wind electricity and biomass-based FT fuel production with CCS turns out to be the cheapest option. Generation of wind electricity is complemented by NGCC, as wind electricity is an intermittent source. The overall shift can be explained by the very low additional costs for CCS with FT fuel production.

The use of biomass is consistent across reduction scenario variants. While the shares of biomass converted to ethanol, FT fuel and electricity shifts with the exact scenario variant, all available biomass is used in our optimisations. Further analysis shows that if a nuclear option is introduced, wind and natural gas are partially replaced by nuclear power. Adoption of electric cars does not lead to an increase in electricity generation capacity, because most of the charging in our model takes place in off-peak times of the day.

In all reduction scenario variants, no PC plants are built with CCS, but 30%-45% of PC plants are later retrofitted with CCS. IGCC is used only in the Utsira variant, where ample CO_2 storage capacity is available.



*1 PJ electricity generated by wind, solar or hydro = 1 PJ in this graph.

Figure 5.2: Energy resources consumed (PJ/year) in transportation, electricity and heat generation in the Netherlands in our scenario variants in 2020 (left) and 2040 (right).

The share of renewables in total energy resources is larger than 20% in 2020 in all of the reduction scenario variants, except the Utsira variant. In the reduction scenario variants, FT fuel plants co-produce 11-21 PJ of base load electricity, or 2%-4% of total electricity.

5.5.2 Fuels and vehicles

Figure 5.3 shows the transportation fuels consumed in our scenario variants in 2020 and 2040. In all scenario variants except the Cheap oil variant, we observe a shift to imported ethanol and FT diesel from regular diesel and petrol derived from oil. By 2020, the cheapest overall transportation system uses less than 50% crude oil derived fuel, and after 2030, oil is not used at all for transportation. This shift is entirely due to the projected oil price of 10€/GJ (90 $/bbl), because oil refining costs have a very limited share of the total cost of diesel and petrol. The partial shift in 2020 is due to limited availability of biomass, except in the No limits variant, where FT fuel is produced entirely from coal.

In the Cheap oil variant, oil retains a significant market share combined with FT fuel made from biomass with CCS to reduce CO_2 emissions. In this variant, biomass is used for electricity generation instead of producing fuels.

Diesel, biodiesel and FT diesel are used in buses, trucks and vans, which together account for almost half of the total fuel consumed. Bio-ethanol is the preferred fuel for cars. Substituted bio-ethanol in 2020 is between 50-170 PJ/year, which would require between 2400-8000 km^2 (at an average yield of 212 GJ$_{ethanol}$/ha/year for cellulosic ethanol)[29]. Cellulosic ethanol is used exclusively in the 2020-2030 timeframe, as it has higher yield per available amount of biomass. However, we also observe a switch back to sugar cane ethanol in later years as the availability of biomass increases. This is because of competition in the model between sugar cane and cellulosic ethanol, with lower cost for sugar cane and more efficient production for cellulosic ethanol. In reality, these ethanol production technologies not interchangeable, as feedstocks for cellulosic ethanol can be grown on a wider range of soil types and climates.

Substituted FT production capacity in 2020 ranges up to 288 PJ/year, replacing up to 160 000 bbl of crude oil per day. In the No limits variant, FT fuel is entirely produced from coal without CCS. In all reduction scenario variants, FT fuel is produced from a varying mix of coal and biomass, with full use of CCS. Methanol and DME did not appear in any of our least-cost configurations.

Total secondary energy used in cars in the Forced electric car variant declines, because the energy efficiency of electric vehicles is higher than of regular cars. However, conversion efficiency of producing electricity in a power plant is lower than the efficiency of oil refining or FT production. The resulting total primary energy consumption is still lower in the Forced electric car variant (compare figure 5.2 to figure 5.3 or 5.4). The same applies *mutatis mutandis* to the Forced fuel cell car variant. This is a shift of energy losses, and related CO_2 emissions, from car drivers to fuel producers, which allows for larger volumes of CCS.

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[29] Compare to a total land area of the Netherlands of 41500 km^2

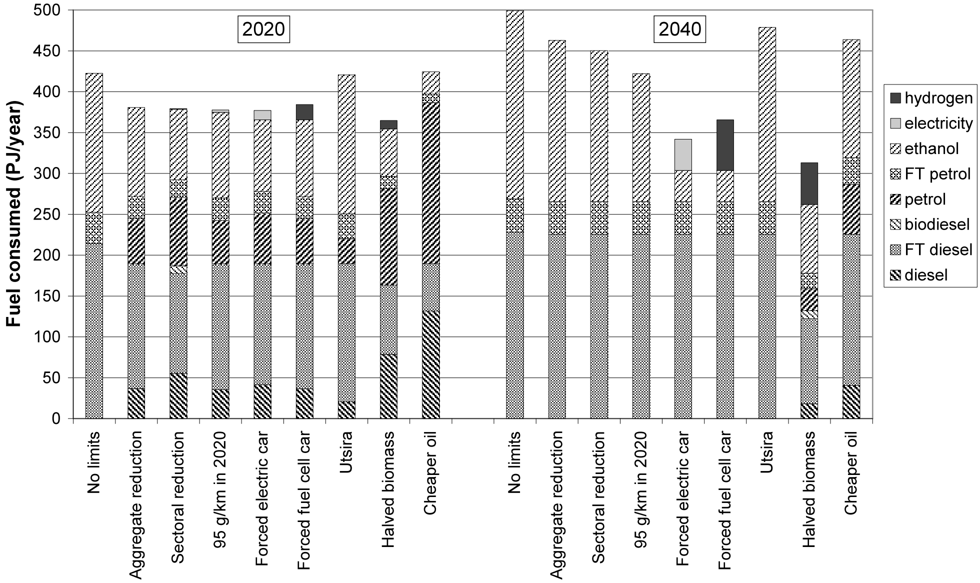


Figure 5.3: Transportation fuels consumed(PJ/year) in the Netherlands in our scenario variants in 2020 (left) and 2040 (right).

Figure 5.4 shows the same total fuel consumption as figure 5.3 by vehicle type. Busses and hybrid vans have such a small share in total fuel consumption that we omitted them from figure 5.4.

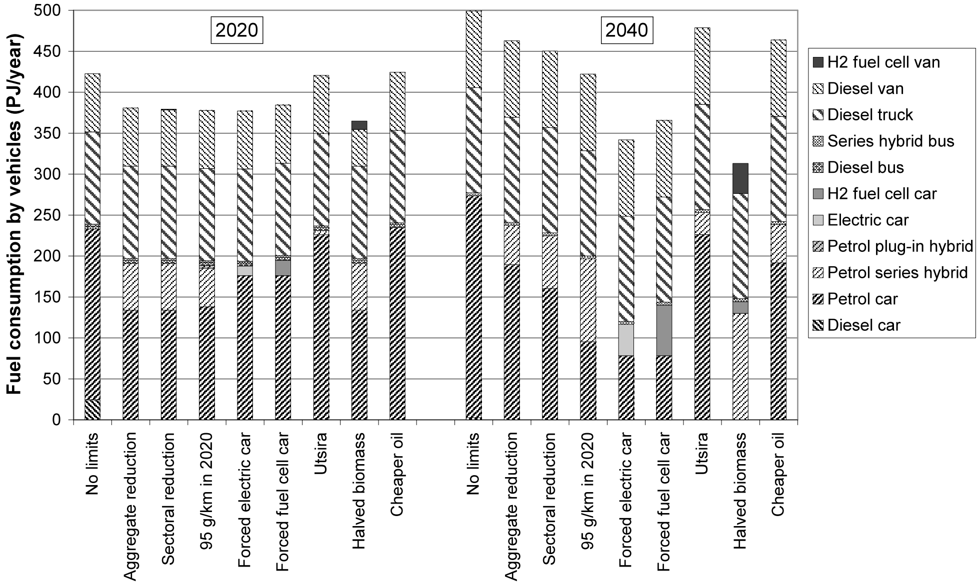


Figure 5.4: Transportation fuel consumed by vehicles (PJ/year) in the Netherlands in our scenario variants in 2020 (left) and 2040 (right).

Figure 5.4 indicates that our model avoids hybrid, electric or fuel cell vehicles, because of the high investment cost of alternative drivetrains. Diesel cars also disappear in all reduction scenario variants due to higher cost of diesel, FT diesel, biodiesel and diesel-fuelled cars compared to petrol, FT petrol, ethanol and petrol-fuelled cars.

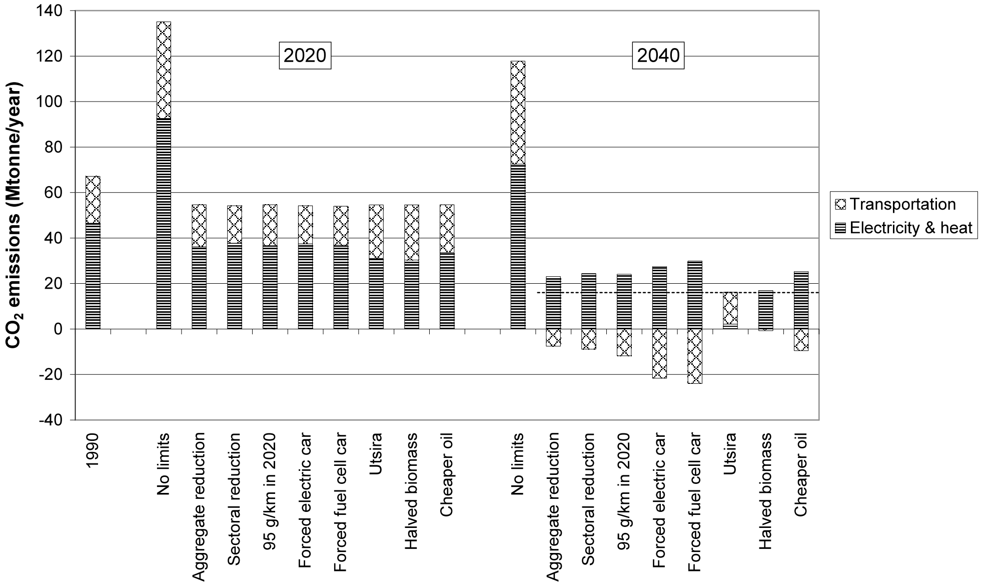
Series hybrid cars are used as the most cost-effective option to reduce fuel demand when not enough low-emission fuel options (biofuels and/or CCS capacity) are available to stay within the CO_2 emissions budget while using regular cars. We tested this further by increasing the relative price of ethanol versus biomass intermediates drives, in which case adoption of hybrid cars increases because the model seeks to accommodate the petrol-fuelled fleet with less biomass resources. In the 95 gCO_2/km in 2020 variant, average vehicle efficiency is improved by more than 20% in 2020, which complements the EU 20/20/20 strategy.

Unless fuel cell cars are forced in, emergence of hydrogen as a transportation fuel in our model is primarily due to hydrogen-powered vans. This is because vans, like many fleet vehicles, are driven large distances compared to private passenger cars. Fuel costs therefore account for a larger share of total driving costs in vans than for regular cars, and vans are therefore switched before cars.

5.5.3 CO_2 emissions

Figure 5.5 shows that direct CO_2 emissions in transportation and electricity production in the No limits variant increase by 100% in 2020 over 1990 levels, mostly due to the increase in consumption of coal. CO_2 emissions in the No Limits variant decline after 2020, as do emissions in reduction scenario variants.

Direct CO_2 emissions of transportation are reduced almost to zero or negative in most of our reduction scenario variants. This is a result of biomass-based FT fuel or hydrogen production with CCS, which has net negative CO_2 emissions, combined with bio-ethanol which has very low emissions.



Note: The dotted line denotes the emissions cap level for 2040 in our scenario variants.

Figure 5.5: Direct CO_2 emissions (Mtonne/year) by sector in the Netherlands in our scenario variants in 2020 (left) and 2040 (right).

Indirect emissions of GHG, due to mining of coal, recovery of oil and gas, and farming, were limited to around 10% of total emissions in 2005. Figure 5.6 show that indirect GHG emissions both increase in absolute terms and take a lager share in the total emissions. Indirect GHG emissions are 34%-54% of total emissions caused by the Netherlands in 2040. These indirect emissions are attributed to the countries that produce the energy resources.

The increase is caused primarily by the use of coal and ethanol, which substitute crude oil-derived fuels that have much lower indirect emissions (see table 5.6). Indirect emissions are lowest in variants with low average fuel consumption of vehicles.

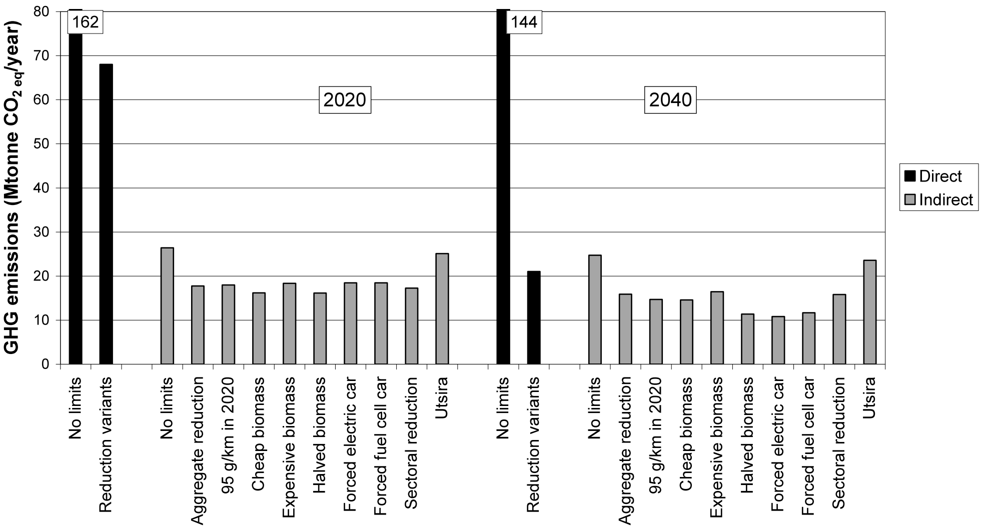


Figure 5.6: Indirect GHG emissions (Mtonne $CO_{2\ equivalent}$/year) in the Netherlands in our scenario variants in 2020 (left) and 2040 (right), compared with direct CO_2 emissions.

The amount of CO_2 stored underground varies with the optimal timing of large scale use of CCS. Figure 5.7 shows that use of offshore storage sites is postponed unless sufficient storage potential is available.

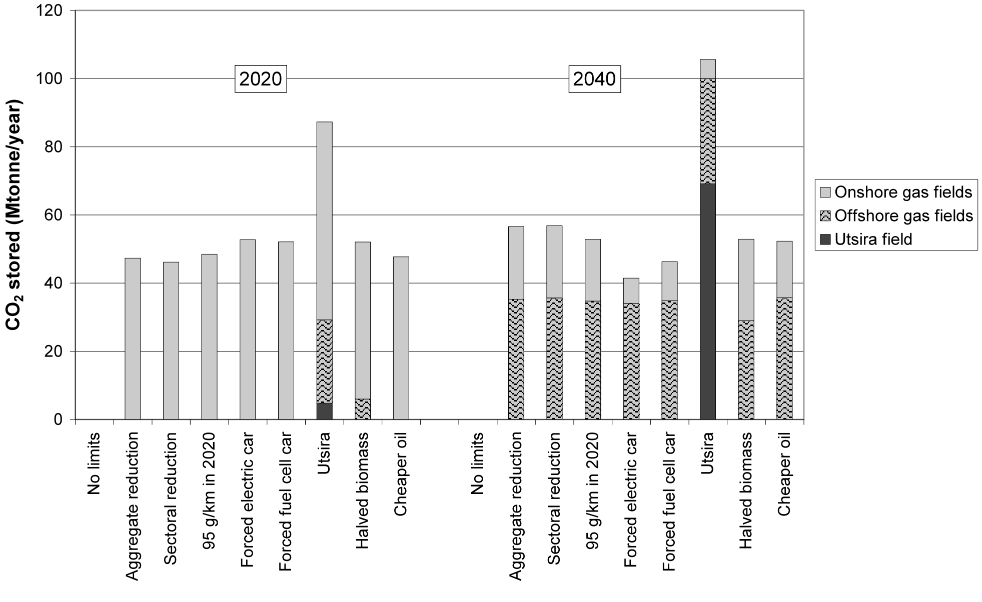
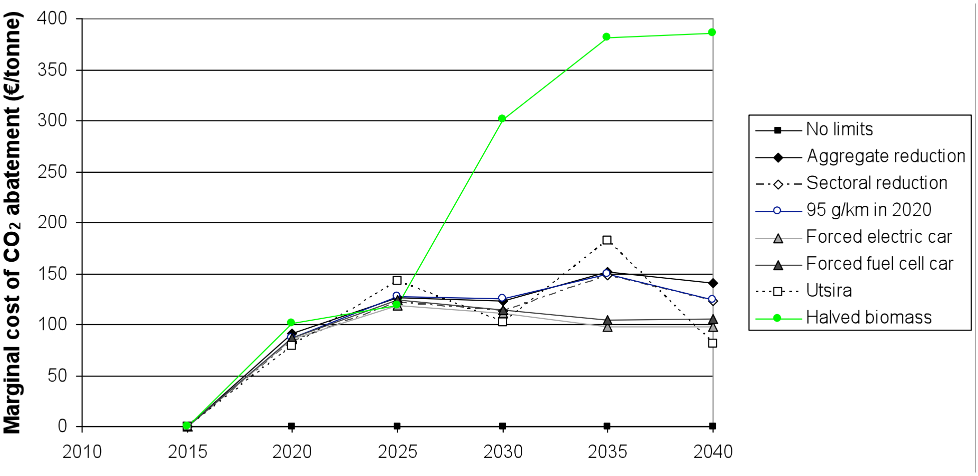


Figure 5.7: CO_2 stored in underground formations (Mtonne/year) in the Netherlands in our scenario variants in 2020 (left) and 2040 (right).

5.5.4 Costs and investment

Figure 5.8 shows the marginal CO_2 abatement costs. As the CO_2 emissions reduction target exceeds 30%, marginal cost of abatement are 100-150 €/tonne CO_2 across our reduction scenario variants, as long as the supply of biomass expands at a sufficient rate. A shortfall of biomass (without having the Utsira field available for CCS) more than doubles abatement costs because more expensive vehicles must be used to attain CO_2 limits.

Due to the nature of linear programming optimisation, the marginal abatement costs in figure 5.8 do not include the costs of the electric and fuel cell cars in their respective Forced car scenario variants. The marginal costs for these scenario variants would be around 400 €/tonne if electric and fuel cell vehicles were included, as demonstrated by the marginal costs in the Halved biomass variant after 2040 (where hydrogen fuel cell cars are the marginal reduction option).



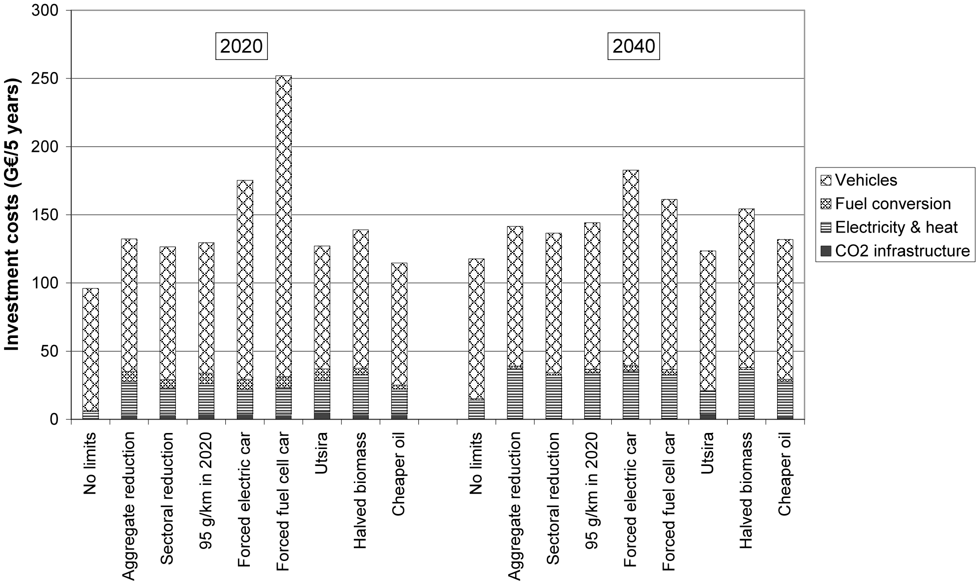
Note: Marginal abatement costs for the Forced electric car and Forced fuel cell car variants do <u>not</u> include additional cost for electric or fuel cell cars, as these are included in the solution before marginal abatement technologies are calculated.

Figure 5.8: Marginal abatement costs of CO_2 emissions in the Netherlands in our scenario variants.

With figure 5.8 in mind, we optimised the same system using a carbon tax instead of an emissions reduction target. Two carbon tax development paths were used; one rising from 46 €/tonne CO_2 in 2020 to 73 €/tonne in 2040, and another rising exponentially from 23 €/tonne in 2020 to 201 €/tonne in 2040.

Optimisations using a rising carbon tax instead of a CO_2 emissions cap show less CO_2 emissions reductions around 2020, but this difference disappears by 2040. A switch in transportation fuel is again the preferred reduction strategy, using ethanol and FT fuel from coal, with an extreme preference for FT fuel from biomass by 2040 if the carbon tax rises exponentially.

Figure 5.9 shows total investment into the development of the Dutch transport and power sectors until 2040. These costs do not include opportunity costs and port facilities.



Note: These costs are not annualised over the life time of technologies, and vehicle investment does not include purchase of trucks.

Figure 5.9: Five-year total undiscounted investment costs (G€) in transport and power sectors in the Netherlands in our scenario variants in 2020 (left) and 2040 (right).

The investment to develop the Dutch transport and power sectors ranges upwards from 19 billion euro per year. More than 80% of the investments are for periodic replacement of vehicles, which already occurs today and is done by consumers. This is in line with results from other studies (e.g. WEO 2009 [5]). In most scenario variants, vehicle replacement in the Netherlands costs 18-21 billion euro per year. The exceptions are the Forced electric car and Forced fuel cell car variants, where investments into cars are 25-45 billion euro per year.

Investment into electricity generation in the No Limits variant compared to the reduction scenario variants is higher in 2015, then lower until 2030 and also lower in total. Investment into electricity generation capacity is the lowest in the No Limit and Utsira variants where coal-fired power plants can be used. In the other variants, more expensive and variable wind electricity is used. This intermittent wind electricity is complemented by electricity from NGCC, which increases the effective cost of wind electricity.

Not including the forced car variants, total investment into transport and power sectors until 2040 ranges between 19 to 31 billion euro per year, or 3.1%-4.5% of Dutch GDP[30] as projected in the WLO Strong Europe scenario [313]. At least 19 billion euro per year of this will be invested in any year in any scenario variant, and over 90% of that is for replacing cars that reach end of life. The difference between the No limits and the other non-forced car reduction variants is 4-7 billion euro per year, equivalent to 0.5%-1.2% of GDP. This is mostly invested in cars and electricity generation capacity.

Higher investment can have both positive and negative effects on economic development (see also [330]) However, we did not calculate possible externalities, economic spinoffs or indirect effects resulting from the changes in the transportation and power sectors.

5.6 Discussion

Modelling inevitably requires assumptions and imperfect data. We discuss the impact of some important assumptions below.

5.6.1 Modelling approach

We deliberately do not put a limit to the construction rate of conversion capacity in our model, choosing instead to show the optimal configuration. In reality, design difficulties, financing requirements, planning produces, construction delays, dependence on infrastructure such as port facilities, vested interests, and other factors constrain the speed at which existing cars and fuels can be substituted, and infrastructure built. The large number of FT plants, high share of ethanol, high uptake of CCS and complete switch away from crude oil that we found may therefore be restricted by many other factors in the real world.

In addition, consumers, producers and regulators may have other criteria to choose fuels and cars, such as impact on air quality, system flexibility, diversification of energy sources, technical familiarity, and/or aesthetics, none of which are taken into account in our model.

Heterogeneity in important markets is also not taken into account in our model. For example, we use one average distance per car per year. However, company-owned cars drive 45%-75% more km per year than privately-owned cars [280]. This can affect the trade-off between higher investment for a new car versus lower fuel consumption and lower fuel costs. We expect a market to exist for more expensive cars with lower per km fuel costs similar to the vans in our analysis. Defining subsets of demand based on driving habits may therefore result in a better estimate of future shares of vehicles types.

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[30] Dutch GDP is projected to grow by around 2.4% per year in the WLO Strong Europe scenario to around 614 billion € in 2020 and 780 nillion € in 2040. All numbers relative to GDP use the GDP of the year for which they are calculated.

Demand for electricity and transportation used in this study is exogenous, but higher electricity or transportation prices may encourage more efficient behaviour and technology development. It would therefore be preferable to expand our optimisation with demand functions. For electricity, this would incorporate the trade-off between cleaner production of electricity and more efficient end-use. For transportation, this would incorporate the trade-off between driving cars and other mobility services (modal shift).

5.6.2 Energy resources

Projections of future energy prices vary considerably. For example, prices of coal, oil and natural gas vary over 50% in some cases between the World Energy Outlook editions of 2009, 2008 and 2007 [5, 3, 4]. However, many alternatives to conventional crude oil become attractive with crude oil prices ranging between 60 and 100 $/bbl [250, 184]. Furthermore, increased market share of these alternatives would dampen a sustained upwards movement of oil prices.

