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Backcasting for sustainable mobility and domestic power provision: a new perspective on fuel cell vehicles and decentralised power production

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Abstract

Hydrogen is an important topic in the transition towards sustainable energy supply as well as in the transition towards sustainable mobility. However, these transitions are seldom considered together. In this paper we argue that a technical and institutional integration around grid-connected electric vehicles could lead to considerable synergy and efficiency improvements, as well as increased potential for achieving sustainability goals. The key to the integrated perspective is that the present utilization of car power-trains is on average possibly only about 5%. This implies that in effect 95% of the time these high-tech products are standing idle at a parking lot. This highly inefficient use of capital investments in a high-tech product offers of large potential for improvement in various ways.

With the renewed interest for the electric vehicle in its various forms like battery electric vehicles (BEV), (hydrogen-driven) fuel cell vehicles (FCV) and various types of hybrid propulsion, the potential role of this technology in the energy transition and possibly a very radical innovation becomes opportune. Connecting all 6 million cars in the Netherlands (assumed to the fuel cell vehicles) to the grid, for example, provides a total generation capacity of about 240 GW, i.e. more than 10 times the installed present electric power production capacity.

The starting points above have been used for developing two future visions that served as an input to a backcasting analysis. In the first vision A FCV's are used to provide power during peak hours and to store surplus power from large-scale renewable energy sources by using a reversible fuel cell. The fuel cell can charge the hydrogen storage devices on board of the FCV's, but hydrogen will also be provided by fuel stations. In the second vision B the power delivered to the grid by the grid-connected FCV's will fully meet the electricity demand, making central power plants obsolete.

The paper discusses and analyses both visions, before it deals with required changes, various implications and recommendations how to address further possibilities to explore research, social and policy issues, using the Netherlands as a case. The paper also discusses current developments with regard to plug-in vehicles, focusing on developments in FCV's. It also discusses the backcasting approach and how it has been applied.

Key words: Fuel cell vehicle; distributed power generation; plug-in; electric vehicle; backcasting; hydrogen energy transition

1. Introduction

Hydrogen is an important topic in the transition towards a sustainable energy supply as well as in the transition towards sustainable mobility. However, these transitions are seldom considered together, whereas a technical, organisational and institutional integration could lead to considerable synergy and efficiency improvements at the (combined) system level. This would also increase the potential for achieving sustainability goals.

The basic idea behind combining these two transitions is to use hybrid and electric fuel-cell vehicles (FCV) as distributed power generators coupled to the electricity grid and possibly to a hydrogen grid in the future, assuming full or at least significant market penetration of these vehicles. This is very well possible, as car power-trains are not used most of the time; on average most cars are only used for about 5% of the time. As a consequence, these high-tech products are standing idle at a parking lot 95% of the time. This highly inefficient use of capital investments thus offers large potential for improvement in various ways.

With the renewed interest for the electric vehicle in its various forms like electric vehicles (EV's), (hydrogen-based) fuel cell vehicles (FCV's) and various types of hybrid propulsion, the potential role of this technology in the energy transition becomes opportune. Briefly, when all 6 million cars in the Netherlands would be replaced by 40 kW fuel cell vehicles and would be connected to the grid, this would provide a total generation capacity of about 240 GW, i.e. about 10 times the installed present electric power production capacity. Moreover, the use of the storage capacity of the batteries in the electric vehicles may also provide a reasonably sized short-term storage capacity for fluctuating renewable energy sources like wind and solar. The storage capacity is even much larger if we assume that the fuel cells can be operated in a reverse mode when needed; thus producing hydrogen that can be stored on board to be converted into electric power again when the need for electric power is high during peak hours.

The main focus of this paper is to show the potential and opportunities for both fuel cell vehicles and various other types of electric vehicles in the future. It starts with a brief overview of the current state and developments in plug-in electric vehicles, fuel cell vehicles and various types of electric hybrids in Section 2. It contains a short introduction to backcasting in Section 3. Then the paper reports on applying the backcasting approach to FCV's providing both electricity and heat by 2050, which builds upon recent student work (De Boks et al 2008) as well as on ideas and work by the authors. Section 4 describes starting points and assumptions for the backcasting study and future visions. Section 5 reports on the two future visions. In the first vision (A) FCV's are used to provide power during peak hours and to store surplus power from large-scale renewable energy sources by using a reversible fuel cell. The fuel cell can charge the hydrogen storage devices on board the FCV's, but hydrogen is also provided by fuel stations. In the second vision (B) the power delivered to the grid by the grid-connected FCV's will fully meet the electricity demand, making central power plants obsolete. Next, Section 6 presents the backcasting analysis of the most radical and far reaching second vision (vision B). Finally, Section 7 presents and discusses conclusions.

2. Plug-in electric vehicles

The introduction and large-scale diffusion of plug-in electric vehicles might become important stepping stones for a transition in which eventually FCV's could function as decentralized virtual power plants, providing electricity to either the grid or directly to dwellings as well as heat to dwellings. This can be illustrated by envisaging that all 6 million cars in the Netherlands will be replaced by FCV's that provide total generation capacity of about 240 GW to the grid (assuming 40 kW per vehicle) and realising that this is more than 10 times the installed present peak power production capacity in the Netherlands.