Crude oil cost represents more than 80% of the cost of petrol and diesel [250]. By contrast, the cost of biomass or coal feedstock is 35%-55% of FT fuel cost [250], and biomass cost is 45%-55% of ethanol cost [262]. Petrol and diesel production is therefore much more vulnerable to feedstock price shifts. Optimising the transport system is therefore most sensitive to oil prices.

Fossil and biomass resource prices used in this study are exogenous, but if oil is largely abandoned, oil prices may fall and prices of alternative energy resources are expected to rise (also depending on tax regimes). We accounted for this in the Cheap oil variant. We use oil prices from the WEO 2009 450 ppm scenario in other reduction scenario variants, which take into account a large drop in oil demand but not the complete switch away from crude oil that we observe. This indicates that in each of our variants, either oil price is unrealistically high or oil consumption is unrealistically low. However, a switch away from oil is found across variants.

It may therefore be preferable to use dynamic energy resource prices based on demand, available stocks and production capacity, e.g. by using supply curves or price elasticities. However, including dynamics in energy resource supply and prices is difficult, because supply projections for biomass have a wide range and uncertainty [374, 352], and the sizes of remaining stocks of fossil resources are highly contentious [375]. For example, Hoefnagels et al. [356], investigated scenarios in which biomass use in the Netherlands in 2030 varies between 150 and 1450 PJ per year.

Investigating the robustness of our results, we find that in optimisations with the price of biomass intermediates rising to 10 €/GJ, demand is equal to the potential supply, indicating that supply volume is more important than price as long as oil prices remain high.

5.6.3 Technological progress and technology cost

The timing of the introduction of more efficient and cheaper technologies in our model expansion is optimistic (see table 5.1) and complements our choice not to put restrictions on speed of construction of new electricity and fuel production plants. In the event, the technologies adopted in our scenario variants do not hinge on the early availability of advanced technologies. For (cellulosic) ethanol, the same saturation of supply is found as for other biomass applications, and the same insensitivity to prices applies.

For fuel cells, cost reductions will depend in part on future production volumes. However, expansion of existing production depends on adoption, which is hindered by current high costs. In case of forced adoption of fuel cell cars, we project investment into cars to double in some of the five year periods. However, doubling the price of cars is unlikely to meet with public enthusiasm. We therefore do not expect hydrogen fuel cell cars to be demanded in appreciable volume, and thus expect fuel cell vehicles to be less economically attractive than in our data set. As our model must be forced into adopting fuel cell cars even in 2040, when we assume fuel cell costs are reduced tenfold from today, our findings are insensitive to the timing of progress in fuel cells. The same rationale applies to a lesser degree to electric cars, as hybrid cars provide a channel for cost reductions of batteries.

Adoption of electric cars does not lead to significant change in electricity generation capacity. As the MARKAL-NL-UU model divides electricity demand and production into six intervals (day, evening and night in both summer and winter), we could not analyse the effect of timing of charging of electric cars in detail. We did not analyse the effect of smart charging systems on load patterns or the mix of electricity production. We recommend more detailed analysis of the impact of charging patterns of large numbers of electric vehicles on electricity demand and resulting cost and CO_2 emissions.

5.6.4 Generalising our results

We describe a case study optimising the Dutch transportation and power sectors. To generalise the results beyond the Dutch situation, we consider that the available technologies and energy resources prices should be roughly the same for industrialised countries. However, the existing (vintage) car fleet, fuel production and electricity generation capacity and structure of demand for fuel and transportation would create country-specific dynamics, particularly in the short term.

Eventually, the existing vehicle fleets, fuel production and electricity generation plants will be replaced anyway, thus reducing their impact on long term optimisations. Assuming that biomass availability increases due to increasing global biomass trade, the major remaining differences between industrialised countries would be the long term potential for wind energy and underground carbon storage capacity, and presence of long-lived facilities like nuclear reactors and large hydroelectric dams.

Other differences between countries, like population density, infrastructure, legislation and public policy are not part of the MARKAL-NL-UU model. We recommend further investigation into these aspects using other methods.

However, in our scenario variants, biomass, CCS, wind with NGCC, hydro and nuclear power capacity were found to be largely interchangeable for production of base load electricity with CO_2 emissions reduction targets. We therefore conclude that our results can be generalised to a large extent for the transportation sector in industrialised countries, and most likely also for the interaction between the transportation and power sectors.

Across scenarios, time periods and reduction targets, our least-cost optimal configurations show a preference for biofuels and hybrid cars over electric or fuel cell cars. In addition to having lower costs, this allows for an easier transition as less infrastructure change is required to support hybrid cars than to facilitate large scale use of electric or hydrogen fuel cell cars (c.f. [24]).

Furthermore, there is little difference between the Aggregated reduction, Sectoral reduction and 95 gCO_2/km in 2020 scenario variants. This suggests that (combinations of) policy approaches that emphasize different aspects of CO_2 emissions reductions, such as technology support, carbon taxes and efficiency targets, could arrive at the same future transportation and power system.

Future feasibility studies should take into account competition for CCS storage and biomass availability. For CCS, the focus of earlier studies has been on its application in electricity, but fuel production may have a large impact on the amount of CO_2 stored per year. For biomass, available supply in countries and allocation between transportation and power sectors has a large impact on CO_2 abatement costs.

5.7 Summary and conclusions

We examined future interactions between the transport and power sectors in the Netherlands using the MARKAL-NL-UU model. We simultaneously examined competition for energy resources, development of CCS, and co-evolution of electricity and fuel conversion capacity.

The existing model data set is expanded with 36 types of cars, buses, trucks and vans that can use 9 different fuels produced with 23 fuel conversion technologies. New fuel conversion technologies are introduced up to 2020 and new vehicle technologies up to 2030. Our model optimises total system cost over a long time horizon, without constraints on construction of new power plants and fuel conversion plants. Transportation and power demand, availability of technologies over time, as well as supply and price of energy resources are included exogenously. Our scenario is based on the WLO, using WEO 2009 energy prices. We create nine scenario variants, including one without emissions reductions, and two with forced market share of electric and fuel cell cars, respectively.

Use of oil decreases considerably in all scenario variants. Our No limits variant shows almost a quintupling of coal consumption due to increased use of coal in electricity generation and to produce FT fuels. As no CCS is used, this caused an 73% increase over 1990 levels of CO_2 emissions by 2020.

Reduction scenario variants show various way of reducing CO_2 emissions by 20% in 2020, 50% in 2030 and 68% in 2040 compared to 1990 levels. We observe that the lowest overall costs are achieved by making reductions in transportation first and using relatively expensive options for emissions reduction in electricity if needed. Use of wind electricity, biofuels and biomass increases significantly across our reduction scenario variants.

We find a preference for using biofuels to reduce emissions from transportation, either by using ethanol or by FT fuels produced with CCS. Biomass potential is fully used in all of our reduction scenario variants, also at biomass feedstock prices up to 10 €/GJ. CO_2 storage potential is also fully used. Series hybrids are used if insufficient low-carbon fuels are available. Electric cars and fuel cell cars appear only when forced into the model solution.

Depending on the availability of biomass and carbon storage capacity, electricity is produced from biomass, coal with CCS, or wind turbines complemented with NGCC. Combining production of FT diesel with CCS is found to be more cost-effective than applying CCS in electricity production.

However, as direct CO_2 emissions are reduced by 68% in 2040, indirect GHG emissions rise to 11-25 Mtonne/year, thereby overtaking direct emissions.

Long term costs of CO_2 emissions abatement rise to 100-150 €/tonne for reduction targets between 30% and 70%. These costs are consistent across reduction scenario variants, provided that sufficient biomass and/or CCS are available. If this is not the case, abatement costs may rise to 400 €/tonne CO_2. The difference between investment in the No limits and the other non-forced car reduction variants is calculated at 4-7 billion euro per year, equivalent to 0.5%-1.2% of GDP. This is mostly invested in cars and electricity generation capacity.

Competition between transportation and power sectors for biomass and CCS storage capacity should be taken into account in future feasibility studies. We recommend further research on the potential impacts of large numbers of electric vehicles on electricity load patterns, and on non-cost barriers to and impacts of a large shift in fuels and cars used transportation.

"Think outside the box, collapse the box, and take a sharp knife to it."

- Banksy

6. Multi-agent simulation of adoption of alternatives to diesel and petrol

This chapter in an expanded version of the publication: van Vliet OPR, de Vries HJM, Faaij APC, Turkenburg WC, Jager W. *Multi-agent simulation of adoption of alternatives to diesel and petrol.* Transportation Research Part D: Transport and Environment 2010;15:326-42. http://dx.doi.org/10.1016/j.trd.2010.03.006

6.1 Introduction

The consumption of petrol and diesel derived from crude oil is considered problematic due to costs, lack of security of supply, greenhouse gas (GHG) emissions, and air pollution [7, 12]. Many potential renewable alternatives are expensive and only price-competitive without subsidies with fossil fuels as long as oil prices remain above $75/barrel or so, to which ethanol from sugar cane is currently the only exception [250, 348, 63]. Moreover, sustainable production biofuels is constrained by impacts on natural habitats, food security, ecology and water consumption [75, 76, 77]. Alternative sources of fossil transport fuels, such as coal to liquids (CTL), gas to liquids (GTL), tar sands, and oil shale, are also expensive and in general produce more GHG emissions than oil-derived fuels [250].

A transition from our current fuels to low-cost, low-carbon alternatives is needed, but the direction is unclear because the multiple goals of restraining price, improving security and reducing emissions seem difficult to reconcile. The current focus seems to be moving away from the visionary, large scale systems implementations (such as the 'hydrogen economy') to a more short-term incremental strategy [46, 47, 40, 48]. This draws on the notion that a gradual transition, that builds on existing infrastructure and technology (especially cars), is more feasible to implement.

Limited uptake of LPG and compressed natural gas notwithstanding, our past experience with full-scale fuel transitions is limited: There has been a slow move from petrol-fuelled cars to diesel-fuelled cars in Europe over many years and a 30-year (ultimately successful) program to stimulate ethanol as a replacement for petrol in Brazil [204, 376]. There has also been a switch from leaded to unleaded petrol in Europe in the late 1980s to early 1990s. Experimenting with a transition towards innovative fuels is impossible in practice, and examining the interactions in a laboratory setting takes the actors and decisions outside context [377]. Instead, we have constructed an agent-based simulation model to examine how a fuel transition may take place, taking into account the preferences of the principal actors.

Fuel technologies and their use co-evolves with the circumstances in the larger system. A model should therefore be able to deal with effects like lock-in (due to capital stocks and vested interests); (technological) learning effects and supply limitations. In addition to price mechanisms and technological progress, motorists' perceptions of alternative fuels play a critical role. If we consider variations in personal circumstances and preferences, limited cognitive resources and limited availability of information, it is likely that social influences affect the decision to adopt a particular fuel.

In this chapter, we examine the dynamics emerging from the interactions of fuel producers and motorists, and the effect of varying some properties of these agents and the fuels. We also explore the impact of external factors such as the price of oil and feedstocks for alternative fuels and perception of financial risk. We show how our model is formalised in section 6.2, and parameterised in section 6.3. In section 6.4 we present the results of some permutations of our model configuration. Finally, we take a critical look at our results in section 6.5 and draw some final conclusions in section 6.6.

6.2 Formalisation – model structure

We consider, in a heavily stylized way, the entire well-to-wheel (WTW) fuel system of transportation, from the resource base (oil, coal, natural gas, crops, residues) to use of the final product (transport fuels and fuel blends used in cars). This WTW system is characterised by many complex interactions and high stakes (financial, economic, environmental, electoral). It involves a large number of actors which makes any transition a policy challenge, although most actors have only an indirect effect on the volume and composition of fuel demand (see figure 6.1).

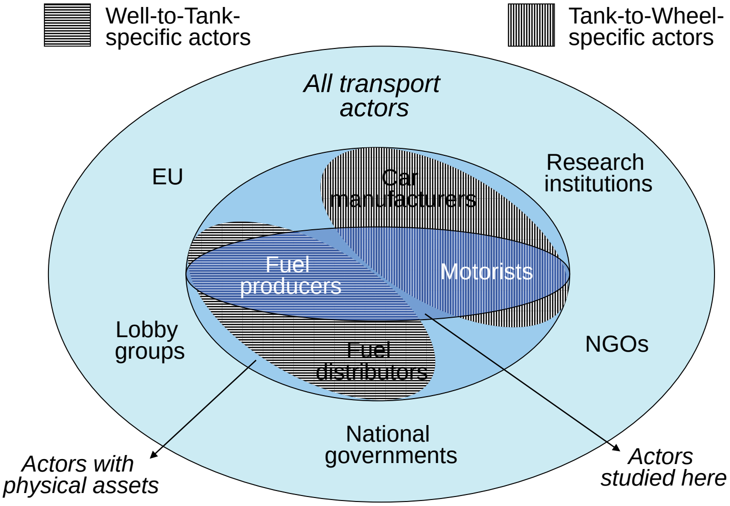

Figure 6.1: Main actors involved in fuel demand and supply

If we focus on drop-in replacement fuels for petrol and diesel, the existing cars and refuelling infrastructure do not need to be changed (much)[31]. If we then assume the context for decisions on fuel choice and investment to be stable, we can limit ourselves to investigating the dynamics between fuel producers and motorists (fuel consumers). It is difficult to capture even these two groups of actors with physical assets in a model. Investment in production of alternative fuels is hesitant [79], with many options remaining open and/or un(der)developed. Motorists are a heterogeneous group, with many subpopulations with specific preferences, particularly private motorists. We also exclude heavy-duty vehicles because there are seven times as many cars as heavy-duty vehicles, and nearly all of the latter are commercial vehicles [204]. We also assume that total fuel demand remains stable.

Given these narrowed-down system boundaries, we choose 6 fuel options: petrol and diesel from crude oil, ethanol blends and biodiesel blends (both 'first generation' biofuels), and synthetic diesel and petrol made by the Fischer-Tropsch (FT) process from coal (CTL), natural gas (GTL) or biomass (BTL) ('second-generation' biofuels, if made from biomass). For the sake of simplicity and a focus on alternative fuels, we leave out petrol and diesel made from heavy crude oil, LPG, natural gas and electricity.

While many studies have used multi-agent models to study stylized dynamics in abstract markets [380, 381, 382, 383, 384, 385], multi-agent simulations have also been used to assess the introduction of real-world consumer products (see for example [386]). We follow the latter approach and use observable real-world data to make our simulation more applicable to the specific task of simulating a transition to alternative (drop-in replacement) fuels. In this way we hope to catch dynamics that stem from heterogeneous behaviour not showing up in simulation models using optimization such as MARKAL, TIMER or MESSAGE [316, 387, 388].

Figure 6.2 indicates the general structure of the model, showing the major blocks of inputs and simulated variables. A heterogeneous set of motorists ('agents') with diverse consumer preferences chooses a fuel, which leads to a demand for various fuels. This determines the evolution of the production capacity by retiring non-profitable and adding potentially profitable plants. Plants then produce and sell fuels to match the demand. Outside (government) interventions are implemented by making changes in the fuel production chains and in the perceived properties of the fuels. We implemented the model in the Laboratory for Simulation Development (LSD) environment [389], with the equations making up some 2300 lines of C++ code, including comments. The model source code, detailed schematics and equations can be found at OpenABM [390].

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[31] We assume that pump options in filling stations do not meaningfully limit the distribution of fuels, other than by limiting the total number of different fuels on offer. However, limited availability of fuels in filling stations was indicated as a limiting factor in adoption by consumers (see [58, 378, 379]).

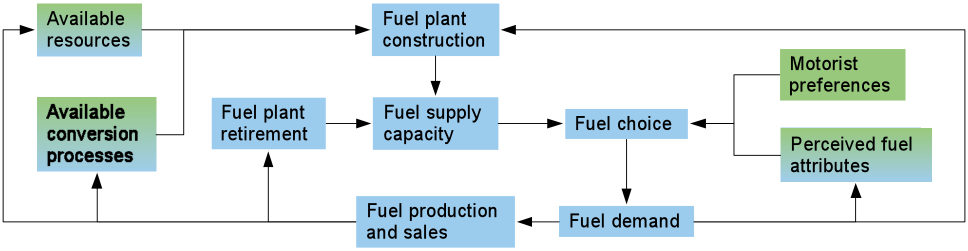


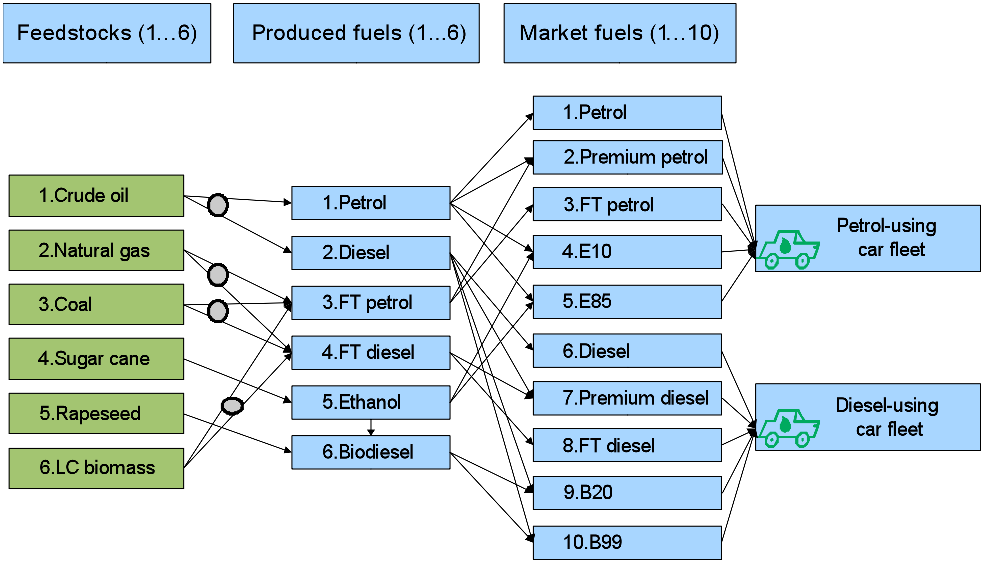
Figure 6.2: General structure of our elaborated model

6.2.1 Supply model

The supply side of fuel production and upstream activities are large scale industrial processes. Major fuel producers insist on high internal rates of return (IRR) for new commercial projects. Our focus is on fuels that are technologically ready to break out into the mainstream, and for this reason we consider producers as economically motivated entities, who evaluate options in terms of financial rate of return.

Long-term costs of fuels are governed by learning and depletion mechanisms (see e.g. [391]). They are expected to fall as the production technology matures, during a continuous process of upscaling, improvements in conversion processes, better management, and other results from RD&D. The cost reductions and better performance will enhance competitiveness and acceptance, leading to more extensive deployment and thereby to more experience with the option and the system around it. How this positive feedback system will evolve for a particular technology is not easy to predict. Expert judgment tends to be over-optimistic in this regard [392].

We model supply options as a progressive series of discrete well-to-tank chains of fuel production. Each chain consists of a series of facilities for the collection of feedstocks, and production, processing and transport of the product (fuel), incorporating a particular set of production technologies (see section 6.3). The feedstocks and fuels considered in this chapter are shown in figure 6.3. There are several types of feedstock, each representing an initial form (coal, biomass, crude oil) and a source location (e.g. Latin America, Eastern Europe). Blended market fuels (e.g. an E85 mix of 85% ethanol and 15% petrol, a B20 mix of 20% biodiesel and 80% regular diesel, or a premium diesel mix of $^1/_6$th FT diesel and $^5/_6$th regular diesel) are created by mixing the produced fuels.



Note: Left arrows represent conversion from feedstock to fuel, the middle arrows represent blending. Circles represent necessary co-production of two fuels in a single chain. LC: lignocellulosic.

Figure 6.3: Fuel chains considered in this chapter.

Fuels are produced in discrete size installations, or plants, i=1..x, each representing one of 13 possible chains. A plant takes in one or more feedstock types, j=1..6, and produces one or more types of fuels f=1..6 (see figure 6.3). The fuels produced in the plants can be blended in order to supply the actually demanded marketed fuels k=1..10 which depends on the choices of motorists. The demand for market fuels D_k is converted to demand for ingredient fuels D_f. Blending does not add any cost for the producer.

Demand D_f, thus generates a demand for feedstocks j. Each feedstock can be supplied from resources which are represented by segments of a given production capacity (in GJ/yr of output) and cost (in €/GJ) in any given year. Ranked by costs, the segments make up a supply cost curve.

Actual demand for a feedstock depends on fuel demand and the chain and associated feedstock mix from which the fuel is produced (see figure 6.3). We assume that the feedstock price p_j equals the marginal cost at which the feedstock is supplied in that year. We then calculate for each plant i the production costs of the associated ingredient fuels, c_{if}, consisting of feedstock costs and conversion costs. The latter is considered fixed and constant over time for each plant.

Sales from a single plant i are the product of fuel price p_f and supply S_{fi} produced in response to demand D_f. Demand for a fuel f is produced by plants in order of cost: first by the lowest-cost plant (in €/GJ), then the next one, and so on until total demand is met.

Each plant i has an installed capacity C_{fi} for every fuel f it produces. The effective capacity is constrained by a reserve margin factor in order to deal with plant breakdowns and sudden demand shifts: $C_{fi,eff} = C_{fi} \cdot \mathit{SpareCapacityFraction}$. If the plants' total effective capacity ($\Sigma C_{f,eff}$) to supply a fuel falls short, this will drive investment decisions, as we will explain later, and the plants (temporarily) produce up to their installed capacity C_{fi}. If motorists want more of a fuel than the total installed capacity (ΣC_{fi}) can produce, the plants produce to their installed capacity ($S_{fi}=C_{fi}$) and the remainder is a latent demand which cannot be satisfied. The producers do not anticipate future developments in demand.

Plants can produce multiple fuels, but always with a fixed output ratio. A plant will produce enough to fill the highest S_{fi}/C_{fi} ratio. If this leads the plant to produce more of another fuel than is demanded, that excess fuel either goes unsold and is presumed lost, or is exported outside the boundaries of the model and provides extra revenue. If one of the fuels that a plant produces goes (partially) unsold, the rate of return (ROR) of that plant drops. If a fuel is set to be exported, production per plant of this fuel can either to satisfy the normal equation for S_{fi}, or to use the highest $\mathrm{CapacityUsed}_{if}$ value for all of the fuels.

The next important element in the model is the investment dynamics. The actual decisions about when to invest in which plants are the outcome of a complex, strategic process. We have simplified it here into a few basic rules:

- Producers use the information on last year's demand for market fuels k and, via the blending ratios, fuels f on possible over- and/or undersupply;
- The criterion to evaluate the performance of plant i is the rate of return, ROR_i, in the previous year, defined as the ratio between sales and costs:

$$ROR_i = \sum Sales_{fi} \Big/ \left(ConversionCost_i + \sum FeedstockCosts_{fi} \right) \qquad (6.1)$$

- Producers require the ROR-value for an existing plant to exceed a certain threshold, ROR_{min}; otherwise the plant is retired and the feedstocks used by a retired plant are freed up for new plants.

Thus, investment decisions about replacement and/or expansion are calculated from a possible shortfall in demand for a fuel f. They depend on the projected ROR of new plants, calculated from projected sales, cost and efficiency of available conversion plants and the projected costs of available feedstocks. Producers require the ROR-value for a new plant to exceed a certain threshold, R_{new}; otherwise the plant is not sufficiently profitable to justify investment. From those plants with a projected $ROR>ROR_{new}$, the plant with the highest ROR is chosen. The selection process is repeated until no more investments are made because either the fuel shortfalls can be supplied when the new plants start producing or all projected $ROR < ROR_{new}$, in which case the shortfall will persist.

After the decision to build a new plant, it is considered to be under construction for a few years. This 'inactive' capacity is taken into account when determining the viability of additional plants but only the active capacity is operated. Once a new plant starts operation, it has a 'grace period' during which it must attain a sufficient production and sales level so that ROR_i exceeds ROR_{min}. The rate at which new plants can be added, and therefore the rate of change in the supply mix, is limited by a maximum construction and retirement capacity per year. If the model exceeds either limit, further construction or retirement is not possible in that year.

A plant can also be initially unavailable and only become available ('unlocked') when a level of cumulative production is reached. This threshold approach simulates technological learning through making cheaper, more efficient plants available only when sufficient experience has been accumulated with existing technology. To account for the vertically integrated nature and large discrete investment required for FT plants, we do not use an (aggregated) learning curve. Instead, we use bottom-up cost and efficiency estimates of (future) fuel chains to construct discrete 'packages' or 'generations' of compatible conversion technologies.

The relation between producers and prices is a complex one. One may expect the producers to strive for larger market shares if the profits (i.e. ROR) are high by lowering the price – unless they benefit from a 'first mover' monopoly. Inversely, if plants underperform there may be a tendency to raise prices – unless subsidies are available to sustain low-ROR plants. We approximated such a price dynamic by assuming that producers of a given fuel respond with a price reduction proportional to the ratio between a desired ROR_{target} and the ROR of plants in the marginal (worst performing) chain making this fuel, in an effort to increase the attractiveness and thereby the market share of their fuels. Conversely, an increase in price will occur when the ROR of plants in the marginal chain is below ROR_{target}.

Because we must estimate a fuel price before fuels can be chosen and sold, we calculate the projected RORs of the producing plants/chains using an initial sales price and feedstock costs based on installed capacity. In other words: we use the projected ROR of plants in the marginal fuel chain (i.e. lowest projected ROR) and adjust the consumer price in such a way that the producer maintains the desired ROR.

We assume production at effective capacity, $C_{f,\,eff}$, in calculating the price adjustment, which leaves out the marginal plants in case of oversupply. All non-marginal plants in the model run at capacity levels between (1-SpareCapacityFraction) and 1. For blended market fuels, we use a linear combination of the RORs of the ingredient fuels, proportional to the blend ratio. How strongly prices respond to divergences in profitability is controlled by raising the price adjustment to a power of α (with $0<\alpha<1$).

For each fuel that is an alternative for another (B99 for diesel, etc.), the prices can be coupled. If the lowest ROR among plants producing any coupled alternative fuel is higher, the fuel price will be lowered to match that of the most competitive fuel. This reduces profit margins but keep the fuel from losing market share. If this coupled adjustment causes the lowest projected ROR of the coupled chains to drop too far, the plants in the marginal chain would have insufficient profit margin to deal with small demand fluctuations. This would cause these plants be retired. To avoid sudden fluctuations, we restrict in such a situation the price drop to keep the plant ROR at a safe level (in all cases, $ROR_{target} \geq ROR_{new} > ROR_{safe} > ROR_{min}$). If no plants exists that produces a particular fuel, we use instead the lowest projected ROR of the chains that could produce this fuel (to ensure at least some capacity for this fuel will be built if there is demand).

6.2.2 Demand model

The demand for fuel is assumed to come from a group of motorists with the following characteristics:

- They own a car for which they need a fuel; we assume consumers replace old cars with similar new ones that use the same fuels. The car uses either petrol (spark ignition) or diesel (compression ignition);
- Their cars use a fixed amount per km driven (MJ_k/km) of either petrol or its alternative blends, or diesel or its alternative blends (recall figure 6.3);
- They drive a fixed distance ($TravelDistance_m$, in km) every year, which depends on the type of car and on private vs. lease ownership;
- They choose the fuel of their preference on the basis of three criteria: 1) cost, 2) emissions and 3) performance (in terms of speed, acceleration, etc.); and
- They interact because their choice also depends on the reputation and popularity of the fuel options.

Thus, the motorists are a heterogeneous population which generates a demand for the various fuels on offer via their individual preferences and a social networking effect. The criteria chosen reflect the empirical finding that price is an important consideration in fuel choice for almost every driver (and the dominant consideration for most), but that some motorists are motivated more by the environmental impacts of driving, the effects of fuels on the performance of their cars or how many friends use a fuel [393, 57, 394].

Corresponding with the three criteria, we assign attributes A1-A3 to each of the available market fuels f:

A1. Driving costs, which is assumed to be equivalent to the price at the filling station (in €/l) including taxes;

A2. Environment, which is narrowed down to some number representing normalized (relative) levels of greenhouse gas and other pollutant emissions from burning the fuel; and

A3. Performance, which is some normalized (relative) performance measure reflecting features such as the fuel's effect on acceleration and smoothness of the engine.

The fourth and final attribute A4, reputation or popularity, is not a property intrinsic to the fuel but measures the (relative) extent to which use of the fuel fulfils social needs or identity needs (cf. [382]). Whereas the authors realize that it is possible to formalize complex social networks between consumers, and make distinctions between various types of social influence (e.g., normative versus informative influences), we took a more parsimonious approach by using actual market share μ_f as a proxy for social influence, thus capturing awareness of and familiarity with a fuel from personal use, word of mouth and marketing. Using this simple formalization further contributes to maintaining the overall level of detail in the model balanced. Depending on the relative importance of the four preferences, one or more subpopulations can constitute a niche market that is a potential market entry point for an alternative fuel [395, 396].

The choice process is at the core of our demand model. We assume that selecting a fuel is not as much of a 'high involvement' process as buying a car (see [57]). To simulate the choice process, we use the following considerations:

- Motorists do not have sufficient information to make a fully informed rational choice on fuel alternatives, or at least have a superficial perception on the information at their disposal [397, 398, 399];
- Motorists, unlike fuel producers, do not base their decisions on the calculation of a shadow price – at least, not explicitly – or make decisions in compensatory ways [58, 400]. Motorists may have plural (incompatible) rationalities that cannot be reconciled by optimization without compensation; and
- Motorists have limited cognitive resources to spend on fuel decisions. They will use heuristics over exhaustive deliberation and optimization [401], reducing the problem of deciding on a fuel to a handful of simple decision rules that yield a satisfactory (not necessarily optimal) choice;

Each motorist only chooses and uses one market fuel (blend) in any given year. We postulate a heuristics-based decision making algorithm for motorists choosing fuels. The motorists' preferences are indicated by their priorities, which determine the order of importance in which they use attributes to evaluate fuels, and their tolerance levels, which determine how much worse a fuel's attribute value can be compared to the best fuel's attribute value if that fuel is to be kept under consideration.

For each of the market fuels k, the attributes (price, emissions, performance and popularity) are given in the matrix A[4,k]. Each motorist m=1..y (y=735) is assigned initial individual preferences, implying that for each motorist, a relative order of priority for the four criteria (1st, 2nd, 3rd or 4th) is set in the matrix B[m,4] and tolerance values (between 0 and 1) for the four criteria are set in the matrix C[m,4]. For the attribute of his highest priority, a motorist compares the relative values of this attribute for each of the possible fuels (selection between petrol or diesel). Then, he eliminates the fuels for which the relative difference of these attribute value is larger than his tolerance. Figure 6.4 is a diagram of this filtering process.

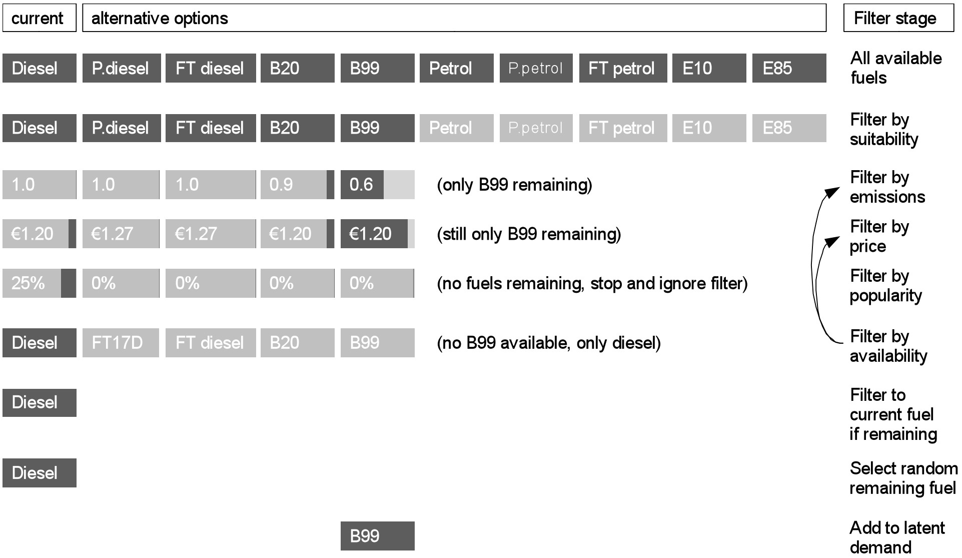
For instance, motorist 1 may opt for petrol (fuel 1) because it is the cheapest option (B_{11} = 1st and A_{11} satisfies C_{11}); motorist 2 could choose to drive on E85 (fuel 5) instead of petrol because it is better for the environment (B_{22} = 1st and A_{25} satisfies C_{22}); motorist 3 could choose E85 because it makes his car drive faster (B_{33} = 1st and A_{35} satisfies C_{33}); and a motorist 4 could choose E85 because lots of his friends use it (B_{44} = 1st and A_{45} satisfies C_{44}). As this example shows, it is possible for a fuel to satisfy several niche markets, building a significant total market share from several multiple small market shares.

Multiple fuel options may remain after a filter. For instance, in the baseline parameterisation, from the four alternatives to diesel, only B20 and B99 survive if their cost values have to be within 3% of the best (diesel) option (see figure 6.4). If more than one option remains, the fuels are compared along the second attribute, again eliminating the underperforming ones. This process continues if needed with a third and fourth round of filtering fuel options, based on the third and fourth priority attributes. This filter algorithm is similar to 'Take-The-Best' and 'LEXSEMI' algorithms described by other authors [402].

The heuristic of comparing to the best for each attribute independently (which, for example, has a motorist compare the cost of biodiesel with cheap CTL diesel and compare the emissions of that same biodiesel with BTL diesel made with CCS) rather than a 'package deal' (for example, compare both cost and emissions of biodiesel with those of CTL diesel) was inspired by observation of this behaviour shown by non-scientists in a workshop on sustainable biomass and biofuels supply [399] and later in media coverage of biofuels. It seems apples are routinely compared to oranges.

After filtering the fuels by preferences, the model checks if there is sufficient production capacity left to supply the remaining demand for fuel(s). If so, the motorist chooses one from the remaining fuel(s) to add to D_f. If more than one fuel is left, the motorist either chooses the fuel used in the last year, or picks randomly from the remaining fuels. This reduces the amount of the chosen fuel that is available for the next consumer.

If none of the preferred fuels have sufficient production capacity, the motorist regresses step-by-step through the elimination filters and checks whether any of the fuels eliminated previously do have sufficient production capacity remaining to fill the fuel needs of this motorist. If this is the case, the consumer chooses such a fuel and adds to D_f as described above. Furthermore, a random fuel is picked from the fuels which would have been preferred to the fallback choice but for which insufficient production capacity exists. The amount of this fuel that the consumer would have used is added to latent demand, which drives investment decisions. Random distribution of preferred fuels should produce an equal spread between latent demand on a population level, with minor fluctuations in time. Figure 6.4 shows an example of this fallback process.



Note: Green motorist tolerances are: cost: 0.03, emissions: 0.2, popularity: 0.8.

Figure 6.4: Decision-making process of a newly introduced 'green' diesel-driving motorist in case of a shortfall in production capacity for a green alternative.

6.2.3 Two illustrative experiments

Figure 6.5 is an illustrative simulation experiment with the following situation: All motorists have driving cost as their first priority and with a low tolerance. Market shares are fixed in the initialisation and the fuel consumption of cars is taken constant. There are plants producing petrol and a single plant which can produce a green alternative to petrol but is retired in the second year because there is no actual demand for green fuels.

Our first experiment starts at the end of year 4 and explores what happens if consumer preferences change. We do this in the form of a demand-side intervention: the first priority of a fraction of the motorists (14%) is switched from cost to environment ($B_{m2} \rightarrow 1^{st}$, $B_{m1} \rightarrow 4^{th}$). One expects this to stimulate green fuels. Indeed, as figure 6.5a shows, there is a surge in the latent demand for the first green fuel. In response to this change in preferences, the supply sector responds with an (initially very small) production of green fuel (figure 6.5b).

Why is the response from the suppliers so small and do most of the green consumers remain dissatisfied? We assume that the sales prices of petrol and its green fuel alternative are coupled. A small volume of feedstock for the green fuel is available at low costs, so the projected production cost for this alternative fuel is quite low. A few green fuel plants are indeed built, that use all of the feedstock available at low prices. If capacity were to increase further, more expensive feedstocks would be needed. The profit margin in the situation of increasing feedstock costs and (too) low sales prices causes the projected ROR of the new plants to become lower than the required ROR_{new}. Therefore, no further expansion takes place. Due to the aggressive competition mechanism in our model, the petrol producers match the resulting sales price (figure 6.5c).

When the green fuel plants begin production, overwhelming demand causes these to work at full (above effective) capacity, which increases their feedstock costs above what was projected earlier. In response to the higher production costs, the price of the green fuel alternative increases (figure 6.5c), and with it the price of petrol (which was kept low to safeguard market share from the green fuel). This allows a small but gradual increase in capacity as more expensive feedstocks can now be profitably used to make green fuel. Eventually, the feedstock and fuel prices reach a point where a large volume of feedstock is available, production expands significantly (figure 6.5b, around year 8), and price stabilises.

Our second experiment starts at the end of year 12 and explores what happens if the oil price suddenly rises. We maintain the consumer population of the previous experiment (14% green) and increase the price of oil from 60 $/bbl to 140 $/bbl. One would expect that such a supply-side intervention improves the market share of green fuels. Indeed, the jump in latent demand (figure 6.5a) causes another expansion of green fuel production (figure 6.5b). However, in an attempt to catch some of the strategic behaviour of fuel producers, also other movements take place.

First, the petrol producers shift part of the increased feedstock (oil) cost to the customers in order to restore the drop in their ROR (figure 6.5d). Hence, petrol sales prices go up (figure 6.5c). Because the prices of petrol and green fuels are coupled, such an increase also makes it more profitable for green fuel producers to enter the market. However, in order to increase market share, they are willing to increase the sales price of green fuel less than the increase in the petrol price, as long as they can stay above the ROR_{target}. To counteract this strategic move, the petrol producers in turn decide to limit the rise in petrol sales price in their turn – so long as their ROR remains above ROR_{safe}. Because of this competition, the sales price of petrol increases by a mere 12%, from 1.32 to 1.48 €/l.

However, this 12% price difference exceeds the tolerance of our majority of motorists, who have price as their 1st priority, and causes them to desire cheap green fuels (figure 6.5a). This leads to a construction boom for green fuels, in which the production capacity of the first green fuel is again expanded (figure 6.5b). However, the expansion of the first green fuel is soon halted because competition from a second green fuel causes latent demand to drop after a few years.

One year after the oil price increase, the first plants that can produce a second green fuel begin construction, and this plant is projected to make cheaper fuel than the first green fuel (figure 6.5c). This is because the chain for producing the second green fuel that was selected by the producers was not the most expensive production chain on which the price was previously based (before any plant for the second green fuel was selected). The actual plants are the same as the one that was scrapped in year 2 due to lack of demand. This causes the sales price of the second green fuel to drop, and thereby causes motorists to change their mind again. The latent demand for the first green fuel drops, and latent demand for the second green fuel takes most of its place (figure 6.5a).

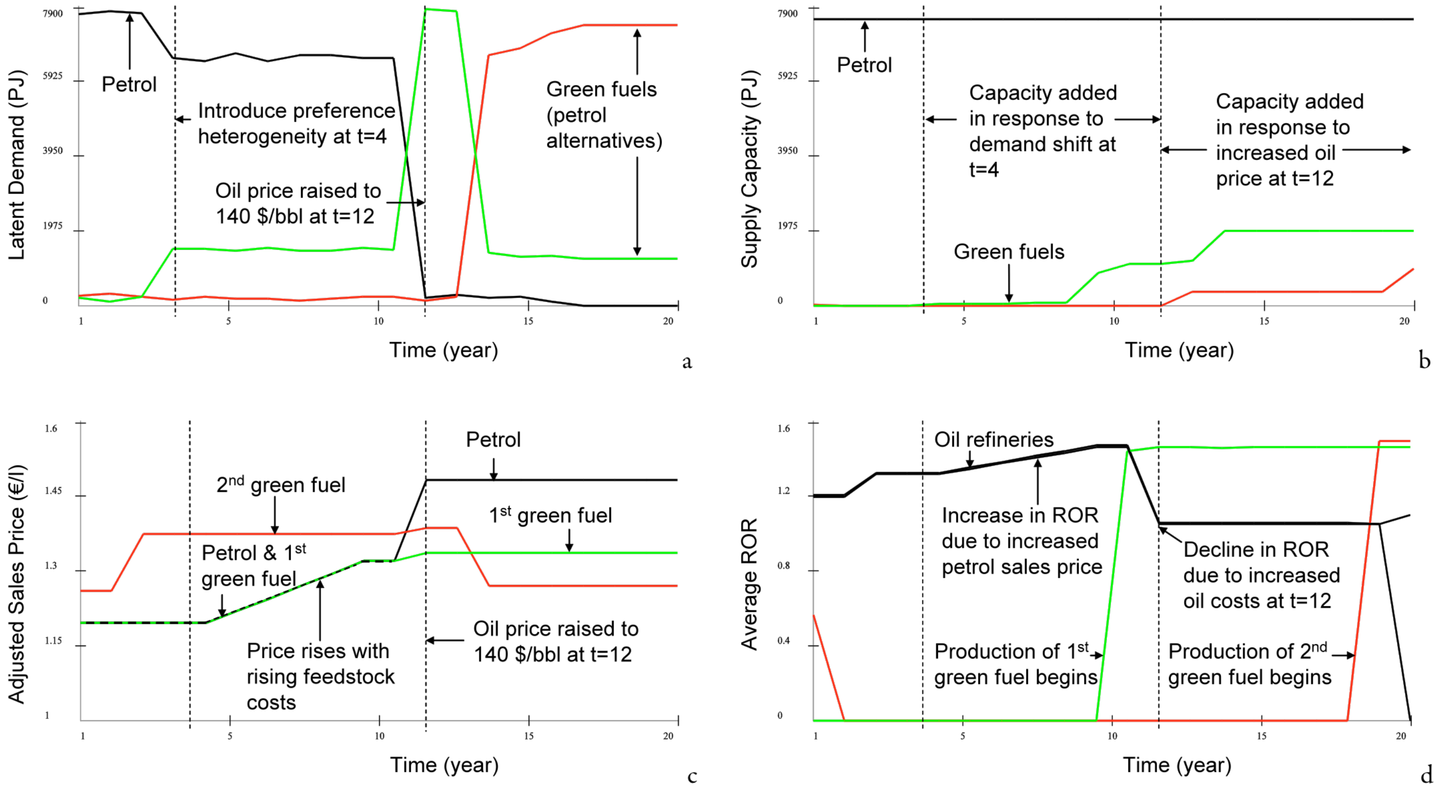
However, the feedstock volume of the second green fuel is limited. The capacity therefore is not expanded further until sufficient cumulative production (experience) is gained and a new generation of technology becomes available that uses a different feedstock. The second green fuel only takes off in the final year of the simulation (figure 6.5b). Also in the final year, we see petrol sales dropping to a point where one petrol plant is no longer used; causing its ROR to drop to zero and marking it to be retired (figure 6.5d).

6.3 Parameterisation – model data

The above illustrative examples show the kind of dynamic behaviour one can expect from our model. Do these dynamics happen in the real world and can the model be used to better understand the complex transition away from conventional transport fuels?

In our parameterisation we use data drawn from real-world sources. We do this not because we aim to create a predictive model. In any case, our data is of insufficient quality and the model insufficiently verified to do so. Instead, we reason that the use of numbers that have at least the correct orders of magnitude (ballpark accuracy) will help us to generate more relevant dynamics in our model than the use of purely theoretical numbers.

We use bottom-up technical data from literature for energy technologies, fuel properties and cars, and survey data from literature to construct a population of agents. We limit our model to the next 20 years, to reflect the time horizon of our technological data. We parameterized our model with a market of the size of the European Union to reflect the scale of a continental market, and to explore how the model dynamics work in a market of relevant size. In this section, we present a summary of the dataset. A more complete description of the dataset and sources used can be found in sections 6.A.2 and 6.A.3.



Note that the model is calculated at one-year intervals: the ramps between years are drawing artefacts.

Figure 6.5a-d: Effect of introducing of heterogeneity in motorist population and high oil prices on latent demand (a, top), (non)development of production capacity (active + under construction) in response to consumer demand (b, upper middle), market fuel sales prices (c, lower middle), and average ROR of producing plants (d, bottom).

6.3.1 Supply (fuel production)

Fuel supply depends on two sets of data: well-to-tank (WTT) chains for converting feedstocks into fuels, and the feedstocks. We examine the following fuels: regular (oil-derived) petrol and diesel, E10 and E85 ethanol blend, B20 and B99 biodiesel blends, and premium petrol or diesel (see figure 6.3, section 6.2.1).

We used data from various sources to define WTT chains [250, 348, 62, 45, 213, 136, 126]. These chains include distribution, conversion to fuels, conversion to intermediates (vegetable oil, wood pellets, torrified wood pellets) where applicable, and transport of raw materials and intermediates.

Our market size is roughly that of the EU, at 17 000 PJ/year, and we assume an oil price of around 60 $/bbl. Including Dutch fuel taxes, this results in consumer prices of 1.25 €/l for regular petrol and 1.30 €/l for premium petrol, 0.99 €/l for regular diesel and 1.30 €/l for premium diesel.

Ethanol is imported from Brazil and GTL is imported from the Middle East. Oil seeds for biodiesel are produced in Eastern Europe, as is lignocellulosic biomass (LC) for BTL. To determine production potential in Eastern Europe, we used the 2010 data from the REFUEL project [352], allocating land areas to oil seed crops (rapeseed or sunflower) or LC biomass (willow, poplar, eucalyptus, or reed canary grass), depending on which crop results in the cheapest fuel.

GTL, biodiesel and LC biomass are supply-limited. Compared to 17 000 PJ/year oil imports, production of oil seeds is limited to 610 PJ/year, and LC biomass to 2700 PJ/year. Use of Middle East natural gas is limited to 2400 PJ/year, based on existing GTL concessions [66]. For ethanol, we assumed unlimited supply potential, with reduced costs if prices remain below a 98 PJ/year EU import quotum (based on [403]). We assume no limits to the potential volume of CO_2 captured and stored (CCS).

Although potential supplies of biomass from the rest of the world could become considerable over time, sustainably setting up infrastructure and production capacity for the volumes considered for FT plants will take considerable time [76, 250].

Production costs of fuels vary because the costs of resources increase as demand increases. The initial cost order for petrol and alternatives is ethanol < GTL < regular petrol < CTL < BTL, and for diesel and alternatives the order is: GTL < biodiesel < regular diesel < CTL < BTL. Large volumes of regular petrol and diesel are initially produced to supply most of the market, with some GTL, ethanol and biodiesel capacity. We allow export of electricity (an FT co-product), and of diesel to account for demand for diesel from heavy-duty vehicles.

6.3.2 Demand (motorists)

We based the public perceptions of environmental impact and performance on expert judgement, and derived motorist fuel prices from literature [204], using either premium or regular diesel/petrol prices. For our base case, the perceptions of alternative fuels were set the same as for regular petrol and diesel with the following exceptions:

- FT petrol and premium petrol (FT/regular mix) were set to premium prices;
- FT diesel and premium diesel (FT/regular mix) were set to premium prices;
- FT diesel and premium diesel give higher performance, B99 slightly higher;
- E85 and premium petrol give higher performance;
- B99 and E85 are perceived as green fuels, B20 as somewhat green.

Because the choice algorithm uses attribute priorities and relative tolerance levels, only the relative levels of the fuel attributes are important.

The preferences of motorists are difficult to obtain. Market shares of individual fuel brands are closely guarded commercial secrets, especially in relation to demographic data. The only hard number we have on the preferences of heterogeneous motorists is that sales of premium petrol (which improves performance) are 4% of total petrol sales in NL [204][32]. We also know that many of the leased car drivers do not pay for their own fuel and are therefore less strict about the price of the fuel they choose [404, 393].

We used various public sources to derive the composition of the Dutch car fleet and fuel consumption [405, 204, 406]. We distinguish diesel and petrol cars, as well as privately owned and leased cars, which are all different in fuel consumption or the average distance driven per year. We combine these with data from JRC [45] for cost, fuel consumption and emissions from cars.

As a substitute for direct preference data, we used Dutch consumer value dispositions from the TNS-NIPO WiN™ model [407, 408, 409] to construct 11 groups of consumers. We gave each of these a (caricature) nickname for easy reference, with properties as shown in table 6.1. Each agent starts out by using either normal petrol or normal diesel, depending on their type of car.

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[32] Market share of premium petrol has declined rapidly from >10% before 2000 to ±4% in 2005.

Group name	Size	Agents	Car type	1st priority	2nd priority	3rd priority	4th priority
Mondeo Man	70.4%	517	petrol	Cost: 3%	Pop: 80%	Perf: 10%	Env: 20%
Golf Man	10.5%	77	diesel	Cost: 3%	Pop: 80%	Perf: 10%	Env: 20%
Conformist P	5.6%	41	petrol	Pop: 70%	Cost: 3%	Perf: 10%	Env: 20%
Big Spender D	3.3%	24	diesel	Cost: 10%	Pop: 80%	Perf: 10%	Env: 20%
Petrolhead	2.7%	20	petrol	Perf: 10%	Cost: 3%	Pop: 90%	Env: 20%
Green P	2.4%	18	petrol	Env: 20%	Cost: 3%	Pop: 80%	Perf: 10%
Big Spender P	2.3%	17	petrol	Cost: 10%	Pop: 80%	Perf: 10%	Env: 20%
Traveller D	1.0%	7	diesel	Perf: 10%	Cost: 10%	Pop: 90%	Env: 20%
Conformist D	0.8%	6	diesel	Pop: 70%	Cost: 3%	Perf: 10%	Env: 20%
Traveller P	0.7%	5	petrol	Perf: 10%	Cost: 10%	Pop: 90%	Env: 20%
Green D	0.4%	3	diesel	Env: 20%	Cost: 3%	Pop: 80%	Perf: 10%

Table 6.1: Agent nicknames, populations, cars used, preferences and tolerances.

6.4 Results

We present results from our simulations, using the data as described above and parameters as described in table 6.2, unless stated otherwise. All simulations are run without modifying parameters during the simulation.