Before elaborating upon this perspective in the forthcoming sections, we first look into current developments and expectations of EV's and FCV's. We describe various aspects of ongoing and expected developments in plug-in vehicles, using insights from technology assessment methodologies yet focusing on mapping developments and prospects. For this step we distinguish between the following kinds of developments (that are in general strongly interrelated): technological, market/product, industrial dynamics (production), regulatory/policy, and other/miscellaneous. Developments are dealt with in a general way, although when it is appropriate more details are given about the Netherlands or the EU. Before looking into specific developments, we would like to mention that rising crude oil and fuel prices will also have a strong (enabling) influence on most of the ongoing developments discussed below.

Technological developments

- In the 1960s the interest in fuel cells increased because of the niche application in the NASA space programs (Gemini and Apollo). The focus was then on low temperature fuel cells, especially the Alkaline Fuel Cell and early versions of the polymer fuel cell. Since the late 1980s a number of countries including the Netherlands have started up national research programs on fuel cells. The main focus was shifted to (high temperature) fuel cells for stationary power with a shift to distributed power later on. However, some R&D also took place on low temperature fuel cells like the alkaline fuel cell and the polymer fuel cell, which were considered to be more suitable for transport applications at that time. Because of the need for pure oxygen, the alkaline fuel cell was not seen as being suitable for large scale transport applications, nor was the polymer fuel cell because of the high costs for the membrane and the platinum catalyst.
- In the late 1990s a revolution took place when Daimler Chrysler teamed up with the Canadian polymer fuel cell company Ballard in an effort to develop fuel cell vehicles and to bring down the cost of the polymer fuel cell. Many other car manufacturers followed and huge investments were made on the development of the polymer fuel cell and fuel cell vehicle design. Consequently, a lot of progress has been made in fuel cell performance and fuel cell vehicle improvement; most major car manufacturers established R&D programmes on FCV's and have shown prototype FCV's (for an overview of FCV developments see e.g. Van den Hoed 2004, 2007). Fuel cells for combined heat and power applications are also gradually emerging in other sectors, such as industry and dwellings. For some current developments and examples, see Hellmann (2007).
- Apart from hydrogen, methanol is studied as a potential fuel for FCV's, using a direct methanol fuel cell (DMFC). However, power densities of the DMFC are presently to low for successful application. Nevertheless, methanol can be reformed relatively easy on-board of a vehicle to produce hydrogen for a polymer fuel cell compared to ethanol or gasoline and has been supported by major oil companies (Van den Hoed 2004).
- Considerable improvements are taking place in batteries. Especially, the performance of Lithium-ion batteries has been strongly improved since the last decade. The use of iron (Fe) instead of more expensive metals like manganese (Mn) or cobalt (Co), while maintaining or even improving performance is expected to lead to significant cost price reductions.
- In spite of increasing R&D on hydrogen related technologies, hydrogen storage and distribution are still critical issues and currently still lead to high efficiency penalties up to 20-40% decrease (e.g. Blanchette 2008, Cherry 2004).
- Fuel cells are increasingly studied in hybrid or product integrated systems in which several renewable energy technologies are combined (e.g. Hemmes et al 2007, Hemmes 2009)

Market and product developments

- Different types of cars can be distinguished that use fuel cells or batteries for propulsion and that are in different development and market diffusion stages. Using Jennings et al (2002:

18), Van den Hoed (2004) and Hekkert and Van den Hoed (2006) we can distinguish between:

- FCV's or Fuel Cell Vehicles having batteries of limited capacity. Most major car manufacturers have presented prototypes of FCV's since the late 1990s.
- BEV's or Battery Electric Vehicles, fully powered by rechargeable batteries having large capacities. In the early 1990s most major car manufacturers had R&D programmes, as well as demonstration and testing programmes on BEV's. These demonstration programmes involved numerous users and vehicles at various places. Hoogma et al (2002) have given an account of several BEV experiments in the European Union in the 1990s. However, this has not lead to large-scale introduction of BEV's in professional or consumer mass markets.
- Hybrid FCV's or hybrid battery-electric Fuel Cell Vehicles having a fuel cell of limited capacity and rechargeable batteries with a large capacity.
- Plug-in hybrid ICEV's or hybrid battery Internal Combustion Engine Vehicles that have a small regular internal combustion engine and rechargeable batteries with a large capacity that can be plugged into the grid.
- Hybrid ICEV's or hybrid Internal Combustion Engine Vehicles having a small ICE and a battery of moderate capacity. First generation types include Toyota Prius and hybrids from Honda and Lexus. These types serve growing niche markets, sometimes stimulated by government regulations, such as tax reductions, as recently introduced in the Netherlands.

- Niche markets have emerged for special types of BEV's (e.g. golf carts, airport transporters and forklift trucks, and street sweeping-machines). However, these niche markets are supplied by specialised producers rather than for (incumbent) global car manufacturers, e.g. the UK firm Smith Electric Vehicles.
- Due to improvements in battery technologies, especially the improved performance of Lithium-Ion batteries, new (proto)types of BEV's were introduced by global car manufacturers quite recently.
- Various new pilots on battery powered vehicles and scooters have also just been started, such as an electric van pilot by TNT in London and the electric scooter pilot in the city of Rotterdam.
- Worldwide, the number of fuelling stations that provide hydrogen is rapidly increasing (see: http://www.netinform.net/H2/H2Stations/Default.aspx). For instance, a hydrogen fuel station has just been opened in Brussels strongly supported by the EU. However, the hydrogen station is not meant to serve FCV's, but will serve BMWs that fuel their ICE with hydrogen, which is a related yet parallel development by a firm that has rejected BEV's and FCV's so far.

Industrial dynamics and production developments

- There is a growing awareness among global car producers that on the long term they also have to cut down their carbon dioxide emissions significantly or even completely.
- Global car manufacturers are also under severe pressure by governments to produce cars that have much lower emissions than present day cars. The state of California has been a front runner in this since the early 1990s.
- Until mid 1990s most global car manufacturers had R&D and pilot programmes on BEV's, which had been forced by zero-emission regulations in California. Due to limited improvement in battery performance at that time and considerable improvement of fuel cell performance most major car producers ended their BEV programmes and shifted to FCV programmes. However, different firms employed different strategies, influenced by new or existing partnerships (Van de Hoed 2004).

- Recently, several car producers have (re)introduced BEV's to the market or are working on this (e.g. Honda, GM, Renault and Volkswagen), while Nissan is implementing plans to supply electric vehicles in large numbers to Israel and Denmark within a few years.
- In the Netherlands the utility company Essent is exploring the market of providing electricity to a large-scale market of BEV's. It has been argued that pump-to-wheel efficiency of BEV when charged by the grid is 80-90%, which is much better than the pump-tot-wheel efficiency of ICE cars, which is only 20-30%. Jennings et al 2002:18) mentions a maximum propulsion efficiency of the ICE car between 30-35%, which does not include 15% efficiency loss for making the fuel).
- However, this comparison does not take into account the efficiency of electricity production, which strongly depends on how it is generated. Traditional power plants typically have conversion efficiencies up to 40-45%, although Combined Heat and Power (CHP) can increase the overall efficiency of traditional power plants considerably.
- Currently, a lot of work is being done on testing of quickly charging batteries at fuel stations as well as on the feasibility of exchanging (almost) empty car battery packs for charged battery packs at fuel stations.

Regulatory, policy and political developments

- Governments of the USA and in Europe, as well as the European Union, have implemented policies that strongly stimulate production and use of biofuels to shares up to 10% in the coming years. This is done by blending of biofuel and regular fuels.
- In the Netherlands the government has introduced a regulation, which couples the fuel efficiency to special car taxes (the so-called BPM tax) when buying a car. Cars receive a fuel efficiency certification, which ranges from A (best) to G (worst) for different specified market segments. Cars having an A score have a BPM tax lowered down to 1,500 Euros, whereas cars having an E/F score are additionally charged with several thousands of Euros.
- Interestingly, another taxation change has been adjusted in the Netherlands, which favours hybrid cars over non-hybrid cars when leasing a car. This has strongly increased the demand for hybrid cars by lease companies and lease car drivers.
- In Europe as well as in the US there is a strong concern and a rising awareness about the dependence on oil, which comes along with an increasing dependency to currently less democratic oil and gas producing countries in Asia, Africa and the Arab World; these countries might become unstable in the future and employ their energy resources for strategic power games, like has already been done by Russia.

Other/miscellaneous

- Increasing crude oil and oil-based car fuel prices that may increase even more.
- Strongly rising fuel and energy demands by emerging economies like China, India and Brazil.
- There is an emerging debate about food versus fuel, as first generation biofuels are made from food crops. There are widespread concerns and increasing evidence that biofuels may compete. As a consequence, food prices are likely to rise further.
- There is a strong quest and increasing policy support for renewable energy technologies.
- Meanwhile, liberalisation of electricity production and use in the EU may lead to new constraints for renewable electricity sources, as well as provide opportunities for renewables. Generating and selling electricity by consumers is such an opportunity.

3. Backcasting: introduction and methodology

Backcasting literally means looking back from the future; it can be seen as the opposite of forecasting, which is about looking to the future from the present. A more comprehensive description of backcasting as an approach is ‘to develop first a desirable future, before looking back how that future could have been achieved and through what pathways or trajectories that could have happened’ (Quist and Vergragt 2006, Quist 2007). This is followed by setting agendas towards that desirable future and defining next steps. Jansen (2003, 2005) has called this ‘from vision to action” and ‘using backcasting for the challenge of sustainable development’. According to Dreborg (1996) backcasting is particularly useful if it concerns highly complex problems on a societal level, if there is a need for a major change, if dominant trends are part of the problem, and if scope and time-horizon are wide enough to leave room for very different choices and development pathways. Sustainability problems are obvious examples of such problems.