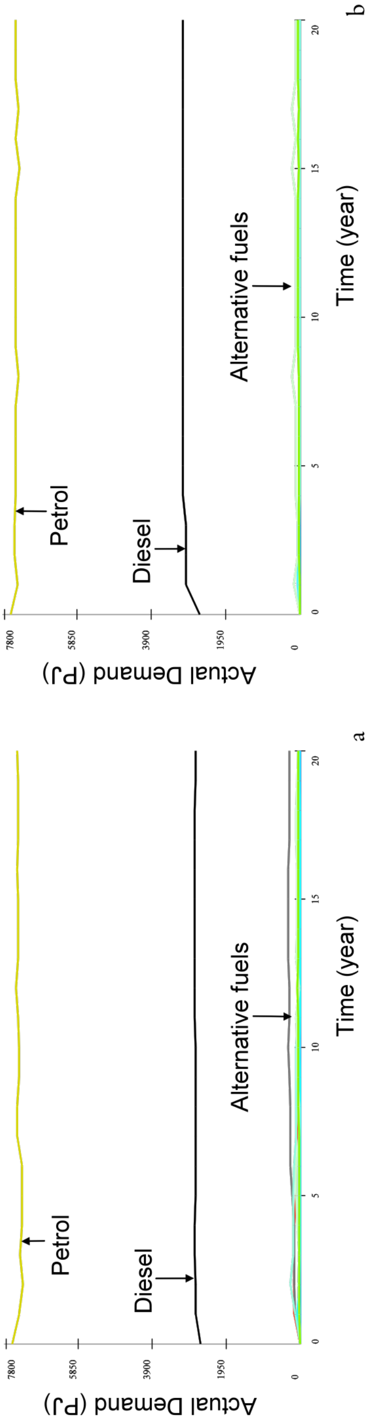
The maximum capacity that can be built or destroyed in a year is 800 PJ/year, which is equivalent to the size of one large and one small oil refinery. The minimum profit margin for new plants is set at 40% ($\mathrm{ROR}_{\mathrm{new}}=1.4$) and at break-even for existing plants ($\mathrm{ROR}_{\mathrm{min}}=1.0$), with the profit target ($\mathrm{ROR}_{\mathrm{target}}$) and safety target ($\mathrm{ROR}_{\mathrm{safe}}$) just above these levels (c.f. section 6.2.1). The delay from the decision to construct to production is 5 years, which is reasonable for small plants but short for a large oil refinery. The grace period to attain a profit is 3 years, starting from the first year of operation.

Maximum build capacity	800 PJ/year
Maximum destroy capacity	800 PJ/year
ROR profit target	1.45
ROR for new plant	1.4
ROR for price adjustment	1.05
ROR for existing plant	1.0
Time to production	5 years
Time to profitability	8 years
Price adjustment exponent	0.6
Spare capacity	5%
Fuels exported from system	Diesel
Chance to ignore last fuel	33%

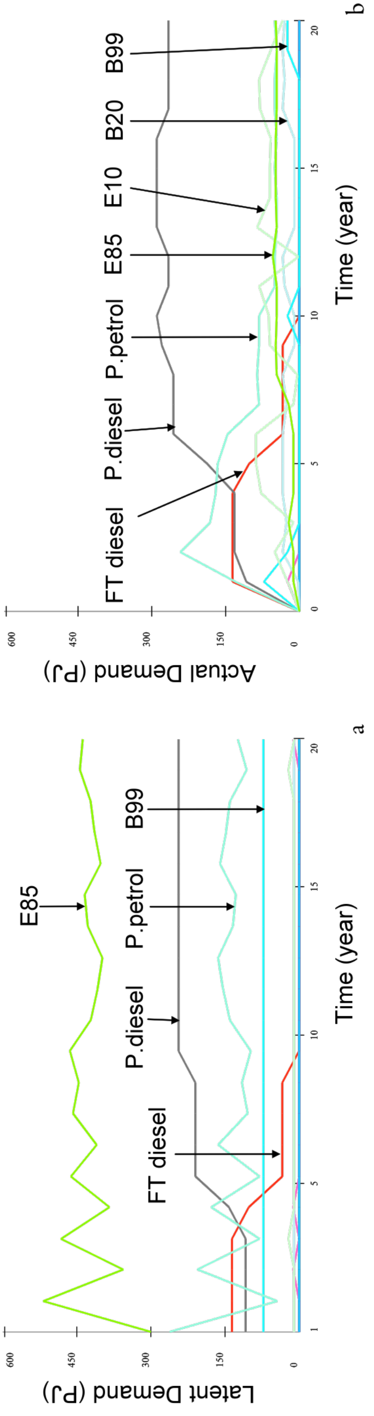
Table 6.2: Base case model properties

6.4.1 Base case results

Using only the base parameters, with our 11 subpopulations of motorists, we observe no significant changes in the fuel mix (figure 6.6a). While there is some activity in all alternative fuels, their market shares remain marginal and the share of biofuels remains below 1%. For comparison, if the simulation is done with homogenous groups of motorists (618 petrol drivers and 117 diesel drivers) who have price as their first and only priority (tolerance set to 0% for price and set to 100% for the other attributes), the penetration of alternative fuels is even smaller (figure 6.6b). Note that the small fluctuations are caused by the random choices for fuels and preferred fuels when multiple options are available (c.f. section 6.2.2).



Figures 6.6a-b: Actual Demand (PJ/year) using base case parameters (a, top), and with homogenous motorists with price as only priority (*homo economicus*) (b, bottom).



Note: The symmetric fluctuations in latent demand for these alternative fuels are due to random allocation to preferred fuels in the model. 'P.' means 'premium'.

Figures 6.7a-b: Latent (a, top) and actual (b, bottom) demand (PJ/year) for marginal alternative fuels using base case parameters.

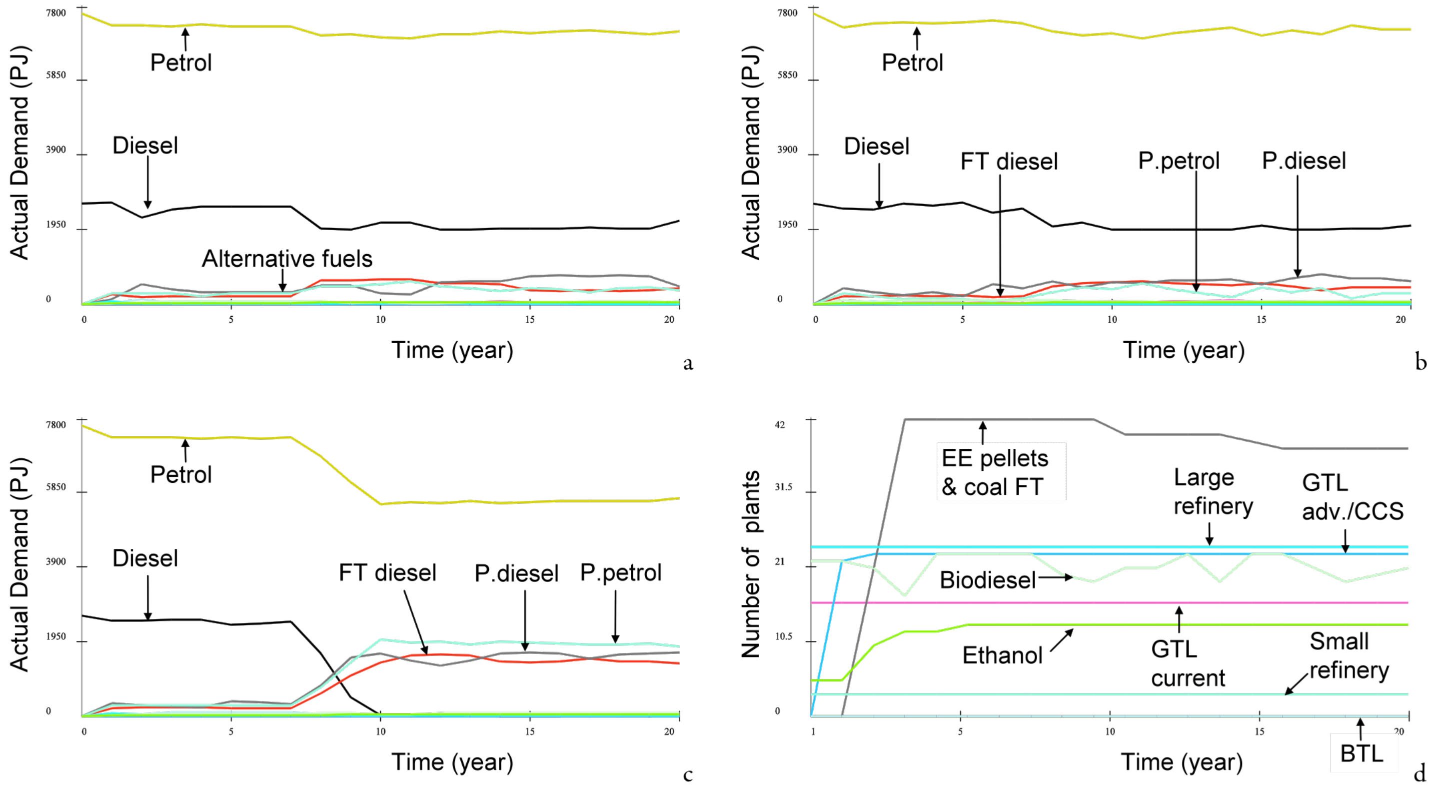
When we compare the latent demand for alternative fuels with actual demand, the low activity in alternative fuel production becomes clear (figure 6.7). As the latent demand curve shows, motorists do not demand B20 and E10 blends because their positive properties are not sufficiently different from the baseline fuel to exceed the tolerance level in our parameterization. There is a latent demand for E85 and B99, but production remains insufficient to satisfy it. For E85 this is because ethanol is competitive in term of production, but the 45% import tariff makes producing more than the quota unprofitable. In a similar sense, the steep supply curve of oil seeds limits the amount of commercially available. In both cases, actual demand remains below the latent demand, as visible in figure 6.7. In contrast, the low supply for FT fuel and the E20 and B10 blends matches latent demand, so these are apparently not very attractive to motorists.

6.4.2 Experimenting with FT production

We perform three model experiments to investigate how FT fuels can become more attractive to the motorist population:

- Reducing the price of FT blends to that of mainstream diesel and petrol;
- Reducing perceived emissions of FT fuels and FT blends (relative to petrol and diesel) to 0.6, analogous to a successful large scale sustainable biomass certification scheme;
- Adding a ‘buzz-factor’ that increases the perceived market share, for instance as a consequence of an advertisement campaign.

Only reducing FT prices to that of mainstream fuels or only reducing perceived emissions does not produce much change in demand, because popularity (priority 2 for most motorists) becomes a limiting factor. The only difference is that environmentally inclined motorists abandon ethanol and biodiesel blends for pure FT if it is perceived to be green, and this is a very small group. Figure 6.8 shows the result of the buzz and combinations of buzz and lower prices and combinations of buzz and lower perceived emissions.



Figures 6.8a-d: Actual Demand (in PJ/year) using a buzz factor of 0.2 for FT fuels and blends (a, top), with both buzz and low perceived emissions (b, upper middle), and with both buzz and prices of mainstream petrol and diesel (c, lower middle). Also shown are the number of plants per chain using both buzz and prices of mainstream petrol and diesel (d, bottom).

When a buzz factor equal to baseline 20% share of the total market is introduced, the FT fuels manage to penetrate all of the niches that are not limited by price and environmental preference. If the buzz is combined with a green image, pure FT diesel takes all but the price conscious consumers. If buzz is combined with mainstream pricing, FT almost corners the diesel market, though motorists from the Green agent groups continue to prefer biodiesel and ethanol. The large demand also causes the deployment of early 80% coal / 20% biomass FT plants in addition to advanced natural gas-based plants (GTL) with CCS to reduce CO_2 emissions.

We perform additional experiments to investigate how the known uncertainties in conversion costs and emissions affect the results of these outcomes:

- Increasing ConversionCost for FT plants by 80%, representing the effects of a construction boom that leads increased costs of manpower and equipment;
- Reducing ConversionCost for biomass-based FT plants (BTL) by 20%, representing (government) support for investment in advanced biofuels;
- Increasing the ROR requirement for new plants to 1.5, representing high uncertainty about regulations and emission caps;
- Reducing the ROR requirement for new plants to 1.1, representing long term certainty about regulations and emissions caps.

Changing the investment costs and required ROR do not change the demand for fuels directly, but does affect the establishment of new plants. Using high costs or high ROR_{new}, no biomass-using plants appear at all and FT is produced from natural gas only (figure 6.9a). At a ROR_{new} of 1.1, an initial boom in 80% coal / 20% biomass plants is followed by the appearance of advanced 50% biomass (willow torrefied pellets) / 50% coal plants with CCS (figure 6.9b). This is due to random fluctuations that cause the older plants to be replaced[33]. The same pattern repeats if BTL cost is reduced by 20%, except that advanced BTL plants with CCS are not sufficiently profitable.

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[33] The advanced 50% biomass / 50% coal plants are constructed because we prohibited the construction of additional early generation 80% coal / 20% biomass plants (which have almost twice the CO_2 emissions of oil refineries). However, their appearance is triggered by a recurring phenomenon that causes several of the early coal/biomass plants to be retired. The trigger circumstances are created by random fluctuations in demand between pure and blended FT fuels (which are regarded as equivalent by our motorists), induced fluctuations in marginal feedstock costs (from rises and falls in production volume) and the price competition mechanism. The plant retirements then create an opportunity when demand for pure FT fuels picks up. If we do not prohibit the construction of 80% coal / 20% biomass plants, these are rebuilt because of a higher ROR, and no advanced plants are built.

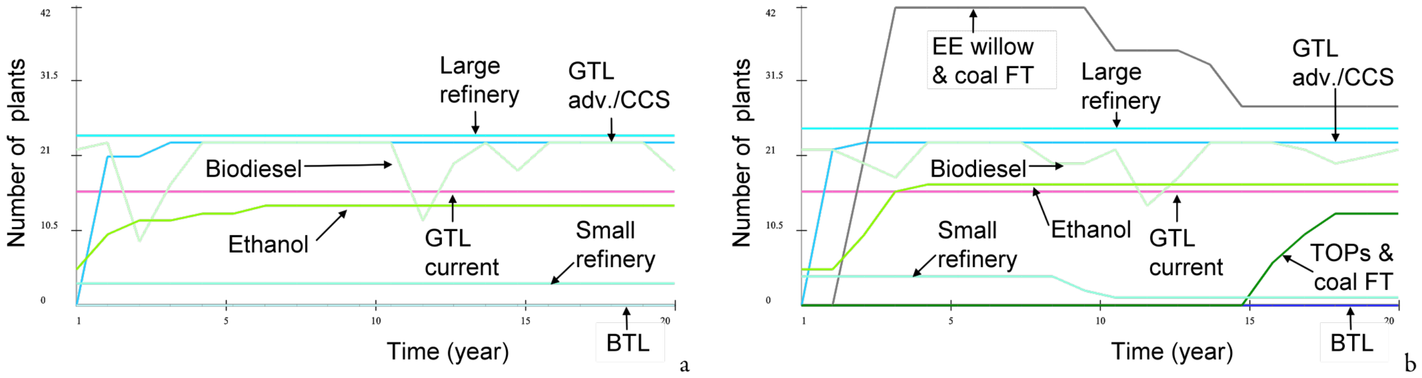

Figure 6.9a-b: Number of plants with investment costs increased by 80% (a, top) and with ROR_{new} requirement reduced to 1.1 (b, bottom).

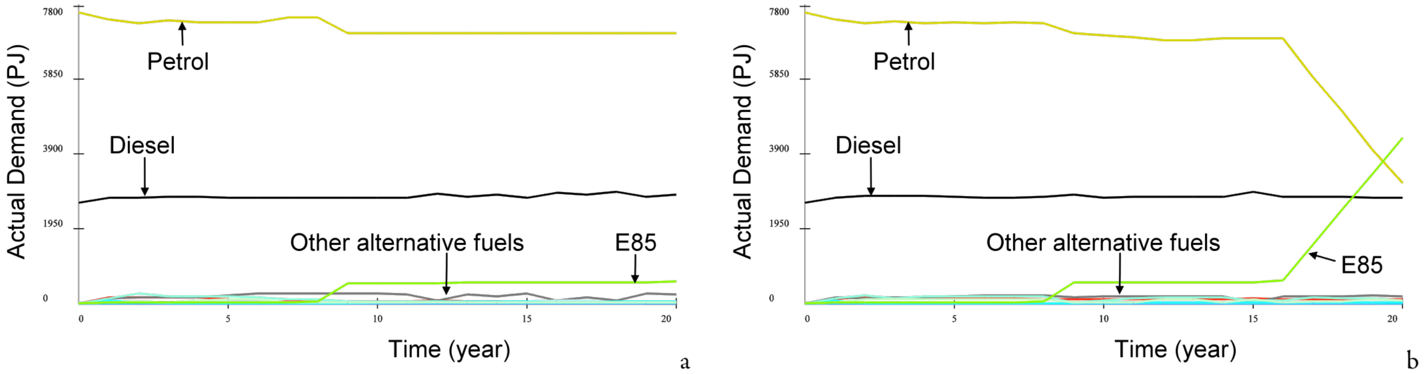

Figure 6.10a-b: Actual Demand (in PJ/year) using a 10% import tariff on ethanol (a, top), and combining a 10% import tariff on ethanol with a buzz factor of 0.1 for ethanol blends (b, bottom).

6.4.3 Experimenting with biodiesel and ethanol production

We subsequently examine how the market share of first generation biofuels responds to:

- Increasing the price of biodiesel to premium fuel price level;
- Exempting biodiesel from excise duty (VAT still applies), with all of the difference pocketed by the producers. This applies only to the biodiesel component in blends;
- Reducing the maximum import tariff on ethanol from 45% to 5%;
- A 'buzz-factor' that increases the perceived market share, for instance as a consequence of an advertisement campaign.

For biodiesel, increasing the price and exempting it from excise duty fail to raise its market share much beyond the base case, even when accompanied by a buzz of 0.2 which should make biodiesel blends acceptable to all diesel consumers in terms of popularity. With buzz and subsidies, the producers can make a profit using more expensive oil seeds, even exhausting the entire supply of oil seeds with the extra profit from exemption of excise duty. However, even with maximum production of around 300 PJ of B99, the resulting graph of realised demand is very similar to figure 6.6a.

Development of biodiesel is also contingent on having enough supply of ethanol: If there is insufficient production, our model will give priority to drivers who did not have their fuel of choice last year, and this will sometimes cause a shortage of ethanol used in the production of biodiesel. Additionally, fluctuations in resource cost and induced changes in fuel sales prices can lead to behaviour similar to pork cycles in model parameterisations with a steep resource cost slope relative to biodiesel plant size.

For ethanol however, the results are strikingly different, as is visible in figure 6.10. The effects of the lower import tariff cause all of the latent demand to be fulfilled, as expected. Adding a buzz factor gives an interesting result: on its own, the buzz is not enough to convince the larger population of petrol drivers to consider ethanol blends. However, once sufficient capacity comes online to satisfy the latent demand in niches, the boost in market share from the buzz convinces the masses, and E85 corners the market.

Not surprisingly, a rise in oil prices causes a wider range of alternatives to become profitable (using a price adjustment exponent >0). This has the same effect as reducing duties on all alternative fuels simultaneously.

6.5 Discussion

Our model is an attempt to incorporate several non-economic attributes and feedback mechanisms, going beyond aggregated price elasticity and s-curves that are common in techno-economic models. We explicitly model motorist preferences, in a way that is easy to link to real-world choice mechanisms and policy interventions. We use this to examine the interaction of the resulting latent and actual demand with a system-dynamics supply model. We assert that such aspects can play an important role in gaining understanding of technological transition dynamics, as demonstrated in the experiments with emergence of advanced FT fuels plants and the adoption cascade for ethanol.

Agent based models are a particularly suitable tool to explore social dynamics such as fashions and hypes that emerge as a result of interactions between many consumers. The more interactions take place between consumers, the more unpredictable the system may behave due to self-amplifying social processes.

For policy making, this is important, as it may ultimately result in locked-in situations which are almost irreversible. Social simulation, if based on sound empirical data, may contribute to the development of early warning systems to identify such unfavourable developments, and may suggest effective counter strategies. More positively framed, social simulation is expected to become a valuable tool in developing strategies for stimulating the social diffusion of beneficial innovations. A modular approach, using agent-based simulation where appropriate within larger (model-based) efforts would balance increased complexity with increased insight.

However, limitations remain: Model simplifications imply that possibly important mechanisms are overlooked. We do not account for the role of new car designs and competition for natural gas and biomass from other sectors (electricity generation, heating) are not considered. Secondly, our data for feedstock supply and prices is rough, and we observe a scarcity of publicly available data on consumer fuel preferences. We attribute this scarcity to the high commercial value of this data to fuel and car producers. Furthermore, as with all agent-based models, it is difficult to find evidence in the data for the decision rules according to which consumers and producers behave.

As a consequence, it is hard to validate a model like this, and we did not validate it against a real-world transition. Yet, in a limited way it incorporates and explores behavioural aspects of the energy transition which are often only treated implicitly or left out altogether - in this sense, we see no alternative than going further down this road.

We observe two possible avenues to trigger co-evolution between supply (construction of new plants) and demand (increase in latent demand):

1. Create parity in all areas where the new fuel is unattractive, as multiple barriers to adoption reinforce each other. Simultaneous sustained action (provide cheap and sustainable feedstocks, investment guarantees, marketing, procurement) on all barriers is needed. All else being equal for producers and consumers, latent demand increases and production capacity of that fuel will expand.

2. Make the incumbent fuel compellingly unattractive in its most important attribute (price and profitability) for sufficient length of time. This could result from a price shock, supply shortfall, or legal restriction or quota. This creates an opening for multiple new fuels.

In our simulations, we find that the introduction of new generations of technologies in FT fuel chains are entirely overshadowed by dynamics in feedstock price and availability: the fixed costs are high but similar across chains, making feedstocks the decisive factor.

In the fuel sales price adjustment we observe tension between gaining market share and conserving high prices that make investment in additional capacity attractive. We model this in a very basic way and do not address the long-term business strategies that competing fuel producers might use (though the resulting dynamics are quite complex). The results from our heterogeneity example (figure 6.5) suggest that predatory pricing may be an interesting strategy for established producers.

For demand dynamics, we find that the exact sizes of the 11 subpopulations did not make much difference to the dynamics that emerged. However, the characteristics of the subpopulations are important, which indicates the need for empirical research to discover salient attributes for future simulations (see also [58]).

To improve social feedback loops among our motorist agents, certain niche groups could be formalised as highly visible early adopters, more influential than strictly determined by their size [410]. However, the visibility of a fuel as a product is much lower than that of a car or a gadget, and presumably plays a smaller role in the real world. Another possible refinement is the use of a diffusion model, such as a small-world network or percolation model to formalise social feedback (c.f. [411, 385]).

Real motorists also switch between cars. While a switch from petrol- to diesel-fuelled cars is observed in real-life, the transition is slowed by the replacement rate for cars [204, 405], and takes similar time as a fuel production transition. Simulating such a transition requires a credible formalisation of motorists' decisions on buying a new car, which is difficult to construct, and outside the scope of this study (c.f. [57, 404, 384, 412]).

6.6 Conclusions

We have formalized and parameterized a detailed multi-agent model for the production of 6 transport fuels and 6 fuels blends from 6 feedstocks through 13 different production chains, and their adoption of by 11 distinct subpopulations of motorists. Our model improves on traditional least-cost optimisation models by including non-economic attributes and social feedback.

Adoption of alternative fuels was most often confined to niche markets with a share of 5% or lower. Only in a single case was a complete fuel transition observed. It was particularly difficult to create a self-sustaining virtuous cycle of adoption. The variety in results indicates that it is not feasible to pick any winners among alternative fuel technologies, because the outcomes of our simulations can be upended in a wide variety of ways. However, the following lessons were learned:

- Price is the major selection criterion for motorists. For a large scale transition, alternative fuels must have, at most, the same price as conventional diesel and petrol. This was also demonstrated by the development of ethanol in Brazil.

- Price is the major criterion in fuel choice, but it is not the only criterion. Whereas significantly cheaper alternatives to petrol and diesel are always likely to find a market, other factors play a role when prices are similar. All relevant barriers must be addressed simultaneously to enable co-evolution .

- Providing transparent information to consumers is important, to prevent that a fuel with a green image but high emissions will achieve an unreasonable market share, and a green fuel that is not known as such will not make headway.

- Separate niche markets might not be large enough to create a complete industry, but even with sufficient demand, biofuels in particular may be more limited by the availability of (sustainable) feedstocks. Producers of a fuel with limited potential for expansion are not served by trying to compete their way of their existing niche market.

- Policy stability is important. The interventions made in our experiments would fail to produce results if they are discontinued before both producers and consumers have entered into a new equilibrium, given a delay in adjusting production capacity to (latent) demand. The effect of cumulative policy measures may take a long time to surface.

In simulating motorists, we found that including salient attributes is more important than the accurate size of subpopulations. Further investigation is recommended into marketing and public perception of existing and alternative fuels, as well as relevant social networking and economic feedback mechanisms.

Appendix 6: FuelAdopt model equations and parameterisation

This appendix contains equation specifications and a detailed explanation of our dataset.

6.A.1 Equations

Rate of return is calculated with the following equations, where p_{fi}=price of market fuel f supplied by plant I, $p_{j,marginal\_segment}$=price of the marginal resource segment, and Q_{j_max}=quantity of feedstock used at installed capacity.