Backcasting was proposed in the 1970s in energy studies. Energy backcasting evolved as a policy analysis oriented approach for generating and analysing alternative energy futures, advocating renewable energy sources and conservation as desirable and attainable (Robinson 1990, Anderson 2001). In the early 1990s the emphasis in backcasting shifted towards its potential for identifying and exploring sustainability solutions (Robinson 1990), for instance in Sweden (Dreborg 1996, Holmberg 1998), Canada (Robinson 2003) and the Netherlands (e.g. Weaver et al 2000, Geurs and Van Wee 2000, Quist et al 2001, Vergragt 2005). This period also showed a shift to stakeholder involvement in backcasting (Weaver et al 2000, Quist et al 2001, Green and Vergragt 2002, Robinson 2003, Van de Kerkhof 2004, Quist and Vergragt 2006, Quist 2007). Up till now backcasting for sustainability has been applied to a wide range of different topics like regions, river basins, domains like transportation and mobility, transforming companies into sustainable ones, sustainable technologies and sustainable system innovations, sustainable households. For a recent overview of developments and applications in backcasting, see Quist and Vergragt (2006) or Quist (2007).

Key elements of participatory backcasting include (Quist and Vergragt 2006, Quist 2007): (1) the construction and use of desirable normative scenarios and goals; (2) broad stakeholder participation and stakeholder learning (on the level of paradigms and values); and (3) combining process, participation, analysis and design using a wide range of methods within the overall backcasting approach. It has been argued that the distinctive features of backcasting make it more appropriate for sustainability applications than regular foresighting and scenario approaches (Dreborg 1996). This has strongly to do with the idea of taking desirable (here sustainable) futures or a range of sustainable futures as a starting point for analysing its potential, its feasibility and possible ways how this future can be achieved.

Though most approaches found in the literature show differences in methods applied, ways of stakeholder involvement and number of steps, it is possible to generalise and translate these into a methodological framework for participatory backcasting consisting of five stages or steps (Quist and Vergragt 2006, Quist 2007). These are:

STEP 1 Strategic problem orientation
STEP 2 Construction of sustainable future visions
STEP 3 Backcasting (analysis)
STEP 4 Elaboration, analysis and defining follow-up and (action) agenda
STEP 5 Embedding of results and generating follow-up and implementation

A wide range of methods and tools are needed in a participatory backcasting framework; essentially, four groups can be distinguished that make up the outline of a toolkit. *Participatory tools and methods* are the first group. Second, there are *design tools and methods,* which are not only meant for scenario construction, but also for elaboration and detailing systems as well as process design tools. Third, backcasting involves a*nalytical tools and methods*. Fourth, backcasting also requires *management, coordination and communication tools and methods.*

In this paper is reported on steps 1-3 (and partly step 4) of a non-participatory backcasting study focusing on FCV's as decentralised electricity providers in 2050. It uses a light version of the backcasting approach that is also used in education at Delft University of Technology since 2001 (Quist et al 2006).

4. Backcasting for FCV's as a virtual power plant: assumptions and current state

This section deals with some assumptions and starting points for the final states in 2050, as well as with data for the current situation with regard to some aspects of energy use. Some key data, using Jennings et al (2002), are summarised in Table 1. A more complete overview of energy demand data in 2000 and 2050 from these authors is given in Appendix I. In brief, Table 1 shows that the energy demand for electricity, mobility and heat was 1300 PJ in 2000 and is estimated to be 1620 PJ in 2050 (using estimates that assume considerable increase of industry in the Netherlands. The 2050 energy demand can be served by an amount of 13.6 billion kg H_2, if combined heat and power is neglected.

- In 2000 the usage of electricity in the Netherlands was to 340 PJ according to Jeeninga et al (2002), which is roughly 95 TWh. This requires an average production capacity of around 10.8 GW and a peak capacity of nearly 20 GW, as there is currently no storage capacity in the Netherlands. Using Jennings et al (2002) the demand for electricity in 2050 will be around 720 PJ or 200 TWh. This assumes an average production capacity of 22.8 GW and a peak capacity of 42 GW under the assumption that no significant storage capacity will be available.
- In 2000 the energy demand for mobility and transportation was about 500 PJ (Jennings et al 2002), whereas in 2050 this will be only 400 PJ under the assumption that all vehicles are replaced by FCV's and that FCV's are a factor 2 more efficient then current ICEV's.
- Heating of buildings and water demanded 470 PJ in 2000, whereas in 2050 this will be around 570 PJ (Jennings 2002). In both years it will be partly provided by CHP, which currently provides more than 40% of the heat demand in the Netherlands (Raven and Verbong 2007). In 2050 FCV may meet a large share of the heat demand, if it has become possible to utilise the heat from the FCV's.