Using the same subscripts, S=production (or supply), D=demand and C=production capacity. $D_{f,actual}$ refers to aggregate actual demand, as opposed to latent demand, C_{active} refers to plants that have finished construction and are producing fuel.

$$ROR_i = \frac{\sum_f NetSales_{if}}{ConversionCosts_i + \sum_j FeedCosts_{ij}} \tag{6.2}$$

$$NetSales_{if} = p_f \cdot S_{if} \tag{6.3}$$

$$S_{if} = \mathrm{MIN}\left\langle D_{f,latent} \middle| C_{if} \cdot CapacityUsed_{if} \right\rangle \tag{6.4}$$

$$D_{f,latent} = \sum_m (D_{mf,latent} \cdot TravelDistance_m) \tag{6.5}$$

$$CapacityUsed_{if} = \mathrm{MIN}\left\langle 1 \middle| \mathrm{MAX}\left\langle \frac{D_{f,actual}}{\sum_i C_{if,active}} \middle| 1 - SpareCapacityFraction \right\rangle \right\rangle \tag{6.6}$$

$$D_{f,actual} = \sum_m (D_{mf,actual} \cdot TravelDistance_m) \tag{6.7}$$

$$FeedCost_{ij} = p_{j,marginal\_segment} \cdot \mathrm{MAX}_f \left\langle CapacityUsed_f \right\rangle \cdot Q_{j\_max} \tag{6.8}$$

Chain availability is evaluated using the following inequation (if a threshold is set), where the plant becomes available if cumulative production increases so that the inequation is true.

$$\sum_f \frac{\sum_{year0 \to t} \sum_i S_{yif}}{MinimumThreshold_f} \geq 1 \tag{6.9}$$

Price adjustment is calculated using the following equation:

$$p_{adjusted} = \left(\frac{ROR_{target}}{\mathrm{MIN}_{chains}\left\langle ROR_{f,projected} \right\rangle} \right)^{\alpha} \cdot p_{base} \tag{6.10}$$

where ROR_f, projected is the ROR of an existing plant (if available) or a possible plant type (if no plant exists that produces this fuel) that makes this fuel, and assuming it produces at effective capacity (so that $CapacityUsed_{projected}$ = 1- SpareCapacityFraction).

WTT plant unit	Input (PJ/year)	Output (PJ/year)	WTW GHG emis. (gCO2/MJfuel)		Conversion & transport (M€/yr)		Maximum ROR	Initial plants
ME NG to 2GW/ATR/SMDS	oil: 0.6, ME NG: 63.3	FT diesel: 16.3, FT petrol: 2.9, elect: 14.1	110	+20	329	200-380	1.3	28
ME NG to 2GW	oil: 0.6, ME NG: 63.3	FT diesel: 20.7, FT petrol: 3.7, elect: 13.3	97	+20	312	190-360	1.6	
ME NG to 2GW/CCS	oil: 0.6, ME NG: 63.3	FT diesel: 20.7, FT petrol: 3.7, elect: 12.9	65	+20	304	180-350	1.6	
EE willow pellets to 400MW	oil: 0.2, LC biomass: 15.3	FT diesel: 5.5, FT petrol: 1, elect: 0.8	25	+220	130	90-150	0.9	
EE willow pellets to 2GW	oil: 1.1, LC biomass: 76.4	FT diesel: 27.6, FT petrol: 4.9, elect: 4.2	25	+220	525	380-590	1	
EE willow pellets to 2GW/CCS	oil: 1.1, LC biomass: 76.4	FT diesel: 27.6, FT petrol: 4.9, elect: 2.8	-87	+230	497	340-560	1	
EE willow to 2GW/CCS EE	oil: 0.6, LC biomass: 76.4	FT diesel: 27.6, FT petrol: 4.9, elect: 2.8	-89	+230	489	340-550	1.1	
Mixed EE willow pellets & coal to plant	oil: 0.2, coal: 52.5, LC biomass: 13.1	FT diesel: 27.3, FT petrol: 4.9, elect: 4.5	159	+39	394	243-450	1.3	
Mixed EE TOPs & coal to plant/CCS	oil: 0.4, coal: 33.3, LC biomass: 33.3	FT diesel: 27.3, FT petrol: 4.9, elect: 3.9	3	+101	483	330-550	1.1	
Large oil refinery	oil: 678.3	diesel: 303.4, petrol: 304.4	88	no data	2563	. . -4630	1.5	24
Small oil refinery	oil: 226.1	diesel: 101.1, petrol: 101.5	88	no data	870	. . -1570	1.5	3
EU REE biodiesel	oil: 0, oil seeds: 6.4	biodiesel: 3	55	+12	7	no data	2.5	22
LA cane to ethanol	oil: 0.1, LA sugarcane: 10.4	ethanol: 3.9	13	+12	29	no data	1.7	5

Note: In the conversion & transport and GHG emissions columns, the left set of numbers is the base value used in this model and the right set are uncertainty ranges. The GHG uncertainties are vs. the base value. Initial plants are the number of units needed to make current production volumes. Sources: [250, 348, 62, 45, 213, 136, 126]

Table 6.3: Selected properties of plants based on WTT analyses.

When fuel price coupling is used, $ROR_{f,\ projected}$ uses the highest ROR among the coupled fuels. With fuel price coupling, if $PriceAdjustement_f{}^*ROR_{f,\ projected} < ROR_{safe}$, a minimum price is calculated with $ROR_{f,\ projected}$ for that fuel and ROR_{safe} used instead of ROR_{target}.

6.A.2 Supply (production and resource) data

Fuel supply depends on two sets of data: WTT chains for converting feedstocks into fuels, and the potential supply of feedstocks. We examine the following market fuels: regular (oil-derived) petrol and diesel, E10 and E85 ethanol blend, B20 and B99 biodiesel blends, pure FT petrol and diesel, and premium petrol or diesel (see figure 6.4, section 6.2.1).

The data used for the WTT chains are summarized in table 6.3. The chains include distribution, conversion to fuels, conversion to intermediates where applicable, and transport of raw materials and intermediates. The natural gas- and willow wood-based FT chains become unlocked (see section 6.3.1) in the order in which they are listed. The biodiesel is rapeseed ethyl ester (REE), which requires some 10% (energy/energy) of ethanol in its production. We used REE instead of methyl-ester biodiesel (FAME) to avoid the added complexity of introducing production data for methanol. We assume rapeseed cake is used as animal fodder and give GHG emissions credit accordingly (as in [45]). We assume that conversion cost and efficiency for sunflower seeds are the same as for conversion of rapeseed. To facilitate calculations, the ethanol input for REE was factored out and included in the blending stage instead (see below).

Uncertainties in costs and/or GHG balances of all fuels are considerable (see [250, 45, 24]). Transport is by truck, rail or ship as appropriate. We require an IRR of 20% for new plants (commercial discount rate, see [179]). This is roughly equivalent to a ROR of around 1.4 for new FT plants, which we use as the ROR_{new} for all new plants. For existing plants we set a break-even ROR_{min} of 1.0.

Upstream from the conversion plants comes the supply of feedstock. The transport fuel market size is roughly that of the EU, at 2.75 Gbbl of crude oil traded per year, or 17 000 PJ/year [413]. We assume that crude is delivered in the EU at a cost of 60 $/bbl as was the case in late 2007/early 2008. For coal, we assume that the price of 2.0 €/GJ [2, 3] is independent from use in FT plants and remains constant without any impact from scarcity or coupling with other fuels.

In the short term, the majority of commercial production of FT fuels for Europe will be based on natural gas from the Middle East (ME). For instance, in Ras Laffan, Qatar, a total capacity of 239 thousand barrels per day (kbpd, 1794 PJ/year) is to come online before 2012 [66]. However, one may expect that natural gas is preferably used for export in liquefied form (LNG), and that production of FT is used only to diversify the existing export portfolio of Qatar. Therefore, no more natural gas will become available for FT than was already allocated and the potential supply is limited to the 1794 PJ/year of existing developments and another 600 PJ/year (80 kbpd) in cancelled projects. The delivery costs of natural gas in these applications are set at 1.0 €/GJ (derived from [3]).

The EU produced also some 1.9 Mtonne of biodiesel (73 PJ) and 0.5 Mtonne of ethanol (13 PJ) in 2004 [65]. For ethanol from Latin America (LA) we assume sugar cane is priced at 3.0 €/GJ [262]. However, the EU has a 45% import tariff on ethanol at present-day price [406, 403]. We include this tariff of 19 €ct/l in the price of sugarcane, which is equivalent to 4.1 €/GJ cane. Therefore, we use 3.0 €/GJ for the volume of 98 PJ cane needed to produce 1.75 million litres of ethanol that were discussed for an EU import quotum in 2008 [403]. For volumes beyond that, we introduce a rapid increase in the cost in steps of 0.45 €/GJ towards 7.1 €/GJ after which no further increase is assumed.

For feedstock for FT biofuels we focus on potential supplies from (Eastern) Europe [352]. Although potential supplies of such biomass from the rest of the world could become considerable over time [76], sustainably setting up infrastructure and production capacity for the volumes considered for FT plants will take considerable time (see [250]).

The supply curve for European biomass was derived from the 2010 data from the REFUEL project [352], by allocating land areas to oil seed crops (rapeseed or sunflower) or lignocellulosic (LC) biomass (willow, poplar, eucalyptus, or reed canary grass), depending on which crop results in the cheapest fuel. For this allocation we used FT processing costs for small scale conversion, reflecting the existing situation. This may lead to an overestimation of the supply of oil seeds and an underestimation of the supply of LC biomass.

Biomass supply curves have been simplified from the original data: small segments of similar price are clustered into larger segments and the upper tail, where feedstock quantity increases slightly and cost increases exponentially is cut off, in order to reduce data intensity and computation time. The resulting supply curve for oil seeds has a maximum of 616 PJ/year, for LC biomass of 2696 PJ/year. These levels correspond with 2% and 8% respectively of the EU transport fuel market. Table 6.4 summarises the data on feedstocks, and figure 6.11 shows the resulting supply curves. Feedstock supply curves are kept the same in all simulations unless noted otherwise.

We assume no limits to the potential volume of CO_2 captured and stored (CCS).

Crude oil		Coal		ME natural gas		LC biomass		Oil seeds		LA sugarcane	
size (PJ/year)	cost (€/GJ)	size (PJ/year)	cost (€/GJ)	size (PJ/year)	cost (€/GJ)	size (PJ/year)	cost (€/GJ)	size (PJ/year)	cost (€/GJ)	size (PJ/year)	cost (€/GJ)
0 - 8414	6.4	unlimited	2.0	0 - 1794	1.0	0 - 173	1.7	0 - 41	4.3	0 - 98	3.0
8414 - 16828	7.2*			1794 - 2394	1.0	173 - 288	1.8	41 - 89	4.3	98 - 109	3.4
16828 - 18510	7.9					288 - 407	1.9	89 - 126	4.5	109 - 119	3.9
18510 - 20193	8.7					407 - 521	2.0	126 - 145	4.7	119 - 129	4.3
20193 - 21876	9.5					521 - 710	2.0	145 - 168	4.8	129 - 140	4.8
						710 - 864	2.1	168 - 203	4.8	140 - 150	5.3
* 7.2 is equivalent						864 - 979	2.1	203 - 232	4.9	150 - 161	5.7
to 60$/bbl						979 - 1149	2.2	232 - 252	4.9	161 - 171	6.2
						1149 - 1268	2.3	252 - 306	5.0	171 - 181	6.6
						1268 - 1416	2.4	306 - 377	5.0	unlimited	7.1
						1416 - 1535	2.5	377 - 397	5.0		
						1535 - 1729	2.8	397 - 421	5.1		
						1729 - 1841	2.9	421 - 440	5.2		
						1841 - 1966	3.0	440 - 459	5.2		
						1966 - 2142	3.2	459 - 486	5.2		
						2142 - 2254	3.3	486 - 513	5.2		
						2254 - 2364	3.6	513 - 544	5.4		
						2364 - 2475	3.9	544 - 571	5.5		

Table 6.4: Feedstock supply segment sizes (PJ/year potential production) and costs (€/GJ) for crude oil, coal, Middle East natural gas, lignocellulosic biomass, oil seeds and sugarcane used in our model experiment.

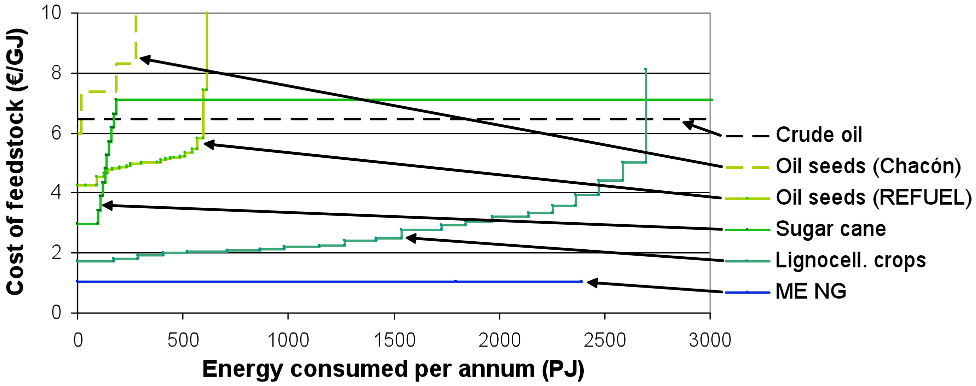

Figure 6.11: Supply curves of feedstocks used in our model experiment.

These producer fuels can be blended into market fuels within certain combinations. Biodiesel and ethanol are available to motorists only as ingredients in blends with regular petrol or diesel. Table 6.5 lists the mix ratios of the blended market fuels considered in our model experiment. We also coupled the sales prices of petrol to its alternatives and of diesel to its alternatives, but not of the alternatives to each other, reflecting that the alternatives cater to different niche markets.

	Mix matrix (BlendFraction)	from producer fuel					
		diesel	FT diesel	biodiesel	petrol	FT petrol	ethanol
to consumer market fuel	diesel	100%	0%	0%	0%	0%	0%
	FT diesel	0%	100%	0%	0%	0%	0%
	biodiesel	0%	0%	90%	0%	0%	10%
	petrol	0%	0%	0%	100%	0%	0%
	FT petrol	0%	0%	0%	0%	100%	0%
	ethanol	0%	0%	0%	0%	0%	100%
	premium diesel	83%	17%	0%	0%	0%	0%
	B20	80%	0%	18%	0%	0%	2%
	B99	1%	0%	89%	0%	0%	10%
	premium petrol	0%	0%	0%	83%	17%	0%
	E10	0%	0%	0%	90%	0%	10%
	E85	0%	0%	0%	15%	0%	85%

Note: The ethanol ingredient of biodiesel, B20 and B99 is the ethanol needed to produce REE.

Table 6.5: Mix ratios of producer fuel compounds to market fuels.

6.A.3 Demand (motorists) data

We use data from JRC for cost, weight, fuel consumption and emissions for cars [45]. We combine this with data from the Dutch federation of auto service companies (BOVAG) on average annual kilometres driven per petrol and diesel car [204].

To parameterize the motorists in our model, we have to make assumptions about the fuel attributes driving price, emissions and performance as perceived by the 735 agents. The data we used for these attributes are normalised to the baseline fuels petrol and diesel and are based on expert judgement. They are summarized in Table 6.6. Note that the absolute values of fuel attributes are not relevant to motorists, only the relative values. Consumer sales prices for petrol and diesel (including VAT and excise duty) are derived from BOVAG data [204]. Producer sales prices (excluding excise and VAT) are derived from consumer sales prices. The popularity of each fuel is proportional to the market share of the fuel, representing one of the feedback loops in the model. Minor exogenic demand stimuli between 1-10 PJ/year are included for alternative fuels to slightly cushion the impact of demand fluctuations, though these are insufficient to drive market development on their own.

Fuel name	Producer price (€/GJ)	Consumer price (€/l)	Performance 'higher is better'	Emissions 'lower is better'	Real emissions (gCO2eq/MJ)	Demand stimulus
diesel	17	0.99	1.0	1.0	88	0
FT diesel	20	1.05	1.3	1.0	-89 to 159	0
biodiesel	29	n/a	n/a	n/a	55	0
petrol	17	1.25	1.0	1.0	88	0
FT petrol	20	1.30	1.0	1.0	-89 to 159	0
ethanol	26	n/a	n/a	n/a	13	0
premium diesel	19	1.05	1.2	1.0	59 to 100	5
B20	19	0.99	1.0	0.9	81	10
B99	29	0.99	1.1	0.6	52	0
premium petrol	19	1.30	1.2	1.0	59 to 100	1
E10	18	1.25	1.0	1.0	81	10
E85	25	1.25	1.2	0.6	24	0

*The producer price for ethanol here also includes applicable import tariffs.

Table 6.6: Fuel properties as perceived by motorists. Prices are in €/GJ, emissions and performance normalised to baseline fuel (petrol or diesel) and based on expert judgement. Producer prices include applicable import tariffs.

We also need to estimate the preferences of motorists and their tolerance levels. Such behavioural parameters are notoriously difficult to obtain. Market shares of individual fuel brands are closely guarded commercial secrets, especially in relation to demographic data. Faced with a lack of international data, we extrapolated attribute priorities, tolerance and agent populations from the Dutch situation to a population with the EU's demand for transport fuels.

Table 6.7 shows the Dutch market shares of cars and fuels. We extrapolated the steadily growing market shares of diesel cars of previous years to a market share of 65% for leased cars [405, 204]. Diesel cars on average drive 2.4 times as many kilometres as petrol cars, which is consistent with leased car profiles[34].

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[34] Leased car drivers are traditionally salesmen, consultants, service engineers and others who travel a lot for their job. They receive a car from their employer to reduce large travel expenses. This is fiscally advantageous in the Netherlands.

	Vehicles on the road		
	on petrol	on diesel	total
private cars	81%	12%	93%
leased cars	3%	4%	7%
total	84%	16%	

	km driven per year		
	on petrol	on diesel	total
private cars	66%	20%	85%
leased cars	4%	10%	15%
total	70%	30%	

	Fuel used per year (energy basis)			
	petrol	premium	diesel	total
private cars	65%	3%	18%	86%
leased cars	4%	0%	10%	14%
total	69%	3%	28%	

Table 6.7: Share of cars, distance driven and fuel used per year in NL in 2005.

Nijhuis found that in choosing cars, customers on average rank price as more important than brand/image and performance, and environment below these three [57]. As fuels are much less noticeable than the cars that drive on them, we assume that brand/image becomes less important. We also know that many of the leased car drivers do not pay for their own fuel and are therefore less strict about the price of the fuel they choose [404, 393]. However, the only hard number we have on the preferences of heterogeneous motorists is that sales of premium petrol (which improves performance) are 4% of total petrol sales [204][35]. For a taxonomy that can define possible niche markets for alternative fuels, we therefore have to rely on other (general) data.

Visser et. al. have conducted surveys to gauge the Dutch consumer's value dispositions within the TNS-NIPO WiN™ model [408, 407]. Out of 8 sections of society (see figure 6.12), the conservative, materialist and broad-minded sections are of interest with regards to our fuel attributes. The key word for conservatives (as defined in this survey) is 'conformist', which would suggest that the popularity of a fuel is important for this section (16% of people). The key word for materialist is 'achievement', which suggests that performance of a fuel is important for this section (11% of people). The key word for broad-minded is 'involved', which suggests that emissions from a fuel are important for this section (7% of people). Veldkamp and TNS-NIPO also found that the broad-minded section was significantly more willing to pay a CO_2-fuel tax than others [409].

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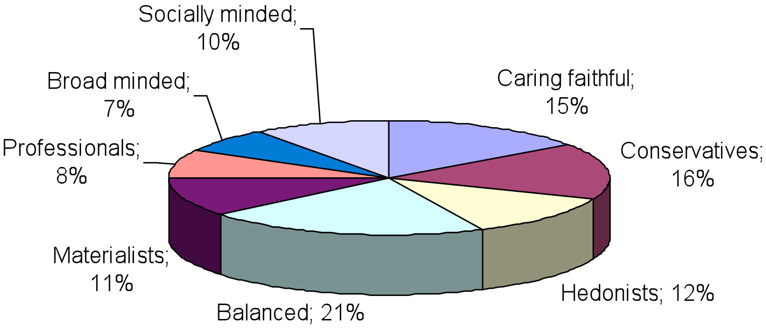
[35] Market share of premium petrol has declined rapidly from >10% before 2000 to ±4% in 2005.



Note: Adapted from MNP [408].

Figure 6.12: WiN value dispositions among the Dutch public.

However, evidence exists of a sizeable gap between attitudes and behaviour [59]. Considering the known market share of premium petrol, we assume that the share of consumers interested in performance is not 11% but 4%. By proportionally downscaling our other sections who do not have cost as their main priority, we derive that the majority (86%) of the Dutch public cares most about cost, another 6% care most about popularity, 4% care most about performance and 3% care most about environment.

We assume leased cars are distributed in proportion to size of the two sections among professionals and cost-minded materialists on one hand (15%) and performance-minded materialists (4%), and we distribute private cars globally among the four shares of the Dutch public (86%, 6%, 4%, 3%). We arrive at 11 populations of agents, each given a (caricature) nickname for sake of easy reference, with properties as shown in table 6.8. Each agent starts out by using either normal petrol or normal diesel, depending on their type of car. The first three groups comprise 635 agents, or 86% of the population, seem least likely to by drawn to alternative fuels, while the remaining 100 agents, or 14% contain all of the groups that are drawn to alternatives.

Group nickname	Size	Agents	Car	Primary	Secondary	Tertiary	Last	WiN Constituents
Mondeo Man	70,4%	517	petrol	Cost: 3%	Pop: 80%	Perf: 10%	Env: 20%	others
Golf Man	10,5%	77	diesel	Cost: 3%	Pop: 80%	Perf: 10%	Env: 20%	others
Conformist P	5,6%	41	petrol	Pop: 70%	Cost: 3%	Perf: 10%	Env: 20%	Conservatives
Big Spender D	3,3%	24	diesel	Cost: 10%	Pop: 80%	Perf: 10%	Env: 20%	Professionals
Petrolhead	2,7%	20	petrol	Perf: 10%	Cost: 3%	Pop: 90%	Env: 20%	Materialists
Green P	2,4%	18	petrol	Env: 20%	Cost: 3%	Pop: 80%	Perf: 10%	Broad minded
Big Spender P	2,3%	17	petrol	Cost: 10%	Pop: 80%	Perf: 10%	Env: 20%	Professionals
Traveller D	1,0%	7	diesel	Perf: 10%	Cost: 10%	Pop: 90%	Env: 20%	Materialists
Conformist D	0,8%	6	diesel	Pop: 70%	Cost: 3%	Perf: 10%	Env: 20%	Conservatives
Traveller P	0,7%	5	petrol	Perf: 10%	Cost: 10%	Pop: 90%	Env: 20%	Materialists
Green D	0,4%	3	diesel	Env: 20%	Cost: 3%	Pop: 80%	Perf: 10%	Broad minded

Table 6.8: Characteristics of agent groups: nicknames, populations, cars used, preferences and tolerances, and value dispositions.

“Le doute n'est pas une condition agréable, mais la certitude est absurde.”

(Doubt is not a pleasant condition, but certainty is absurd)

– Voltaire, letter to Frederick II of Prussia, 6 April 1767

7. Summary and conclusions: Evolutionary strategies towards new fuels and cars

There is a need to determine feasible options for reducing emissions of greenhouse gas (GHG) emissions and diversifying our energy resources used for road transport. To this end, chapters 2-4 present energy use, cost and GHG emissions of various alternative fuels and vehicles in a well-to-wheel (WTW) chain perspective.

There is a further need to examine how the fuels and vehicles detailed in chapters 2-4 may be deployed to replace our existing ICE cars and crude-oil derived fuels. To this end, chapter 5 presents a cost optimisation model of the transportation and energy sector and chapter 6 an agent-based model of fuel adoption that takes motorist preferences into account.

Three recurring issues are encountered in doing these analyses: uncertainty in costs and GHG emissions of alternatives, competition between alternatives in relation to path dependency, and non-cost barriers to implementation and adoption by motorists.

7.1 Fuel options

On the fuels side, potential costs and GHG emissions of 15 Fischer-Tropsch (FT) chains are assessed in chapter 2. The results are compared with conventional diesel from crude oil, biodiesel and diesel made from synthetic crude oil (SCO, from tar sands or oil shale). In chapter 5, data are added for petrol and ethanol from sugar cane and ligno-cellulosic biomass.

FT plant configurations are combined with data on coal and natural gas supply, biomass production, conversion to biomass intermediaries such as pellets or torrefied wood pellets (TOPs), transport costs, vehicle costs and GHG emissions to arrive at complete WTW chains. Based on technological developments described in literature, assumptions are framed for these developments until 2020. These include moving towards biomass conversion at the source, improvements in process efficiency, and the use of carbon capture and storage (CCS) to (further) reduce CO_2 emissions.

Given the extent of the uncertainties that we and others have found, cost and GHG emission values for FT diesel in chapter 2 should be interpreted as best-guess estimates.

Costs of FT diesel depend in large part on feedstock prices and conversion plant efficiency. Gas-to-liquids (GTL) is found to be competitive with oil-based diesel in terms of cost at an oil price above 33 $/bbl. For coal-to-liquids (CTL), oil prices should be above 60 $/bbl. For biomass-to-liquids (BTL), oil prices should be above 75 $/bbl.