Table 1 Annual energy demand in 2000 and 2050 (based on Jennings et al 2002: 12)

	2000	2050	2050 hydrogen[1]
Electricity	340 PJ	720 PJ	$6.0*10^9$ kg H_2
Mobility	490[2] PJ	330[3] PJ	$2.8 *10^9$ kg H_2
Heat (<100 °C)	470[4] PJ	570[4] PJ	$4.8 *10^9$ kg H_2 [5]
Total	1300 PJ	1620 PJ	$13.6 *10^9$ kg H_2

[1] The volumes of hydrogen are calculated using its energy content of 120 KJ/g. Figures are not corrected for conversion efficiencies of hydrogen and should thus be seen as an indication.
[2] Using Jennings et al (2000: 18) the efficiency of turning crude oil into car fuel is set at 85%, which makes the energy content put in the Dutch vehicles 416 PJ. The maximum efficiency of ICE propulsion is 20-35% (the so-called pump-to-wheel efficiency). The well-to-wheel efficiency is thus 25-30%.
[3] Jennings et al (2002:12,18) assume that the fossil fuel based energy demand for transport will be 770 PJ in 2050. However, when correcting for the efficiency of turning crude oil into gasoline (85%) and assuming 50% efficiency for FCV pump-to-wheel efficiency, the energy demand becomes 330 PJ.
[4] Heat (<100 °C) demand by households and offices (service sectors and government). This is exclusive the demand by industry, agriculture and horticulture of 214 PJ in 2000 and of 246 PJ in 2050 (see Appendix I).
[5] This figure turns the heat demand fully into the amount of hydrogen required and neglects the reduction due to combined heat and power.

With regard to FCV's the following assumptions have been made:

- Current FCV prototypes (GM, Honda, Toyota) have capacities between 80 and 120 kW, whereas on averaged ICE vehicles have capacities between 60 and 100 kW. Under the assumption that the car will have become more efficient by 2050 (e.g. due to lower weight), it is estimated that the averaged capacity of a FCV in 2050 can be set at 40 kW.
- The Dutch Ministry of the Environment has indicated that by 2050 the numbers of cars in the Netherlands will be between 8 and 12 Million; it is assumed here that in 2050 there will be 10 Million FCV's. This implies that the maximum total capacity of the FCV fleet will be 400 GW.

Finally, it is necessary to calculate the volume of hydrogen that needs to be produced in 2050 to provide all FCV's in the Netherlands with hydrogen.

- The energy content of hydrogen is 120 KJ/g. Under the assumption that the fuel cell has a maximum system efficiency of 70% (Kolke 1999) for producing electricity and a pump-to-wheel efficiency of 50% (Jennings et al 2002), this implies that for the Netherlands annually 13.6 million tonnes of hydrogen are needed. If efficiencies will become lower, then more hydrogen will be needed.
- Currently, global annual hydrogen production is around 50 Million tonnes, which is made from fossil fuels and is applied in various industries. In the petrochemical industry hydrogen is used to extract sulphur form natural gas, in the chemical industry to produce ammonia and polystyrene, while in the food industry hydrogen is needed to saturate unsaturated fat acids. This indicates that the required annual amount of hydrogen needed for the Netherlands can be produced; it might even be possible to produce it in the Netherlands, if current production capacity will be extended.
- It is assumed, however, that by 2050 hydrogen should be produced in a more sustainable way using other (energy) sources. Reversible fuel cells may provide part of this by reversed operation on board.
- Table 1 neglected the possibilities for CHP, though it has been mentioned that up to 40% of current heat demand in the Netherlands is provided by CHP. Applying CHP with the FCV's will decrease the demand for fuel (e.g. hydrogen) for the production of heat. It is assumed here that in 2050 also 40% of the heat will originate from CHP by FCV's, this will decrease hydrogen for this application with a similar share, whereas higher shares are very well possible.
- Table 1 also shows the volumes of hydrogen needed for different types of energy demands. However, energy is also needed to produce, store and distribute hydrogen and to supply it with the right features in a safe way. This should be better looked into, including to what extent conversion efficiencies have been included in Jennings et al (2002).

After having discussed some basic assumptions, the next section presents two future visions. Vision A describes a final state in which FCV's buffer the fluctuating supply from renewable sources as well as peak demand, whereas in the more far reaching Vision B the FCV's will provide all electricity and most of the heat demand in houses and offices, making traditional large-scale power plants entirely obsolete.

5. Future visions

5.1 Vision A: FCV's as a buffer plant in 2050

The key to the first vision is that by 2050 all 10 million ICE cars in the Netherlands are replaced by FCV's, while the FCV's will function as a buffer in the sense of a decentralised and distributed virtual peak power plant. In 2050 about 50% of the electricity produced will be from wind turbines and PV (each providing 25%); the other 50% stems from traditional fossil fuel driven power plants. When renewable electricity production exceeds the demand, the surplus will be used to produce hydrogen by means of electrolysis, which happens at locations in a way that transportation of hydrogen is minimised, for instance at fuel stations or by reversed operation on board. Hydrogen is distributed by fuel stations in a similar way as gasoline and liquefied natural gas nowadays or produced on board. FCV's that are coupled to the grid at large car parks and near private homes will provide peak demand. When the renewable sources cannot meet regular demand due to fluctuations, this will be supplied by the (parked) FCV's too. Transformers that are currently used to bring down the voltage from the grid to 220 V to be used in homes and offices will also be capable to upgrade low-voltage power from the FCV's to a grid-relevant level in sufficiently large volumes. Coupling the FCV to the grid is done by the driver who has a contract with the electricity distributor under what conditions (e.g. price, maximum volume) electricity will be supplied. Both electricity and data on the volumes are transported through the coupling.

It has already been mentioned that on average FCV's will have a capacity of 40 kW, which brings the total capacity in the Netherlands to 400 GW. This is about ten times the predicted maximum peak demand of 42 GW (assuming that total and peak demand will rise proportionally over time). This shows that 10% of the FCV's are capable of providing the entire peak demand, which will further reduce the number of traditional power plants needed.

5.2. Vision B: FCV's meeting full electricity demand in 2050

The key to the second vision is that FCV's not only have fully replaced ICE cars in 2050, but also that FCV's provide all electricity needed in the Netherlands. As a consequence traditional fossil fuel and nuclear power plants have been phased out and have all been closed down over time. In 2050 FCV's thus provide both mobility and 720 PJ of electricity annually. Moreover, FCV's also provide most of the heat demanded by office buildings and households, which is another 570 PJ annually. Heat exchangers in the car allow that heat from the fuel cell, which has a temperature between 80 and 120 ^{o}C, when it is a polymer fuel cell, is exchanged to water through the liquid that cools the fuel cell. No natural gas is needed anymore for heating or cooking; cooking will be done fully electrically. Heat production will be backed by burning hydrogen in the building, when the supply from FCV's is insufficient to meet (local) demand.

FCV's are coupled to buildings through a triple connection: for electricity; for heat (transported through water); and for hydrogen. Data about how much hydrogen is provided and how much electricity and heat are supplied will also be transported through the connection too. Electricity is directly supplied to homes and buildings, but FCV's produce also for the grid that will bring it to locations where FCV's are lacking or are producing too little electricity to meet the demand. Hydrogen is supplied to homes and office through a pipeline network similar to the current natural gas pipeline network. FCV's get their hydrogen at home or at other places where they are parked, such as parking lots at work or near flats. FCV owners can ensure that only electricity is supplied to the grid, when the price for the electricity allows for a reasonable profit margin at a level set by the owner. However, the system and contracts are organised in such a way that always sufficient electrify can be supplied.

This vision also assumes that cheap, reliable and sustainable large-scale production of hydrogen is possible and might even take place in the Netherlands, where currently significant hydrogen is produced in the industrial areas of the greater Rotterdam region. Although it is important to indicate what the hydrogen sources are, this has not been included in this backcasting exercise study so far[1].

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[1] One might for instance think of coal gasification with subsequent carbon capture and storage (CCS) as a large-scale abundant source of hydrogen, although more sustainable sources would be preferred. See also Edwards et al 2008 who also emphasise that CCS is not a proven technology yet and has a huge energy penalty (30B-40% decrease of the conversion efficiency).

Table 2: Some key characteristics of the two visions

	Vision A	**Vision B**
Functions of FCV	Transportation and decentralised buffer plant using hydrogen as buffer.	Transportation, full electricity supply and large share of heat supply
Space heating	Traditional way by natural gas	Heat from FCV, buffered by burning of hydrogen
Hydrogen production	From surplus of electricity during off-peak hours by electrolysis of water	Large-scale H2 production sites (cheap and highly efficient).
Hydrogen distribution	Hydrogen fuel stations.	Hydrogen is distributed by pipelines similar to natural gas nowadays
Way(s) of coupling	Electric connection between FCV's and buildings.	Connection between FCV and built environment includes modes for electricity, heat (through water) and hydrogen.

6. Backcasting analysis

Table 2 summarises some key characteristics of both future visions. Although both visions have been positioned in 2050, we argue that Vision B is considerably more far-reaching and radical than Vision A. Because of the full replacement of fossil fuel driven power plants, it is also assumed that Vision B has a larger sustainability potential, although this should be checked and confirmed by further research. Therefore, we argue that it is more interesting to see Vision A as an intermediate state in a more radical and further reaching transition to Vision B. As a consequence, we only subject Vision B to the backcasting analysis here. Backcasting results are described below and are grouped into: (i) technological changes; (ii) cultural changes; (iii) structural changes; (iv) organisational changes, and; (v) stakeholders needed to prepare, facilitate and realise the changes.

Technological changes

- Development and large-scale production of fuel cells and FCV's; this includes looking into the feasibility and possibilities of high-temperature fuel cells, as more permanent operation of the fuel cells prevents short warming-up times.
- Reversed operation of the fuel cell reduces the need for producing hydrogen elsewhere. However, it requires differences in the design and technology of the fuel cell and it may affect the performance and efficiency of both normal and reversed operation. It also asks for specific requirements for storage of hydrogen. Currently, storage by means of metal hydrides is most promising.
- Adjustment of the grid in a way that it enables that FCV's supply electricity to the grid. This includes transformer technology to upgrade the electricity to voltages with 'grid-relevant features', which has to take place at the level of buildings or blocks.
- Development of a coupling-connection between FCV's and buildings that allows for supplying electricity and heat to the building, for providing hydrogen to the vehicle and for exchanging data about the deliveries and supplies.
- Development of a so-called smart grid and related communication system that tracks deliveries to and supplies from specific FCV's and processes these into (financial) administrations and transactions.
- Strong improvement of technologies allowing storage of hydrogen, such as compression, liquefaction and binding to metal hydrides.