GHG emissions from FT diesel depend almost completely on the efficiency of conversion plants, the efficiency of conversion to biomass intermediates, and the feedstock used. CTL is found to increase our transport-related GHG emissions by 25%-110%. Diesel from synthetic crude oil (SCO) increases GHG emissions by 13%-60% and GTL chains without CCS by 10%. GTL with CCS is found to reduce GHG emissions by around 5% compared to fossil diesel. The net emissions from BTL can be an order of magnitude smaller and can be made negative by application of CCS.

It is possible to have net climate neutral driving by replacing around 50% diesel or petrol from crude oil with BTL produced with CCS. This requires that biomass gasification and underground CO_2 storage can be made to work on an industrial scale and the biomass feedstock is obtained in a sustainable (climate-neutral) manner. Results suggest that it is worth further exploring FT fuel production using the latest in technology and conversion as early in the chain as possible. In practice this would mean BTL or mixed FT plants with CCS, either in the country of origin of the feedstock or using an easily processed intermediate such as TOPs.

7.2 Car options

On the vehicles side, potential costs and emissions of four diesel-fuelled series hybrid (SHEV), four diesel-fuelled plug-in hybrid (PHEV) and four fuel cell car configurations are assessed in chapter 3. Energy efficiency, cost and GHG emissions are based on real-world data and projections for the future. Results are compared to regular internal combustion engine (ICE) cars and parallel hybrid cars. The same is done in chapter 4 for two petrol-fuelled series hybrid, two petrol-fuelled plug-in hybrid and four fully battery-powered electric car (BPEV) configurations. The focus in chapter 4 is on GHG emissions resulting from charging car batteries amid existing demand and supply of electricity.

Analysis in chapter 3 shows that series hybrid cars may reduce fuel consumption by 34%-47% compared to reference petrol and diesel cars. In this way, WTW GHG emissions can be reduced to 89-103 $gCO_{2\,eq}$/km using regular diesel. WTW GHG emissions from electric driving depend most on the fuel type (coal or natural gas) used in the generation of electricity for charging. Emissions range between 0 g/km (best case using renewables) and 155 g/km (worst case using electricity from an old coal-based plant). Based on the generation capacity projected for the Netherlands in 2015, electricity for electric vehicle (EV) charging would be generated using natural gas, emitting 35-77 $gCO_{2\,eq}$/km, depending on the exact power plants used. This would mean a reduction of GHG emissions of 51%-78% compared to current cars and fuels.

Given existing demand patterns for industrialised countries, uncoordinated charging of EV would increase national peak load of the electricity system by 7% at 30% penetration rate of EV. Household peak demand would increase by 54%. Such load may exceed the capacity of existing electricity distribution infrastructure, particularly at the street or district level. At 30%

penetration of EV, off-peak charging would result in a 20% higher and more stable base load, no additional peak load at the national level and up to 7% higher peak demand at the household level. Therefore, if off-peak charging is successfully introduced, electric driving need not strain infrastructure even in case of a 100% switch to electric vehicles.

Series hybrid cars with wheel motors have lower weight and 7%-21% lower fuel consumption than series hybrid cars with central electric motors. Results in chapter 3 project that wheel motors may become the cheapest and most efficient drivetrain in the future. The possibility to use wheel motors is the main benefit of a series drivetrain. However, series hybrid cars currently cost €5000-€10 000 more to purchase than ICE cars.

Total cost of ownership (TCO) of a wheel motor series hybrid car is currently higher than one with a central motor, but the difference is less than 500 €/yr at driving distances where series hybrid cars are preferred over a petrol car. TCO of future wheel motor PHEV may become competitive with regular cars and series hybrid cars without tax incentives when batteries cost 400 €/kWh, as long as one battery pack can last for the lifespan of the vehicle. Results suggest that it is worth further exploring wheel motor series hybrid drivetrains.

Battery powered EV and fuel cell cars are currently uncompetitive by a large margin. If, despite their current financial unattractiveness for use in cars, the production of fuel cells would increase so that the costs come down by 90%, series hybrids are still found to have slightly lower TCO. If the cost of batteries would come down by 85% to 150 €/kWh, BPEV can compete with (plug-in) series hybrids. However, it is unknown when these large reductions in costs of fuel cells and batteries may be achieved.

7.3 Adoption of fuels and vehicles

Switching to hybrid, plug-in, electric or fuel cell cars, and/or to renewable fuels can all reduce GHG emissions from cars and reduce dependence of the transportation sector on crude oil. However, this does not reveal how vehicle and fuel costs affect adoption of these alternatives in the context of the larger energy system.

To examine future interactions between the road transportation and power sectors in the Netherlands, in chapter 5 the MARKAL-NL-UU model is expanded with the data from chapter 2-4 to. The expanded model is used to simultaneously examine competition for energy resources, development of CCS, and co-evolution of electricity and fuel conversion capacity.

MARKAL optimises total system cost over a long time horizon, in this case without constraints on construction of new power plants and fuel conversion plants. Road transportation and power demand, availability of technologies over time, as well as supply and price of energy resources are included exogenously.

Results show that use of oil decreases considerably in all scenario variants, given the assumptions that are used. Absent GHG emissions limits, coal consumption almost quintuples due to increased use of coal in electricity generation and to produce FT fuels. As no CCS is used in this scenario variant, this development causes a 73% increase over 1990 levels of CO_2 emissions from road transportation and electricity generation by 2020.

When necessary GHG reductions in road transportation and electricity generation are considered together, lowest overall costs are achieved by using both biomass and CCS to maximum potential, and by using the least-cost CO_2 emissions reduction options in road transportation, even if that reduces biomass and CO_2 storage capacity available for electricity generation. Series hybrids are used if insufficient low-carbon fuels are available. Combining production of FT diesel with CCS is found to be more cost-effective than applying CCS in electricity production at coal or biomass fired plants.

The difference between investment in the scenario variant without GHG emissions limits and the variants with GHG reduction of 68% by 2040 (excluding those with forced adoption of electric and fuel cell cars) is 4-7 billion euro per year, equivalent to 0.5%-1.2% of GDP. This is mostly invested in cars and electricity generation capacity.

Electric cars and fuel cell cars have CO_2 abatement cost of 400 €/tonne CO_2 or more. These technologies are avoided if other options are available. By contrast, SHEV, ethanol, several BTL chains, and GTL+CCS can have negative CO_2 abatement costs. Options for an evolutionary transition (e.g. hybrid cars, biofuels) are therefore both less complex (as argued in chapter 1) and less costly (as results from WTW analyses and cost optimisation in chapters 2-5) than an invasive transition (electric cars, fuel cell cars and required infrastructure) of our road transportation system.

However, an alternative will not necessarily be adopted just because it is affordable. To go beyond cost optimisation, an agent-based model was created, as described in chapter 6. This model simulates production of fuels and blends from feedstocks and their adoption by heterogeneous motorists.

The agent-based model, though still a heavily simplified representation of fuel adoption, improves on traditional least-cost optimisation models. This is because it explicitly models motorist preferences in a way that is easy to link to real-world choice mechanisms and policy interventions. The model is used to examine the interaction of the resulting latent and actual demand with a system-dynamics supply model.

The agents in the model represent heterogeneous motorists. They choose fuels based on price, non-economic attributes of perceived vehicle performance and emissions to the environment, and on the market share of the fuel. Only drop-in replacement fuels (CTL, GTL, BTL, biodiesel, and ethanol) are considered and cars are taken as constant. Fuel production is limited by feedstock availability and demand. Conversion and blending into fuels is done with progressively advancing technologies. Fuel prices are dynamically determined from production costs and prices of competing fuels.

Results show that for a large scale transition, alternative fuels must have, at most, the same price as conventional diesel and petrol. If prices of alternatives are higher, the role of non-economic factors and social feedbacks is limited to niche markets. The variety in results indicates that it is not feasible to pick winners among alternative fuel technologies, because the outcomes of our simulations can be upended in a wide variety of ways.

It is particularly difficult to create a self-sustaining virtuous cycle of adoption of alternative fuels. This is because few fuels get in a position to improve on performance or emissions of incumbent fuels (thereby providing a reason for adoption) and have a similar cost to incumbent fuels and also gain sufficient market share to get accepted by the majority of motorists. If non-economic attributes and social feedback are included in the agent-based model, then adoption of alternative fuels is most often confined to niche markets with a share of 5% or lower. A complete fuel transition is observed in only one simulation, in case of sufficient supply of sufficiently cheap ethanol combined with a marketing campaign.

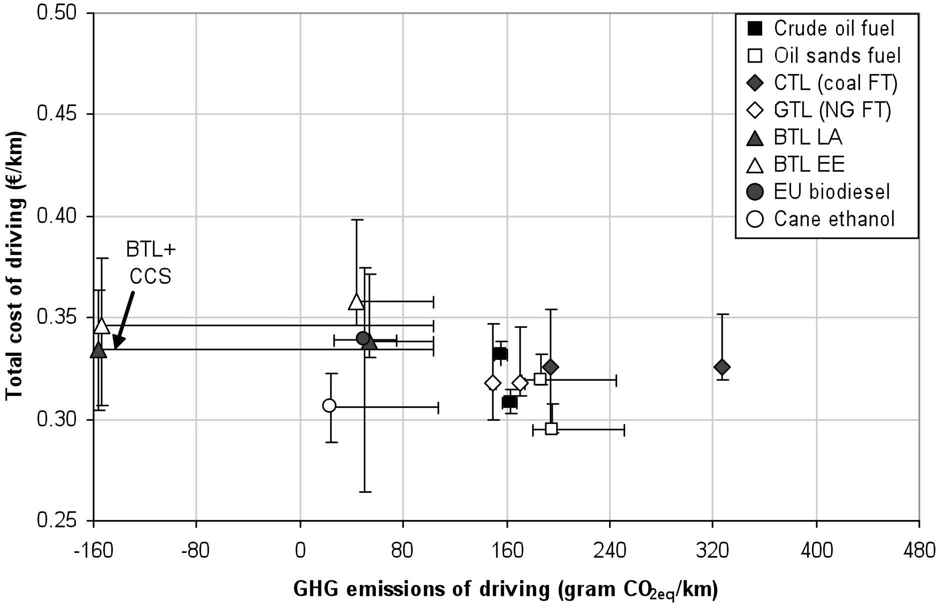
This indicates non-economic factors have far-reaching and unpredictable impacts that should be incorporated into energy system modelling efforts aimed at understanding market developments. Agent based models are a particularly suitable tool to explore social dynamics. Social simulation is therefore expected to become a valuable tool in developing strategies for stimulating the social diffusion of beneficial innovations.

7.4 Recurring issues: uncertainty

All of the alternative fuels and drivetrains examined in this thesis reduce our dependence on crude oil. Given sufficient available energy resources, drop-in replacement fuels and hybrid cars can reduce direct GHG emissions significantly, even to negative emissions per km when biofuels are produced with CCS.

However, significant uncertainties remain in the cost of alternative fuels. This is also the case for the GHG reductions unless sustainable production of renewable feedstocks can be guaranteed. For example, uncertainties to order of tens of percents were found in the data for costs of FT plant component costs, variability in prices of feedstocks and by-products, and the GHG impact of producing biomass. Significant uncertainties also exist in the future efficiency and costs of drivetrains.

Figure 7.1 and 7.2 show to the cost (€/km) and GHG emissions (gCO_{2eq}/km) ranges of using various fuels and drivetrains, compared to driving a reference compact diesel or petrol car with a crude oil price of 80 $/bbl[36]. Although fuels and drivetrains are shown in separate graphs, some of the fuel and drivetrain options can be used together (e.g. ethanol with a hybrid vehicle) to achieve higher GHG reductions and/or lower cost.



Note: Two symbols for the same fuel type indicates one chain using CCS (left) and one without CCS (right) for FT fuels, and diesel (top left) and petrol (bottom right) for crude oil and oil sands fuels.

Figure 7.1: Cost vs. emissions of fuel options, based on chapters 2 and 5.

Whereas all fuels derived from fossil feedstock have approximately the same or higher GHG emissions than regular diesel or petrol, biofuels can reduce GHG emissions significantly, even more than 100%. However, as reported in chapter 2, results should be interpreted as best guess estimates within ranges of uncertainty. Furthermore, the probability density within the ranges has a flat (possibly uniform) shape.

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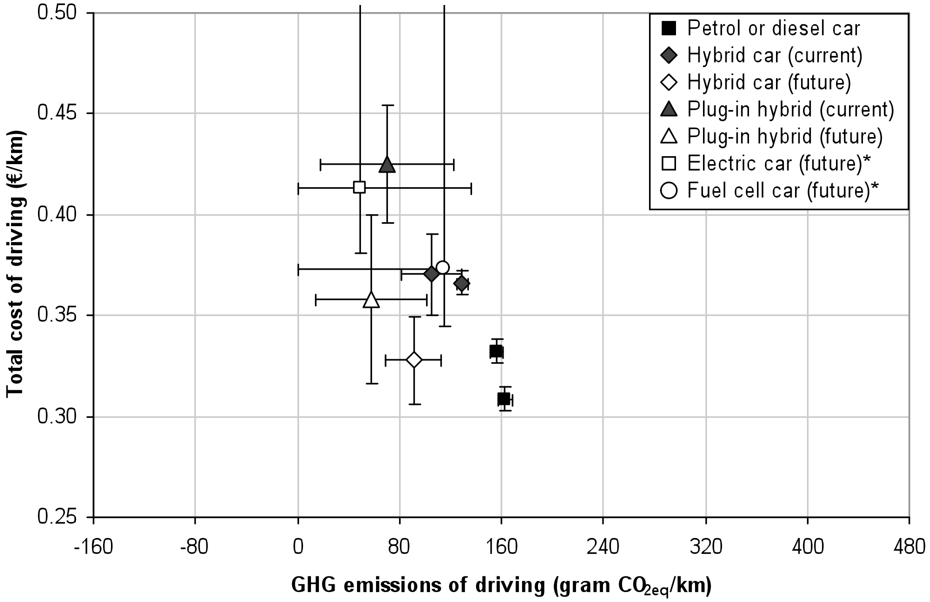
[36] Includes data used in chapters 2-5 from [45, 63, 184, 350, 262, 348] on conventional diesel and petrol, biodiesel, ethanol and SCO. Ranges calculated using minimum biofuels GHG reduction of 35%, NG extraction energy use of 1%-4%, oil refinery losses of 0.08-0.12 MJ_{feed}/MJ_{prod} for diesel and 0.064-0.92 MJ_{feed}/MJ_{prod} for petrol, oil price of 60-100 $/bbl, rapeseed costs of 7.4 to 17.5 €/GJ, ethanol cost of 8.0 to 18.4 €/GJ, CO_2 price of 0-122 €/tonne, fuel plant equipment cost range of 80%-200%, 2010 DICI and 2010 PISI for reference cars, central electric motors for current EV, wheel motors for future EV, average Dutch CO_2 emissions for electricity generation, 14000 annual vehicle km, current battery cost of 960 €/kWh, future battery costs of 400-800 €/kWh, fuel cell costs of 110-1000 €/kW, 70% depth of discharge for batteries, FT discount rate of 20%, motorist discount rate of 10% and no country-specific taxes but including 19% VAT.

Major sources of uncertainty in costs of fuels are short-term variability in prices of feedstocks (energy resources), by-products (naphtha from FT, feedcake and glycerine from biodiesel), and investment costs for processing plants. These tend to move in step with macro-economic cycles [193, 188]. In addition, fuel prices for motorists may reflect changes in oil prices rather than production costs (c.f. [214]).

The major source of uncertainty in the GHG emissions of fuels is possible unsustainable production of biomass feedstock. Sustainability criteria for biomass have been defined to mitigate this risk (e.g. [20, 346]). The EU 'Directive on the promotion of the use of energy from renewable sources' stipulates that GHG reductions from biofuels only count if at least 35% reduction is attained [20]. As of 2018, the minimum reduction is raised to 60%. However, these criteria have yet to be implemented to the scale required to produce the volume of biofuels needed to replace a large share of petrol and diesel from crude oil. Figure 7.1 does not include potential loopholes or fraud in GHG certification of biofuels.



Note: Two symbols indicate parallel hybrid (lower right) and SHEV (upper left) for the current hybrid cars, and for diesel car (top left) and petrol car (bottom right) for regular cars. * Current electric cars cost more than 0.6 €/km. Current fuel cell cars cost more than 0.9 €/km.

Figure 7.2: Cost vs. emissions of drivetrain options, based on chapters 3 and 4.

Figure 7.2 does not include negative emissions options such as driving on electricity generated with biomass and CCS. Major sources of uncertainty in costs of drivetrains are related to engine, battery and fuel cells. Developments in ICE indicate petrol and diesel engines may become more similar (see [205, 414]), and hybrid and plug-in hybrid cars with these engines are therefore aggregated in figure 7.2. As discussed in chapters 3 and 4, future costs of electric and fuel cell cars strongly depend on whether projected reductions in costs of batteries and fuel cells can be realised.

Major sources of uncertainty in GHG emissions of drivetrains are drivetrain efficiency and sources of electricity and hydrogen. The uncertainty in GHG emissions from production of electricity and hydrogen applies only to their specific drivetrains, but is otherwise similar to uncertainty in GHG emissions from FT fuels.

Figure 7.1 and 7.2 show that the cost of reducing GHG emissions via vehicles is generally higher than via fuels, but that uncertainty is generally higher in GHG emissions reduction via fuels. This makes a strong case for efforts to restrict emissions from the production of fuels (including electricity) (e.g. [20, 415, 416]).

Significantly reducing these uncertainties *ex ante* seems impossible: economic circumstances vary, outcomes of research and development cannot be predicted beforehand, and impacts of biofuel, hydrogen and electricity production are specific to the means and location of production. Many uncertainties will therefore remain until the actual concrete adoption takes place. Case-specific studies may be used to validate cost and GHG emissions of fuels and vehicles.

With our current knowledge, no option can be considered superior to another with certainty if their uncertainty ranges on cost and GHG emissions overlap pair-wise in figures 7.1 and 7.2. This is the case for biodiesel, BTL, future series hybrid and future plug-in hybrid cars, as well as for fuel cell and electric cars, and also for CTL with CCS and SCO. This suggests it is not wise to focus exclusively on one alternative ('picking the winners').

It seems wise at least to further develop both hybrid cars and biofuels (c.f. [28], see also [52]). However, technology-specific support policies may be counterproductive from an innovation perspective [417], and any stimulus to adoption should therefore be as generic as possible.

Furthermore, technological progress in several alternatives, such as biofuel production chains, fuel cell chains and EV charging, depends on the co-evolution of multiple 'symbiotic' technology elements. The rates of development or adoption of these elements are not necessarily the same. How each of these technology elements then influences further development of other elements becomes a complex and non-linear source of more uncertainty.

7.5 Recurring issues: competition & path dependency

While fuels account for nearly all of GHG emissions from driving a car, fuel costs comprise only 1%-19% of the total cost of driving. If fuel and vehicle choices to reduce GHG emissions were based on total cost of driving only, then the majority of motorists would therefore choose the cheapest (regular) cars achieve reductions through use of low or zero carbon fuels.

Simulations in chapter 5 indicate that the overall lowest cost of the energy system with GHG emissions reduction is achieved by using biomass to produce fuels to reduce emissions from road transportation, either by using ethanol or by FT fuels produced with CCS. This result is quite robust with respect to cost uncertainty, but less so to uncertainty in GHG reductions from alternatives.

As we have seen, some fuel options can increase GHG emissions from driving, particularly if CTL or SCO are used. There exists then a risk of a net increase of GHG emissions from road transportation unless 'dirty' fuel options are restricted, because CTL, SCO, GTL without CCS, and biofuels from unsustainable sources would be economically attractive alternatives to regular diesel and petrol when oil prices are above 60-80 \$/bbl. As fuel production and electricity generation plants have a lifespan of at least 20 to 30 years, this could also lead to a lock into a high-emissions fuel systems (c.f. [32]) in absence of effective GHG emissions reduction policies.

Compounding this risk is that the supply of fuels with low GHG emissions is limited, partially because the logistics of sustainable biomass supply are currently underdeveloped. Now and into the future, the rate of sustainable expansion of biomass supply is also restricted by the needs of preservation of natural habitats, food security, ecology and water consumption [75, 76, 78]. Furthermore, there is competition for the available supply of biomass for making transportation fuels from use of biomass in electricity, heat generation and industrial processes. Similar competition is projected for the currently non-existent CCS infrastructure and locally limited potential to store CO_2 underground.

For cars, the situation is quite different, because of the EU 'Regulation on emissions performance standards for new passenger cars' [19]. It will force vehicle makers to reduce average emissions to 95 gCO_{2eq}/km by 2020with technical measures, or to 85 gCO_{2eq}/km including use of renewable fuels. Car manufacturers will be penalised if the average fleet sales exceed these standards. Unless fuel cells or batteries become very cheap very soon, this legislation will presumably force a shift to hybrid vehicles, or else bring about emissions reductions of over 40% through improvements in ICE efficiency, vehicle weight reduction and/or aerodynamics (c.f. [418, 419]).

Given the short time frame until 2020 and uncertainty about progress in cost reduction in fuel cell and electric cars, there exists a significant possibility that (wheel motor) (plug-in) hybrid cars will be adopted *en masse*. Further GHG emissions reductions can then be attained through sustainable drop-in replacement fuels (and/or zero or low carbon electricity) when these become available in the volumes required for high market shares. Sustainable second generation biofuels made with CCS can potentially reduce GHG emissions from road transportation below zero in this case.

If biofuels cannot be made sustainably in sufficient volumes, plug-in hybrid and fully electric cars make for a less invasive transition than hydrogen cars. Reducing GHG emissions from road transportation via EV would require additional investments in coordinated chargers, batteries and low or zero carbon electricity production. The main advantage over fuel cell cars with an infrastructure for distribution of hydrogen is that introduction of EV can be done without the need for a critical mass of vehicles to make the infrastructure viable.

7.6 Recurring issues: non-cost barriers

Whereas significantly cheaper alternatives to driving on petrol and diesel are always likely to find a market, other factors play a role when prices are similar, especially in niche markets. These niche markets result from the heterogeneity of motorists (see chapter 6 and e.g. [404, 59, 420]).

Agent-based simulations described in chapter 6 indicate that multiple barriers to adoption of alternative fuels reinforce each other, making it much harder to bring mainstream adoption about. All relevant barriers must therefore be addressed simultaneously to enable co-evolution of fuel demand and production. This presumably applies to cars as well, though considerable differences can be expected between the way motorists regard a car, which is a durable and expensive investment, and fuels, which are consecutively purchased commodities.

The safest starting point for bringing about mainstream adoption of sustainable biofuels and hybrid cars among motorists, is that these will be adopted on grounds of GHG emissions reduction benefits, *all else being equal* (see also [57, 58]). For both sustainable biofuels and hybrid cars, the first policy challenge is therefore to limit the price difference so that motorists do not discard these evolutionary options out of hand. Financial policy instruments have been used to close the price gap for consumers, possibly shifting some of the costs to public finances (e.g. [215, 421] see also [259]).

For biofuels, the public at large would need to see benefits other than GHG emissions reduction to convince it to shift to alternative fuels, even if the price is the same. Wide uncertainty in the GHG emissions reductions may well cause motorists in potential niche markets for drop-in replacement fuels to turn away. Even if the adoption of biofuels were to take place exclusively through mandated blending, as done in EU 'Directive on the promotion of the use of biofuels or other renewable fuels for transport' [422], public political support for such a mandate is still necessary. Similarly, for competitive reasons, the improvements to fuel efficiency that are required from automakers must be made without compromising comfort, performance and safety features (c.f. [57, 423]).

There is also a need for consistent and stable mandates and support policies (see also [52]). As observed in the simulations in chapter 6, cumulative policy measures may take a long time to effect mainstream adoption. If there is a delay in adjusting production capacity to (latent) demand and mobilising that demand, and if interventions are discontinued before producers and motorists have entered into a new equilibrium, no adoption of alternative fuels results. Niche markets may be considered a hedge by producers in case mainstream adoption fails to materialise [52].

7.7 Some lessons learned and recommendations for further research

Examining the feasibility of alternatives to driving on diesel and petrol, at least four major lessons can be learned from this thesis that may be of use to other researchers:

1. For assessment of generic conversion plants and vehicles, a relatively simple spreadsheet model is not significantly less accurate than a flowsheet made with specialised engineering software. This is due to large uncertainties in input data. Developing detailed engineering models of fuel plants and vehicles therefore may to add value especially in case-specific investigations that allow for more detailed input parameters.

2. Competition for biomass and CCS storage capacity between the transportation and the electricity and heat generation sectors should be taken into account in feasibility studies of energy systems.

3. Agent-based models incorporate and explore some behavioural aspects of the energy transition which are often only treated implicitly or left out altogether. Despite the difficulties of finding credible formalisations and lack of data, there seems to be no alternative than going further down this road. A modular approach, using agent-based simulation where appropriate within larger (model-based) efforts would balance increased complexity with increased insight.

4. In simulating motorists, determining and including salient attributes is more important than the accurate size of subpopulations.

Finally, based on the studies in chapter 2-6, further investigation is suggested in the following areas:

- Integration of life cycle energy use and emissions (manufacture and disposal) of cars and fuels into WTW analysis, particularly for electric and fuel cell cars (see chapter 2, 3 and 4).

- Integrating impacts of non-GHG emissions from car and fuel options into WTW analysis (see chapter 2, 3 and 4).

- Cost-supply curves for sustainable biomass, taking into account preservation of natural habitats, food security, ecology, water consumption and potential socially-motivated restrictions on use of land for growing energy crops (see chapters 2, 5 and 6).