- Technologies that enable large-scale reliable, cost-effective and sustainable production of hydrogen and a pipeline distribution network delivering hydrogen to buildings and fuelling stations. This could include coal gasification and carbon capture storage.
- Integration of the necessary artefacts and products (Transformers, DC-AC converters, hydrogen, adjusted heating equipment etc.) in the built environment. This includes that wires in the homes are capable of handling larger volumes that will be supplied to the grid.

Cultural and user (behaviour) changes

- FCV owners must get used to their new role of electricity and heat producer and have to adjust their use patterns in such a way that it suits them and can make optimal use of the advantages of the new system. This includes using and accepting the coupling-connection of the car to the building and the changes in the built environment enabling the changes.
- Broad public acceptance of hydrogen for replacing car fuels is needed, as well as for replacing natural gas for heating.
- Cultural changes among electricity distributors are needed, as well as at the organisation that manages the grid (that is currently Tennet).

Structural and institutional changes

- Current large-scale power plant-based electricity and combined heat production will disappear, just as natural gas distribution and use in households and other buildings.
- A new hydrogen industry will emerge that produces large amounts of hydrogen in a sustainable way; current electricity producers may turn themselves into hydrogen producers.
- Current fossil car fuel distribution system including fuel stations will disappear.
- The electricity grid as well as the built environment needs to be adjusted to the new situation.
- There will be structural changes necessary in the car industry, their suppliers over the whole supply chain and in the maintenance providers.
- The system must be structured in such a way that always enough FCV's are connected to grid. This is more than possible with the overload of capacity, also during rush hours.
- The government needs to adjust regulation and policies to the new systems

Organisational changes

- Organisational changes are needed among the grid management organisation, electricity and hydrogen distributors, car maintenance and repair providers, building constructors, architects and private and cooperative house renters, heating and electricity installers etc.
- The contacts between FCV owners that supply electricity to the grid and electricity distribution companies that also provide hydrogen will be organised very differently and require very different agreements and contracts. For example utility companies may be leasing the fuel cell vehicles to the customer, provided that they are hooked up to the grid for a certain percentage of the time.

Some key stakeholders needed for bringing about the vision and realising the transition have already been mentioned in the backcasting analysis. These include producers of various artefacts related to the FCV's, while producers of renewable energy technologies, hydrogen and infrastructure components as well as utilities. The other key group are end-users of FCV's that are also end-users of electricity, hydrogen for mobility and heat supplied by the FCV's. In addition, two more (groups of) stakeholders can be distinguished. First, knowledge and research bodies both from public and industrial research are needed to develop technologies and relevant (non-)technological knowledge. However, a large part of this knowledge development for instance the development of fuel cells and FCV's will take place abroad, Second, this transition will require policy and regulatory changes, as well as investments and implementation support by the government not only at the national level, but also at the regional and local level. The needed activities by these groups of stakeholders need to be elaborated in follow-up activities. Furthermore, public interest groups may become an important enabling or constraining factor, which has not been dealt with in this paper.

7. Conclusions

This paper has looked into current developments in electric vehicles and fuel cell vehicles. It has also shown that FCV's are capable of meeting full electricity demand and most of the heat demand (from houses and offices) in 2050, as well as of replacing all traditional fossil fuel driven and nuclear power plants. This has been shown by applying a backcasting approach and developing two future visions and applying backwards-looking analysis of the most far-reaching one (Vision B). The backcasting analysis has also provided a list of needed changes, which implies a follow-up agenda as well as what stakeholders are needed.

A comparison with other visions reported will be of help too (e.g. McDowall and Eames 2007, 2008), especially to get a better understanding of societal aspects and user concerns. Moreover, user and societal acceptance is crucial and for this reason public and user views. For instance, these visions pre-suppose that personal mobility will remain dominated by private cars and it excludes a shift to more collective or public or shared personal mobility systems. Moreover, extending the functionality by introducing FCV’s that will be used as distributed electricity and heat suppliers may result in a rebound that it enhances car ownership and stimulate the number of cars in society. By this it may become more difficult to live without a car, while this may eventually come along with higher costs as non-owners are not part of the energy trading system, but are solely consumers that may get less influence in this market than car owners. Other relevant social and user aspects include traceability and related privacy concerns, the collective responsibility of such a distributed system (who is to blame when electricity supply fails and the entire system or a considerable part of it faces a breakdown), safety concerns, convenient use by users and does it allow for a range of use patterns that are seeked for by car owners and their families and also the power balance in such a large-scale energy trading system. In addition, costs will remain a critical user issue. However, decreased geopolitical dependence with regard to energy may be regarded as a very positive aspect of such a system.