- Benchmarking fuel consumption of electric drivetrain options using standardised vehicle platform and a single representative drive cycle. This can clarify the differences in efficiency between transmission attached to ICE and electric drivetrains, and between central motor and wheel motors (see chapters 3 and 4).
- Cost developments for batteries and charging equipment for plug-in hybrid cars (see chapters 3 and 4).
- Use of decentralised electricity generation options for charging of electric vehicles (see chapter 4).
- Effect of EV charging on local electricity distribution grids (see chapter 4).
- Marketing and public perception of existing and alternative fuels and cars (see chapter 6).
- Social networking and economic feedback mechanisms relevant for fuel and car choices (see chapter 6).
- Impacts of a large shift in fuels and cars on the wider economy, both for growing industries (e.g. biofuels) and industries set to shrink (e.g. crude oil refining).

8. Samenvatting en conclusies: Evolutionaire strategieën voor nieuwe auto's en brandstoffen

Er is een behoefte om realiseerbare mogelijkheden te bepalen voor het terugdringen van de uitstoot van broeikasgassen (BKG) emissies en diversifiëren van de energiebronnen die we gebruiken voor wegvervoer. Hiertoe onderzoeken we in dit proefschrift het huidige energieverbruik, de kosten en de uitstoot van broeikasgassen van diverse alternatieve brandstoffen en voertuigen zien. We doen dit in een ketenperspectief, zogenaamd *well-to-wheel* (WTW – bron tot wiel). Deze resultaten zijn te vinden in hoofdstukken 2-4.

Hierop volgt een behoefte om uit te zoeken hoe de brandstoffen en voertuigen die in hoofdstukken 2-4 worden beschreven kunnen worden ingezet om onze bestaande, met verbrandingsmotoren uitgeruste auto's en onze diesel en benzine uit ruwe olie te vervangen. Hiertoe is hoofdstuk 5 een kostenoptimalisatie model van de sectoren wegvervoer en energie beschreven en in hoofdstuk 6 een *agent-based* model van het overstappen op andere brandstoffen dat rekening houdt met de voorkeuren van automobilisten.

Tijdens het uitvoeren van deze analyses kwamen drie terugkerende vraagstukken naar voren: onzekerheid in de kosten en de uitstoot van broeikasgassen van alternatieven, concurrentie tussen alternatieven in relatie tot padafhankelijkheid[37], en niet-financiële belemmeringen voor grootschalig overschakelen op andere brandstoffen en aandrijvingen door automobilisten.

8.1 Opties voor brandstoffen

Voor brandstoffen worden in hoofdstuk 2 de potentiële kosten en de uitstoot van 15 Fischer-Tropsch (FT) ketens onderzocht. De resultaten worden vergeleken met conventionele diesel uit ruwe olie, biodiesel en diesel gemaakt van synthetische ruwe olie (SCO), uit teerzand of oliehoudende leisteen. In hoofdstuk 5 worden gegevens toegevoegd voor benzine en ethanol dat uit suikerriet en houtige biomassa kan worden gemaakt.

Configuraties van FT fabrieken worden in hoofdstuk 2 gecombineerd met gegevens over aanvoer van kolen en aardgas, productie van biomassa, voorbewerking tot geperste houtkorrels of getorrificeerde en geperste houtkorrels (TOP), transportkosten, kosten van voertuigen en uitstoot van BKG om zo te komen tot een beschrijving van complete WTW ketens. Er is ook onderzocht in de literatuur hoe de technologieën die in deze ketens gebruikt worden zich tot 2020 kunnen ontwikkelen. Deze ontwikkelingen zijn onder meer het overstappen naar conversie van biomassa

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[37] Padafhankelijkheid betekent dat een eenmaal ingeslagen weg steeds moeilijker te verrruilen is voor een andere, meestal tengevolge van schaalvoordelen bij hoge maarktaandelen of gebrek aan interoperabiliteit. Voorbeelden zijn de overheersende positie van Microsoft Office®, gebruik van 220V in Europa en 110V in de VS, en combinatie van auto's op benzine of diesel en tankstations die makkelijk te bereiken zijn.

bij de bron, verbeteringen van de verwerkingsefficiëntie, en toepassing van CO_2-afvangst en opslag (CCS) voor (verdere) vermindering van de CO_2 uitstoot.

Gezien de omvang van de onzekerheden die wij en anderen hebben gevonden, moeten de kosten en BKG emissiewaarden voor FT diesel in hoofdstuk 2 worden gezien als beste mogelijke schattingen.

De kosten van FT diesel hangen voor een groot deel af van de grondstofprijzen en de efficiëntie waarmee grondstoffen worden verwerkt. Het maken van vloeibare brandstof uit aardgas (GTL) kan qua kosten concurreren met het maken diesel uit ruwe olie bij een olieprijs boven 33$/vat. Het maken van vloeibare brandstof uit kolen (CTL) is concurrerend bij een de olieprijs boven 60 $/vat. Het maken van vloeibare brandstof uit biomassa (BTL) is concurrerend bij de olieprijs boven 75 $/vat.

BKG uitstoot van FT diesel hangt bijna volledig af van de efficiëntie van de verwerkingsfabriek, de efficiëntie van de voorbewerking van biomassa, en de grondstof die wordt gebruikt. CTL verhoogt de uitstoot van BKG van vervoer met 25%-110%. Diesel van synthetische ruwe olie (SCO) verhoogt de uitstoot met 13%-60%, en GTL zonder CCS met 10%. GTL met CCS vermindert de uitstoot met ongeveer 5% ten opzichte van diesel uit ruwe olie. De netto BKG uitstoot van BTL kan een orde van grootte kleiner zijn, en ook negatief worden gemaakt door toepassing van CCS.

Het is mogelijk om netto klimaatneutraal te rijden als ongeveer 50% van de diesel of benzine uit ruwe olie wordt vervangen door BTL brandstof die met CCS is geproduceerd. Hiervoor moet vergassing van biomassa en de ondergrondse opslag van CO_2 op industriële schaal worden gerealiseerd en de biomassa grondstof op een duurzame (klimaatneutrale) manier wordt verkregen. De resultaten suggereren dat het de moeite waard is om FT brandstofproductie verder te onderzoeken, met gebruik van de nieuwste technologie, en met verwerking van biomassa zo vroeg mogelijk in de keten. In de praktijk zou dit het bouwen BTL of van gemengde FT fabrieken met CCS betekenen, ofwel in het land van herkomst van de grondstof, danwel elders mits de biomassa wordt bewerkt tot bijvoorbeeld TOPs.

8.2 Opties voor auto’s

In hoofdstuk 3 worden de potentiële kosten en uitstoot van BKG onderzocht van vier configuraties van serie hybride auto’s (SHEV) met dieselmotor, vier configuraties van plug-in hybride auto’s (PHEV) met dieselmotor en vier configuraties van brandstofcel auto’s op waterstof. In de analyses van energie-efficiëntie, kosten en uitstoot van broeikasgassen is gebruik gemaakt van gegevens uit de praktijk en van prognoses voor toekomstige ontwikkelingen. Tevens wordt een vergelijking gemaakt met auto’s met een normale interne verbrandingsmotor (ICE) en parallel hybride auto's. Hetzelfde wordt gedaan in hoofdstuk 4 voor twee configuraties van serie hybride auto's met benzinemotoren, twee configuraties van plug-in hybride auto's en vier configuraties van volledig elektrische auto's op accu's (BPEV). De focus in hoofdstuk 4 is op de uitstoot van broeikasgassen als gevolg van het opladen van auto accu's bovenop de uitstoot die het gevolg is van de bestaande vraag naar en aanbod van elektriciteit.

Uit de analyses in hoofdstuk 3 blijkt dat serie hybride auto's het brandstofverbruik met 34%-47% kunnen verminderen in vergelijking met referentie benzine- en dieselauto's. Daarmee kan de WTW uitstoot van BKG worden verminderd tot 89-103 $gCO_{2\ equivalent}$/km als normale diesel gebruikt wordt. De WTW uitstoot van BKG van elektrisch rijden is vooral afhankelijk van het soort brandstof (steenkool of aardgas) dat wordt gebruikt voor het opwekken van elektriciteit voor het opladen. De uitstoot ligt tussen 0 g/km (beste geval, met behulp van hernieuwbare energie) en 155 g/km (slechtste geval, met behulp van elektriciteit uit een oude kolencentrale). Op basis van de verwachte productiecapaciteit voor Nederland in 2015, zou elektriciteit voor het opladen van elektrische voertuigen (EV) worden gegenereerd uit aardgas, en daarmee 35-77 $gCO_{2\ eq}$/km uitstoten, afhankelijk van de precieze inzet van elektriciteitscentrales. Dit zou een vermindering van uitstoot van BKG betekenen van 51% -78% ten opzichte van de huidige auto's en brandstoffen.

Gezien de bestaande vraagpatronen voor de geïndustrialiseerde landen zou ongecoördineerd opladen van auto's de nationale piekbelasting van het elektriciteitssysteem verhogen met ongeveer 7% bij een 30% penetratiegraad van EV. De huishoudelijke piekvraag zou met 54% toenemen. Een dergelijke belasting zou de capaciteit van de bestaande infrastructuur voor de distributie van elektriciteit kunnen overschrijden, met name op straat- of wijkniveau. Bij 30% penetratie van EV zou opladen in daluren resulteren in een 20% hogere en meer stabiele basisbelasting, geen extra piekbelasting op nationaal niveau en tot 7% hogere piekvraag op het huishoudelijk niveau. Mits opladen in daluren met succes wordt geïntroduceerd, hoeft elektrisch rijden geen overbelasting van infrastructuur te veroorzaken, zelfs als 100% wordt overgeschakeld naar elektrische voertuigen.

Serie hybride auto's met wielmotoren hebben een lager gewicht en 7%-21% lager brandstofverbruik dan serie hybride auto's met een centrale elektromotor. Resultaten in hoofdstuk 3 geven aan dat wielmotoren in de toekomst de goedkoopste en meest efficiënte aandrijving kunnen gaan leveren. De mogelijkheid om wielmotoren te kunnen gebruiken is een belangrijke voordeel van serie aandrijving. Serie hybride auto's kosten momenteel in de aanschaf echter € 5000-€10 000 meer dan ICE auto's.

De totale kosten voor bezitten en rijden (TCO) van een serie hybride auto met wielmotoren is op dit moment hoger dan voor een auto met centrale motor. Het verschil is echter minder dan 500 €/jaar bij het aantal gereden kilometers waar de serie hybride auto de voorkeur krijgt boven een benzine auto. De TCO van toekomstige PHEV met wielmotoren kan concurreren met normale auto's en serie hybride auto's zonder fiscale stimulansen als de accu’s 400 €/kWh kosten, en de accu de hele levensduur van het voertuig mee kan. De resultaten suggereren dat het de moeite waard is om serie hybride aandrijving met wielmotoren bij auto’s verder te verkennen.

Elektrische auto’s die alle energie uit accu’s halen en brandstofcelauto’s zijn op dit moment met een ruime marge niet concurrerend. Indien de kosten van brandstofcellen zouden dalen met 90% hebben serie hybride auto’s nog steeds een iets lagere TCO. Als de kosten van accu’s zouden dalen met 85% tot 150 € / kWh, kunnen BPEV concurreren met (plug-in) serie hybride auto’s. Het is echter onbekend hoe en wanneer deze grote dalingen van de kosten van brandstofcellen en van accu’s kunnen worden bereikt.

8.3 Inzet van brandstoffen en voertuigen

Overschakelen op hybride auto’s, plug-in elektrische auto’s of brandstofcel auto's, en/of hernieuwbare brandstoffen kan de uitstoot van BKG door auto's en de afhankelijkheid van de transportsector van ruwe olie verminderen. Dit laat echter niet zien hoe de kosten van voertuigen en brandstoffen de inzet van deze alternatieven beïnvloeden wanneer wordt gekeken naar het functioneren van het energie systeem in bredere zin.

Om toekomstige interacties tussen de wegvervoer en energie sectoren in Nederland te onderzoeken is in hoofdstuk 5 het bestaande MARKAL-NL-UU model uitgebreid met de gegevens van hoofdstuk 2-4. Het uitgebreide model is gebruikt om concurrentie voor energiebronnen, de ontwikkeling van CCS, en co-evolutie van de capaciteit voor productie van elektriciteit en brandstoffen in samenhang te onderzoeken.

MARKAL zoekt de laagste totale kosten voor het totale systeem over een lange tijdshorizon, in dit geval zonder beperkingen vooraf op de bouw van nieuwe centrales en brandstoffabrieken. De vraag naar wegvervoer en elektriciteit, de beschikbaarheid van technologieën in de tijd, alsmede het aanbod en de prijs van energiebronnen worden exogeen ingevoerd.

Resultaten laten zien dat in alle scenario varianten, onder de gemaakte veronderstellingen, het gebruik van olie aanzienlijk vermindert. Zonder beperkingen op de uitstoot van BKG vervijfvoudigt het verbruik van kolen bijna als gevolg van het toenemende gebruik van steenkool in de elektriciteitsproductie en voor het produceren van FT brandstoffen. Aangezien er in deze scenario variant geen CCS wordt gebruikt, leidt deze ontwikkeling tot een stijging van de uitstoot van CO_2 als gevolg van wegvervoer en het opwekken van elektriciteit met 73% in 2020 ten opzichte van 1990.

Wanneer de noodzaak van BKG reducties in het wegvervoer en bij het opwekken van elektriciteit gezamenlijk worden bekeken, worden de laagste totale kosten bereikt door maximaal gebruik te maken van het potentieel van zowel biomassa als CCS en met gebruik van de goedkoopste opties voor vermindering van CO_2-uitstoot in het wegvervoer, zelfs als daardoor minder biomassa en CO_2 opslagcapaciteit beschikbaar zijn voor het opwekken van elektriciteit. Serie hybride auto's worden ingezet indien er onvoldoende koolstofarme brandstoffen beschikbaar zijn. De combinatie van de productie van FT diesel met CCS blijkt kosteneffectiever dan de toepassing van CCS in de productie van elektriciteit bij kolen- of biomassa gestookte centrales.

Het verschil tussen de investeringen in de scenario variant zonder beperkingen in de uitstoot van BKG en de varianten waarin de BKG uitstoot wordt teruggebracht met 68% in 2040 (met uitzondering van de varianten met geforceerde toepassing van elektrische en brandstofcel auto's) is 4 tot 7 miljard euro per jaar, wat gelijk staat aan 0,5%-1,2% van het BBP. Dit betreft vooral investeringen in auto's en het opwekken van elektriciteit.

CO_2 reductie door middel van elektrische auto's of auto's met brandstofcellen kost 400 €/ton CO_2 of meer. De toepassing van deze technieken wordt vermeden als er andere opties beschikbaar zijn. Daarentegen kunnen SHEV, ethanol, verschillende BTL ketens en GTL + CCS negatieve kosten voor CO_2 reductie hebben. Opties voor een evolutionaire transitie (zoals hybride auto's en biobrandstoffen) zijn dus zowel minder complex (zoals betoogd in hoofdstuk 1) als minder kostbaar (zoals blijkt uit de resultaten van de analyses en de optimalisatie van WTW kosten in de hoofdstukken 2-5) dan een ingrijpende transitie van ons wegvervoer systeem (elektrische auto's, brandstofcel auto's en de benodigde waterstofinfrastructuur).

Toch zal een alternatief niet noodzakelijkerwijs worden gebruikt omdat het betaalbaar is. Ook andere factoren dan laagste kosten spelen een rol. Om hiervan een eerste analyse te maken is een agent-based model ontwikkeld, beschreven in hoofdstuk 6. Dit model simuleert de productie van (mengsels van) brandstoffen uit grondstoffen en hun gebruik door heterogene groepen automobilisten.

Ondanks dat het model de brandstofkeuze sterk vereenvoudigd weergeeft is het model een verbetering van het traditionele aanpak waarbij wordt gezocht naar de techniek met de laagste kosten. Dit is omdat in het agent-based model de voorkeuren van automobilisten expliciet gemodelleerd zijn op een manier die eenvoudig is te koppelen aan praktische keuzemechanismen en beleidsmaatregelen. Het model is gebruikt het om de interactie te onderzoeken tussen de latente en feitelijke vraag naar en het aanbod van autobrandstoffen.

De agenten in het model vertegenwoordigen heterogene groepen automobilisten. In het model kiezen zij brandstoffen op basis van prijs, en van de niet-economische kenmerken waargenomen prestaties van het voertuig en emissies naar het milieu, en van marktaandeel van de brandstof. In het model worden alleen uitwisselbare brandstoffen (CTL, GTL, BTL, biodiesel en ethanol) beschouwd en wordt aangenomen dat zowel het aantal als de typen auto's niet verandert. De productie van brandstoffen wordt beperkt door enerzijds de beschikbaarheid van grondstoffen en anderzijds de vraag. Conversie en mengen van brandstoffen wordt gedaan met geleidelijk voortschrijdende technologieën. Brandstofprijzen worden dynamisch bepaald op basis van de productiekosten en de prijzen van concurrerende brandstoffen.

Resultaten laten zien dat om een volledige transitie te bereiken, alternatieve brandstoffen ten hoogste dezelfde prijs mogen hebben als gewone diesel en benzine. Als de prijzen van de alternatieven hoger zijn spelen niet-economische factoren en sociale feedback alleen een rol in nichemarkten. De variatie in de resultaten geeft aan dat het niet haalbaar is om nu al winnaars te identificeren als het gaat om marktpenetratie van alternatieve brandstof technologieën.

Het is bijzonder moeilijk om een blijvende opwaartse spiraal in het gebruik van alternatieve brandstoffen te bewerkstelligen. Dit komt omdat weinig brandstoffen in staat zijn om de prestaties van de gevestigde brandstoffen te overtreffen (en daarmee de consument een reden om over te stappen te geven) én om vergelijkbare kosten te bereiken als gevestigde brandstoffen én ook nog voldoende marktaandeel te behalen om voor de meerderheid van de automobilisten aanvaardbaar te zijn. Als in het agent-based model rekening wordt gehouden met niet-economische kenmerken en sociale terugkoppelingen, dan is het gebruik van alternatieve brandstoffen meestal beperkt tot nichemarkten met een aandeel van 5% of lager. Een volledige brandstof transitie is slechts in één simulatie waargenomen, namelijk bij voldoende aanvoer van goedkope ethanol met bijbehorende marketing campagne.

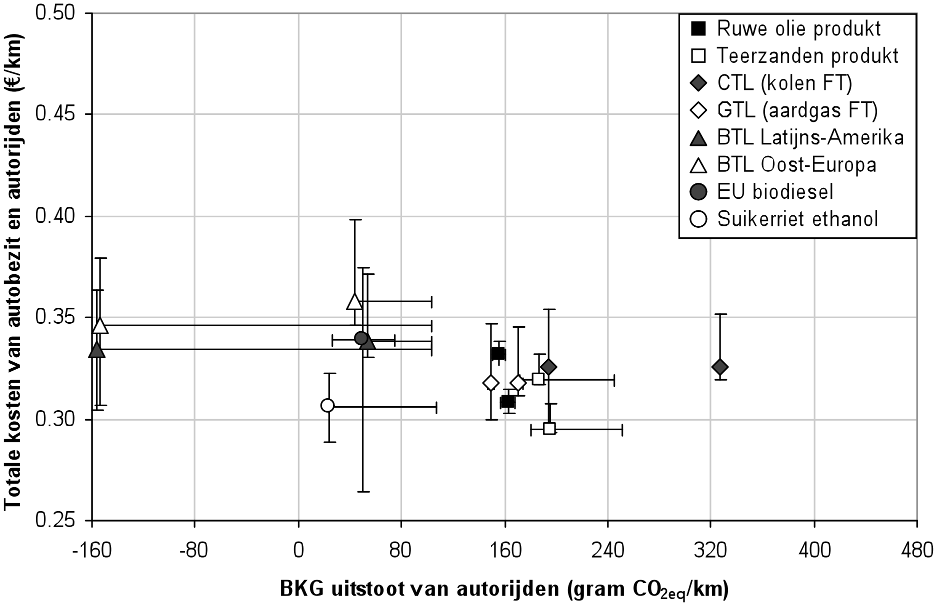
Dit duidt erop dat niet-economische factoren verregaande en onvoorspelbare effecten kunnen hebben die moeten worden meegenomen in het modelleren van energiesystemen bij het onderzoeken van mogelijke marktontwikkelingen. Agent-based modellen zijn een instrument bij uitstek om sociale dynamiek te verkennen. De verwachting is dan ook dat sociale simulatie een waardevol instrument wordt bij de ontwikkeling van strategieën voor het stimuleren van de diffusie van nuttige innovaties in de samenleving.

8.4 Terugkerende vraagstukken: onzekerheid

Alle alternatieve brandstoffen en aandrijvingen die in dit proefschrift zijn onderzocht verminderen onze afhankelijkheid van ruwe olie. Bij voldoende beschikbaarheid van de relevante energiebronnen kunnen uitwisselbare brandstoffen en hybride auto's de directe uitstoot van BKG aanzienlijk doen dalen, en zelfs tot negatieve emissies per kilometer leiden als biobrandstoffen worden geproduceerd in combinatie met CCS.

Er blijven echter grote onzekerheden in de kosten van alternatieve brandstoffen. Dit geldt ook voor de reducties in de uitstoot van BKG die kunnen worden bereikt tenzij de duurzaamheid van de productie van hernieuwbare grondstoffen kan worden gegarandeerd. Bijvoorbeeld zijn onzekerheden van tientallen procenten gevonden in de gegevens voor de kosten van onderdelen van FT fabrieken, de variabiliteit in de prijzen van grondstoffen en bijproducten, en de BKG effecten van de productie van biomassa. Er zijn ook belangrijke onzekerheden in de toekomstige efficiëntie en kosten van aandrijvingen in auto's.

Figuur 8.1 en 8.2 laten de kosten (€/km) en de uitstoot van broeikasgassen (gCO_{2eq}/km) zien van het gebruik van verschillende brandstoffen en aandrijvingen, vergeleken met het rijden in een standaard compacte middenklasse auto's op diesel of benzine, uitgaande van een ruwe olieprijs van 80 \$/vat[38]. Hoewel brandstoffen en aandrijvingen in aparte grafieken worden weergegeven, kunnen sommige brandstoffen en aandrijvingen samen worden ingezet (bijv. ethanol in een hybride voertuig) om uitstoot van BKG en/of kosten te verminderen.



N.B.: Twee symbolen voor hetzelfde brandstoftype geven voor FT brandstoffen een keten met behulp van CCS (links) en een zonder CCS (rechts) aan en voor brandstoffen uit ruwe olie en oliezanden diesel (linksboven) en benzine (rechtsonder).

Figuur 8.1: Totale kosten van bezit en autorijden uitgezet tegen de BKG uitstoot van diverse brandstofopties, gebaseerd op hoofdstukken 2 en 5.

Hoewel alle brandstoffen die uit fossiele grondstoffen worden geproduceerd ongeveer dezelfde of een hogere uitstoot van BKG hebben dan gewone diesel of benzine, kunnen biobrandstoffen de uitstoot van broeikasgassen aanzienlijk verminderen, zelfs met meer dan 100%. Maar de gevonden resultaten moeten, zoals vermeld in hoofdstuk 2, worden gezien als beste mogelijke schattingen met marges van onzekerheid. Bovendien is de kansverdeling binnen de onzekerheidsmarges min of meer vlak.

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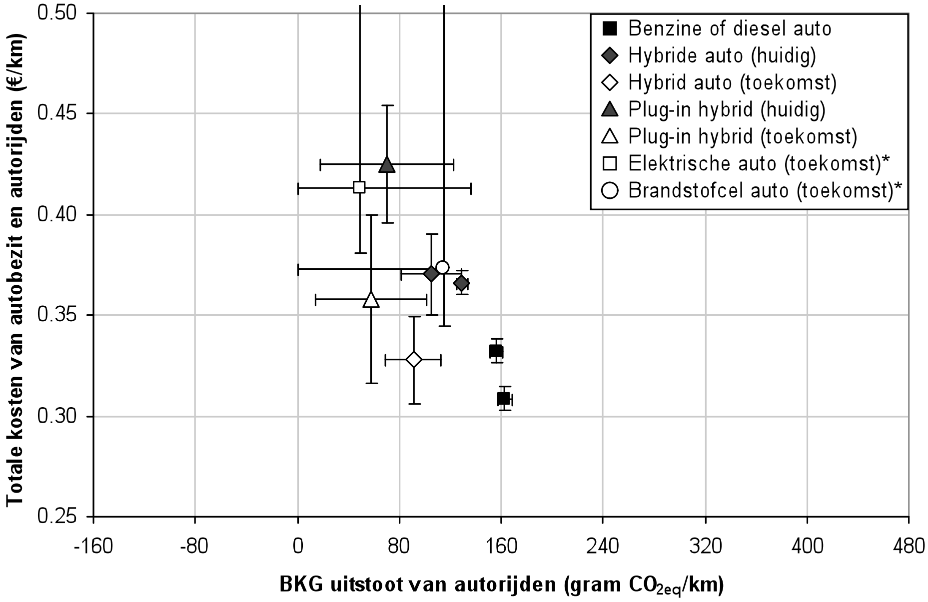
[38] Kosten inclusief BTW, maar zonder land-specifieke belastingen. Zie voetnoot in sectie 7.4 voor uitleg van de onzekerheidslijnen in de grafieken 8.1 en 8.2.

Belangrijke bronnen van onzekerheid in de kosten van brandstoffen zijn korte-termijn variabiliteit in de prijzen van grondstoffen (energiebronnen), bijproducten (nafta van FT, diervoeder en glycerine van biodiesel) en investeringskosten voor de verwerkingsfabrieken. Deze ontwikkelen zich meestal synchroon met macro-economische cycli [193, 188]. Daarnaast kunnen de brandstofprijzen voor de automobilist ook veranderingen in de olieprijs weerspiegelen in plaats van veranderingen in de productiekosten (vgl. [214]).

De belangrijkste bron van onzekerheid in de uitstoot van BKG van brandstoffen is mogelijke niet-duurzame productie van de biomassa grondstof waar de brandstoffen van worden gemaakt. Om dit risico te beperken zijn duurzaamheidcriteria voor biomassa gedefinieerd (zie bijvoorbeeld [20, 346]). In de 'Richtlijn ter bevordering van het gebruik van energie uit hernieuwbare bronnen' van de EU is bepaald dat de BKG reducties van biobrandstoffen alleen worden meegeteld indien ten minste 35% reductie wordt bereikt [20]. Met ingang van 2018, stijgt de vermindering die tenminste moet worden bereikt tot 60%. Deze criteria moeten echter nog worden toegepast op een schaal die nodig is om de hoeveelheid biobrandstoffen te produceren die nodig is om een groot deel van de benzine en diesel uit ruwe olie te vervangen.



N.B.: Twee symbolen geven voor de huidige hybride auto's een parallelle hybride (rechtsonder) en SHEV (linksboven) aan, en voor gewone auto's dieselauto (linksboven) en benzine auto (rechtsonder). *Huidige elektrische auto kost meer dan 0,6 €/km. Huidige brandstofcel auto kost meer dan 0,9 €/km.

Figuur 8.2: Totale kosten van bezit en autorijden uitgezet tegen de uitstoot van diverse aandrijvingen, gebaseerd op hoofdstukken 3 en 4.

Figuur 8.2 bevat geen opties met negatieve emissies, zoals het rijden op elektriciteit die wordt opgewekt met biomassa en CCS. Belangrijke bronnen van onzekerheid in de kosten van aandrijving zijn gerelateerd aan de motor, accu's en brandstofcellen. Ontwikkelingen in de ICE geven aan dat benzine- en dieselmotoren meer op elkaar kunnen gaan lijken (zie [205, 414]), en hybride en plug-in hybride auto's met deze motoren zijn daarom samengevoegd in figuur 8.2. Zoals besproken in hoofdstukken 3 en 4, is het onzeker of de noodzakelijke en door sommigen ook verwachte verlagingen van de kosten van accu's en brandstofcellen kunnen worden gerealiseerd.

Belangrijke bronnen van onzekerheid in de uitstoot van BKG van aandrijvingen zijn de efficiëntie van aandrijvingen en de bronnen van elektriciteit en waterstof.

Figuur 8.1 en 8.2 laten zien dat de kosten van de vermindering van de uitstoot van BKG door middel van een verandering in het voertuig in het algemeen hoger zijn dan via een verandering van de brandstof, maar dat onzekerheid in de uitstoot van BKG over het algemeen hoger is bij vermindering van de BKG uitstoot door verandering van brandstof. Dit is een sterke drijfveer om de BKG uitstoot van de productie van brandstoffen (waaronder elektriciteit) te beperken (zie bijvoorbeeld [20, 415, 416]).

Het vooraf significant verkleinen van deze onzekerheden lijkt onmogelijk: economische omstandigheden variëren, uitkomsten van onderzoek en ontwikkeling kunnen niet van tevoren worden voorspeld en de effecten van biobrandstoffen, waterstof en elektriciteit worden bepaald door de productiewijze en de plaats van de productie. Veel onzekerheden zullen dus blijven totdat opties in de praktijk worden ingezet. Studies voor specifieke projecten kunnen echter worden gebruikt om de kosten en de uitstoot van BKG van brandstoffen en voertuigen te valideren.

Met onze huidige kennis kan geen optie met zekerheid als beter worden bestempeld dan een andere indien de kosten en de uitstoot van BKG paarsgewijs overlappen, zie figuur 8.1 en 8.2. Dit is het geval voor biodiesel, BTL, toekomstige serie hybride en toekomstige plug-in hybride auto's, evenals voor de brandstofcel en elektrische auto's, en ook voor CTL met CCS en SCO. Dit suggereert dat het niet verstandig is om beleid uitsluitend op één enkel alternatief te richten ('de winnaars kiezen').

Het lijkt in ieder geval verstandig om zowel de hybride auto als biobrandstoffen verder te ontwikkelen (vgl. [28], zie ook [52]). Beleid voor technologiespecifieke ondersteuning kan echter contraproductief zijn vanuit een innovatie perspectief [417], en wat er voor pleit om stimulerings maatregelen zo algemeen mogelijk op te zetten.

Daarnaast hangt de technologische vooruitgang van verschillende alternatieven af van de co-evolutie van meerdere 'symbiotische' technologie-elementen. Het tempo waarmee deze elementen ontwikkeld of ingezet worden hoeft niet hetzelfde te zijn. Hoe elk van deze technologische elementen vervolgens de verdere ontwikkeling van andere elementen beïnvloedt, is een complexe en niet-lineaire bron van onzekerheid.

8.5 Terugkerende vraagstukken: concurrentie & padafhankelijkheid

Hoewel brandstoffen bijna alle BKG uitstoot van autorijden voor hun rekening nemen, vormen de kosten van deze brandstoffen slechts 1% -19% van de totale kosten van autorijden. Als keuzes voor voertuigen en brandstoffen die uitstoot van BKG terug moeten dringen alleen gebaseerd zouden zijn op de totale kosten van autorijden, dan zou de meerderheid van de automobilisten kiezen voor de goedkoopste (normale) auto's en voor het bereiken van reducties door middel van het gebruik van koolstofarme of koolstofneutrale brandstoffen in deze auto's.

Simulaties in hoofdstuk 5 geven aan dat voor vermindering van de uitstoot van BKG de laagste totale kosten voor het energie systeem worden bereikt door de inzet van biomassa voor de productie van brandstoffen, in de vorm van ethanol of FT brandstoffen met CCS. Dit resultaat is zeer robuust met betrekking tot de onzekerheid in kosten, maar in mindere mate in relatie tot de onzekerheid in de BKG reducties die met de alternatieven worden bereikt.

Zoals we hebben gezien, kunnen sommige brandstofopties leiden tot een toename van uitstoot van BKG van autorijden, met name als CTL of SCO wordt gebruikt. Er bestaat derhalve een risico van netto stijging van de BKG uitstoot van het wegvervoer tenzij 'vuile' brandstof opties beleidsmatig worden beperkt, want CTL, SCO, GTL zonder CCS en biobrandstoffen uit niet-duurzame bronnen zijn met olieprijzen boven 60 tot 80 \$/bbl economisch aantrekkelijke alternatieven voor gewone diesel en benzine. Daar brandstoffabrieken en elektriciteitscentrales een levensduur hebben van ten minste 20 tot 30 jaar, kan dit er zonder effectief beleid ter vermindering van de uitstoot van BKG ook toe leiden dat we vast komen te zitten aan brandstofsystemen met hoge uitstoot (vgl. [32]).

Bovenop dit risico komt dat het aanbod van brandstoffen met een lage uitstoot van BKG beperkt is, deels omdat de logistiek van duurzame biomassa nog onderontwikkeld is. Nu en in de toekomst wordt het tempo van de duurzame uitbreiding van de biomassa ook beperkt door de behoeften van behoud van de natuurlijke habitats, voedselzekerheid, ecologie en waterverbruik [75, 76, 78]. Verder is er concurrentie voor het beschikbare aanbod van biomassa voor het maken van autobrandstoffen vanuit het gebruik van biomassa voor productie van elektriciteit en warmte en voor industriële processen. Vergelijkbare concurrentie is te verwachten voor de nu nog niet-bestaande infrastructuur voor transport en opslag van CO_2.

Voor auto's is de situatie heel anders, vanwege de 'Verordening tot vaststelling van emissienormen voor nieuwe personenauto's' van de EU [19]. Deze dwingt autofabrikanten om de gemiddelde BKG uitstoot van auto's te verminderen tot 95 gCO_{2eq}/km in 2020 met technische maatregelen, of tot 85 gCO_{2eq}/km met inbegrip van het toepassen van hernieuwbare brandstoffen. Autofabrikanten zullen worden beboet als de gemiddelde verkochte vloot deze normen overschrijdt. Tenzij brandstofcellen of batterijen heel binnenkort heel goedkoop worden, zal deze wetgeving vermoedelijk een verschuiving afdwingen naar hybride voertuigen, of anders een emissiereductie van meer dan 40% teweeg brengen door verbeteringen in de efficiëntie van ICE, vermindering van het gewicht van voertuigen en/of aerodynamische eigenschappen (vgl. [418, 419]).

Gezien de korte tijd tot 2020 en de onzekerheid over het tempo van kostenreductie in brandstofcel- en elektrische auto's bestaat er een aanzienlijke kans dat (plug-in) hybride auto's (met wielmotoren) massaal zullen worden ingezet. Verdere vermindering van de uitstoot van BKG kan dan worden bereikt door middel van het inzetten van uitwisselbare brandstoffen uit duurzame bronnen (en/of koolstofarme of koolstofneutrale elektriciteit).

Als biobrandstoffen niet in voldoende hoeveelheden duurzaam kunnen worden gemaakt, brengen plug-in hybride en volledig elektrische auto's een minder ingrijpende transitie met zich mee dan waterstof auto's. Vermindering van de uitstoot van BKG van wegvervoer door middel van EV zou forse investeringen vergen in gecoördineerde oplaadapparatuur, accu's en productie van elektriciteit met lage of geen CO_2 uitstoot. Het belangrijkste voordeel ten opzichte van auto's met brandstofcellen en een infrastructuur voor distributie van waterstof is dat op EV kan worden overgeschakeld zonder dat er een kritische massa van voertuigen nodig is om de infrastructuur levensvatbaar te maken.

8.6 Terugkerende vraagstukken: niet-financiële belemmeringen

Hoewel er voor aanzienlijk goedkopere alternatieven voor het rijden op benzine en diesel waarschijnlijk altijd een markt te vinden zal zijn, spelen andere factoren een rol wanneer prijzen vergelijkbaar zijn, vooral in nichemarkten. Deze nichemarkten zijn het gevolg van de heterogeniteit van de automobilisten (zie hoofdstuk 6 en bijv. [404, 59, 420]).

Uit de agent-based simulaties die zijn beschreven in hoofdstuk 6 is gebleken dat meerdere barrières voor het overschakelen op alternatieve brandstoffen elkaar kunnen versterken, waardoor het veel moeilijker wordt om deze alternatieven op grote schaal in te voeren. Alle relevante barrières moeten dus tegelijk worden aangepakt om co-evolutie van vraag naar en productie van brandstoffen mogelijk te maken. Dit geldt vermoedelijk ook voor auto's, hoewel er forse verschillen te verwachten zijn in de manier waarop automobilisten een auto zien (wat een duurzame en dure investering is) en brandstoffen zien (wat bulkgoederen zijn die steeds weer moeten worden gekocht).

Het veiligste uitgangspunt voor grootschalig overschakelen op duurzame biobrandstoffen en hybride auto's is dat ze op grond van lagere uitstoot van BKG door automobilisten zullen worden gekozen, *mits alle andere eigenschappen hetzelfde zijn* (zie ook [57, 58]). Voor zowel duurzame biobrandstoffen en hybride auto's is de eerste uitdaging voor beleid dan ook om het prijsverschil te beperken, zodat automobilisten deze evolutionaire opties niet op voorhand uitsluiten. Er zijn al financiële beleidsinstrumenten gebruikt om het prijsverschil voor de consument te verkleinen, bijvoorbeeld door een deel van de meerkosten te verschuiven naar de belastingbetaler (zie bijvoorbeeld [215, 421] en [259]).

Voor biobrandstoffen zou het grote publiek andere voordelen dan emissiereductie moeten zien om een verschuiving naar alternatieve brandstoffen te bewerkstelligen, zelfs als de prijs hetzelfde is. Grote onzekerheid in de BKG emissiereducties kan er ook toe leiden dat automobilisten in potentiële nichemarkten zich afkeren van uitwisselbare brandstoffen. Zelfs als de inzet van biobrandstoffen uitsluitend zou plaatsvinden door middel van voorgeschreven bijmenging, zoals gedaan in de 'Richtlijn ter bevordering van het gebruik van biobrandstoffen of andere hernieuwbare brandstoffen in het vervoer' van de EU [422], is openbare politieke steun voor een dergelijk regel nog steeds nodig. Op dezelfde manier moeten automakers, om de concurrentie voor te blijven, de noodzakelijke verbeteringen in efficiëntie behalen zonder afbreuk te doen aan comfort, prestaties en veiligheid (vgl. [57, 423]).

Er is ook behoefte aan consistente en stabiele regels en ondersteuning door het beleid (zie ook [52]). In de simulaties in hoofdstuk 6 is waargenomen dat het lang kan duren voor dat op elkaar gestapelde beleidsmaatregelen tot grootschalig overschakelen leiden. Als er een vertraging zit tussen de aanpassing van de productiecapaciteit aan de (latent aanwezige) vraag en het mobiliseren van die vraag, en als beleidsinterventies worden gestaakt voordat de producenten en de automobilisten een nieuw evenwicht hebben bereikt, zullen alternatieve brandstoffen niet worden ingezet. Niche markten kunnen door de producenten als een hedge worden beschouwd voor het geval dat grootschalige toepassing niet wordt gerealiseerd [52].

8.7 Enkele lessen en aanbevelingen voor verder onderzoek

Uit het onderzoek in dit proefschrift naar de haalbaarheid van alternatieven voor het rijden op diesel en benzine, kunnen ten minste vier belangrijke lessen worden getrokken uit die van nut kunnen zijn voor andere onderzoekers:

1. Voor de beoordeling van generieke conversie-eenheden en voertuigen is een relatief eenvoudig spreadsheet model niet significant minder nauwkeurig dan een flowsheet dat is gemaakt met gespecialiseerde software engineering. Dit komt door de grote onzekerheden in invoergegevens. De ontwikkeling van gedetailleerde engineering modellen voor brandstoffabrieken en voertuigen levert daarom vooral toegevoegde waarde op in geval van onderzoek naar specifieke projecten waarin meer gedetailleerde invoergegevens kunnen worden gebruikt.

2. In haalbaarheidsstudies van energiesystemen zou (meer) rekening moeten worden gehouden met concurrentie voor het gebruik van biomassa en het benutten van CCS opslagcapaciteit tussen de sectoren vervoer en energie.

3. Agent-based modellen bevatten en verkennen gedragsmatige aspecten van de energietransitie die in analyses vaak slechts impliciet worden behandeld of geheel worden weggelaten. Ondanks de moeilijkheden van het vinden van een geloofwaardige formalisatie en het gebrek aan gegevens, lijkt er geen alternatief mogelijk dan verder te gaan op deze weg. Een modulaire aanpak, waarin agent-based simulatie op toepasselijke onderdelen wordt gebruikt binnen grotere (modelgebaseerde) activiteiten zou een evenwicht geven tussen toegenomen complexiteit en een vergroot inzicht.

4. Bij de simulatie van automobilisten is het vinden van de meest relevante thema's belangrijke dan de precieze omvang van subpopulaties.

Ten slotte wordt op basis van de studies in hoofdstukken 2-6 verder onderzoek voorgesteld op de volgende gebieden:

- Integratie van energiegebruik en emissies over de hele levenscyclus (productie en verwijdering) van auto's en brandstoffen in WTW-analyses, in het bijzonder voor elektrische en brandstofcel auto's (zie hoofdstuk 2, 3 en 4).

- Integratie van effecten van uitstoot van andere gassen dan BKG van auto- en brandstofopties in WTW-analyse (zie hoofdstuk 2, 3 en 4).

- Kosten-aanbod curves voor duurzame biomassa, rekening houdend met het behoud van de natuurlijke habitats, voedselzekerheid, ecologie, waterverbruik en potentiële sociaal gemotiveerde beperkingen op het gebruik van land voor de teelt van energiegewassen (zie hoofdstukken 2, 5 en 6).

- Vergelijkend meten van brandstofverbruik van een elektrische aandrijving met behulp van een gestandaardiseerde carrosserie en één enkele representatieve rijcyclus. Dit kan de verschillen duidelijk maken in efficiëntie tussen een overbrenging die gekoppeld is aan een ICE of aan een elektrische aandrijving, en tussen een centrale motor en wielmotoren (zie hoofdstukken 3 en 4).

- Ontwikkeling van kosten van batterijen en laadapparatuur voor plug-in hybride auto's (zie hoofdstukken 3 en 4).

- Gebruik van gedecentraliseerde opties voor de productie van elektriciteit voor het opladen van elektrische voertuigen (zie hoofdstuk 4).

- Effect van opladen van EV voor lokale elektriciteitsdistributienetten (zie hoofdstuk 4).

- Marketing en de publieke perceptie van de bestaande en alternatieve brandstoffen en auto's (zie hoofdstuk 6).

- Sociale netwerken en economische terugkoppelingsmechanismen die relevant zijn voor keuzes van brandstoffen en auto’s (zie hoofdstuk 6).

- Effecten van een grote transitie in brandstoffen en auto's op de lokale en nationale economieën, zowel voor groeiende industrieën (bijvoorbeeld biobrandstoffen) als voor industrieën die zouden krimpen (bijvoorbeeld raffinage van ruwe olie).

“Er wordt teveel abstract gedingest.”

– Loesje

9. List of abbreviations

1st gen fuel	ethanol from sugar (cane, beets, grapes) and starch (corn, wheat), biodiesel and pure oil from seed plants (soy, oil palm, rapeseed, sunflower)
2nd gen fuel	ethanol from ligno-cellulosic feedstock as well as Fischer-Tropsch synthetic petrol and diesel from gasified biomass
ABM	agent based model (or modelling)
AIC	annualized investment costs
ASU	air separation unit (oxygen factory)
ATR	autothermal reformer (type of natural gas reformer)
B20	a blend of 20% biodiesel and 90% regular diesel
B99	a blend of 99% biodiesel and 1% regular diesel
BAT	best available technology
bbl	barrel of oil (standardized unit: 42 U.S. gallons, 158.9873 litres)
BFB	bubbling fluidized bed (type of chemical reactor)
BKG	broeikas gas (Dutch translation of greenhouse gas)
BOVAG	Bond van Garagehouders (Dutch car trade association)
BTL	biomass to liquid
BPEV	battery powered electric vehicle
CATO	CO_2 capture and storage
CBS	Centraal Bureau voor de Statistiek (Dutch statistics agency)
CCS	carbon capture and storage
CFB	circulating fluidized bed (type of chemical reactor)
CGP	central gathering point (logistical and intermediate processing facility)
CHP	combined heat and power (electricity & heat plant)
CI	compression ignition (engine runs on diesel-like fuels)
CM	central motor
CTL	coal to liquid
DI	direct injection (engine uses in-cylinder fuel injection nozzles)
DME	dimethyl ether (CH3-O-CH3)
DoD	depth of discharge (range between minimum and maximum charge)
DPF	diesel particulate filter
DR	discount rate (measure of time preference in economics)
E10	a blend of 10% ethanol and 90% regular petrol
E85	an azeotropic blend of 85% ethanol and 15% petrol
ECN	Energieonderzoek Centrum Nederland (energy research centre)
EE	Eastern Europe
EF	entrained flow (type of gasification reactor)
EJ	gigajoule (= 10^{18} joule)
EREV	extended range electric vehicle (series hybrid car with large battery capacity)
ETSAP	Energy Technology Systems Analysis Program (IEA implementing agreement)
EU	European Union

EV	electric vehicle (PHEV or BPEV)
F2F	feed to fuel
FAME	fatty acid methyl ester (biodiesel)
FCEV	fuel cell electric vehicle
FER	fossil energy requirement
FFB	fixed fluidized bed (type of chemical reactor)
FOB	free on board (equipment cost without accessories)
FR	forestry residues
FT	Fischer-Tropsch (chemical reaction)
GDP	Gross domestic product (measure of economic activity)
GHG	greenhouse gas
GIS	geographic information system
GJ	gigajoule (= 10^9 joule)
GJ_{prod}	gigajoule produced as output of the process (= 10^9 joule)
GTL	gas to liquid
GW_{th}	gigawatt thermal input (= 10^9 watt = 10^9 joule/second)
ha	hectare (= 10 000 m^2)
HFO	heavy fuel oil
HHV	higher heating value (includes latent heat of water vaporization)
HPC	heavy paraffin conversion (Shell chemical process unit)
ICE	internal combustion engine
IEA	International Energy Agency (intergovernmental organisation)
IGCC	integrated gasification / combined cycle (type of electricity plant)
INL	Idaho National Laboratory (home to the Advanced Vehicle Testing Activity)
IPCC	Intergovernmental Panel on Climate Change (climate science body)
IRR	internal rate of return (measure of profitability)
ISBL	inside battery limits (equipment cost with some accessories)
JRC	Joint Research Centre (directorate of the European Commission)
kbpd	1000 barrels (bbl) per day (measure of processing capacity for refineries)
LA	Latin America
LC	lignocellulosic (biomass contains significant amounts of lignine and cellulose)
LHV	lower heating value (excludes latent heat of water vaporization)
Li-ion	Lithium-ion (battery technology)
LPG	liquified petroleum gas (refinery fraction, C3 and C4 alkanes)
M&R	maintenance and repair
MARKAL	MARKet ALlocation (energy system optimisation model)
ME	Middle East
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impact (energy system optimisation model)
MJ_{exp}	megajoule expended as extra input that is lost in the process (= 10^6 joule)
MRT	maintenance, repair and tires (for automobile)
MW_e	megawatt electric power (= 10^6 watt = 10^6 joule/second)
NEDC	new European driving cycle

NG	natural gas (largely methane)
NGCC	natural gas combined cycle (type of electricity plant, Dutch abbreviation: STEG)
NiMH	nickel-metal hybride (battery technology)
NL	the Netherlands (country in North-Western Europe, EU member state)
O&M	operation and maintenance
OSBL	outside battery limits (equipment cost with most accessories)
PBL	Planbureau voor de Leefomgeving (Dutch planning agency, formerly MNP)
PC	pulverised coal (type of electricity plant)
PCE	power controller electronics (regulates battery power to electric motor)
PEM	proton exchange membrane
PFF	primary forest fuel
PHEV	plug-in hybrids electric vehicle (uses a series drivetrain), sometimes called EREV
PI	port intake (engine uses a carburettor or injection into the intake manifold)
PJ	gigajoule (= 10^{15} joule)
PM_{10}	fine particulate matter, concentration of particles <10 nm
ppm	parts per million (= 10^{-6})
PV	photo-voltaic (solar cells)
REE	rapeseed ethyl ester (type of biodiesel)
ROR	rate of return
SCO	synthetic crude oil (extracted from tar sand or oil shale and cracked with hydrogen)
SHEV	series hybrid electric vehicle
SI	spark ignition (engine runs on petrol-like fuels)
SMDS	Shell Middle Distillate Synthesis (chemical process)
SNG	synthetic natural gas (contradiction in terms that means non-fossil methane)
SPD	Slurry Phase Distillate (Sasol chemical process)
SUV	sports utility vehicle (station wagon type car built on a light truck chassis)
TCI	total capital investment
TCO	total cost of ownership (includes initial purchase, maintenance, fuel and taxes)
TIMER	Targets IMage Energy Regional (energy system simulation model)
tonne	1000 kg (no imperial measurements are used in this chapter)
TOPs	torrefied wood pellets (similar to charcoal pellets)
TTW	tank to wheel
TWh	terawatt-hour (= 10^{12} watt-hour = 3.6 x 10^{15} joule)
VAT	value added tax
WE	Western Europe
WEO	World Energy Outlook (annual IEA publication)
WGS	water gas shift (reactor, $CO + H_2O \boxtimes CO_2 + H_2$)
WLO	Welvaart en Leefomgeving (Dutch long-term policy assessment)
WM	wheel motor
WTT	well to tank
WTW	well to wheel
XTL	a combination of coal and biomass to liquid

“*Everyone steals in commerce and industry. I have stolen a lot myself. But at least I know how to steal.*”

– Thomas Alva Edison

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"Among those whom I like or admire,
I can find no common denominator,
but among those whom I love, I can:
all of them make me laugh."

– W.H. Auden

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Curriculum Vitae

Oscar Patrick Réne van Vliet (1976) was born in Uithoorn and grew up in Papendrecht. After attending the Erasmiaans Gymnasium and Willem de Zwijger college, he moved to Utrecht University in 1994. He studied chemistry, graduating in 2001 after an eleven-month internship at the Lawrence Berkeley National Lab in California. He also studied environmental science, graduating in 2002 after three months of solo field work in Ecuador.

He started his professional career at SIRA Consulting, but left after a year and a half, and went on to a Ph.D. position at the department of Science, Technology and Society, which is part of the Copernicus Institute for Sustainable Development and Innovation. His project was entitled Quantified backcasting: methodological design of transition strategies in the area of sustainable transportation chains, and part of an interdisciplinary project together with the department of Innovation Sciences. Most of the research done for this project is bundled in this thesis, and led to several academic publications.

After his Ph.D. research was completed in April 2010, Oscar joined the International Institute for Applied Systems Analysis (IIASA) in Laxenburg, Austria as a Research Scholar.

Peer-reviewed publications:

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(two more articles forthcoming, see chapters 4 and 5)

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