Next steps that are recommended include further elaboration and analysis of the future visions, as well as stakeholder consultation and starting a participatory multi-actor follow-up project. This will also provide further insight into the feasibility of the presented visions and in the opportunities and possibilities that various actors see as well as willingness to contribute to some of the ideas and identified changes needed. Moreover, more insight is needed into additional barriers and advantages. Whereas it might be easy to bring up barriers originating from existing lock-ins, path dependencies and vested interests, there will also be considerable advantages from the proposed decentralised electricity production, such as enhanced electricity security, enhanced flexibility and gradually reduction of the peak capacity needed, apart from the strong reduction in non-renewable resource use. For relevant discussions on some of these issues, see elsewhere (e.g. Edwards et al 2008, Shinnar 2003, Cherry 2004).

So far, the issue of large-scale sustainable hydrogen production has not extensively been dealt with as part of the current research activities, but should be done too and could hook up with . state of the art as reported in the literature (e.g. Blanchette 2008, Kruger 2008, Mueller-Langer et al 2007). It is also necessary to look into the potential environmental gain and sustainability potential of both visions, which will provide recommendations for increasing their potential with regard to this. This will for instance strongly depend to how the hydrogen will be produced and handled and to what extent conversion losses will be compensated by the advantages of hydrogen storage at the system level.

Furthermore, the possibilities and opportunities of electric vehicles as stepping stones for a transition to FCV's need further attention too. Despite the title of this paper, this has been dealt with only in a limited way here and therefore calls for follow-up elaboration. Several approaches can be applied here. One approach is to elaborate trajectories towards the envisaged futures within a backcasting framework. Another approach is to apply regime analysis (e.g. Hoogma et al 2002, Elzen et al 2002) or to develop regime-based socio-technical scenarios following Elzen et al (2002, 2004), yet aligned with generated future visions. This could also contribute to further methodology development from which both the backcasting approach and the socio-technical scenario methodology could benefit.

Finally, Delft University of Technology is considerably extending research into electric vehicles that are capable of supplying electricity peak demands by storing electricity during off-peak hours, which is among others supported by the utility company Essent.

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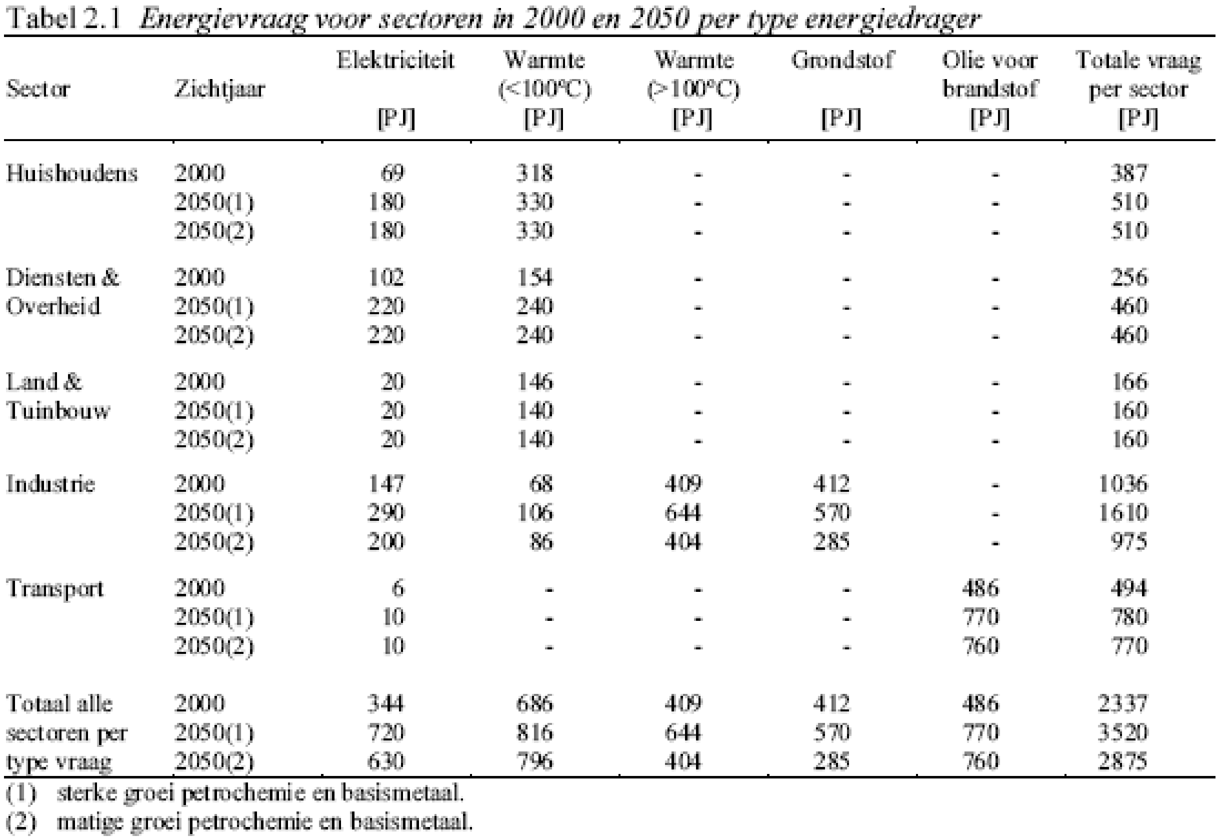
Appendix I:

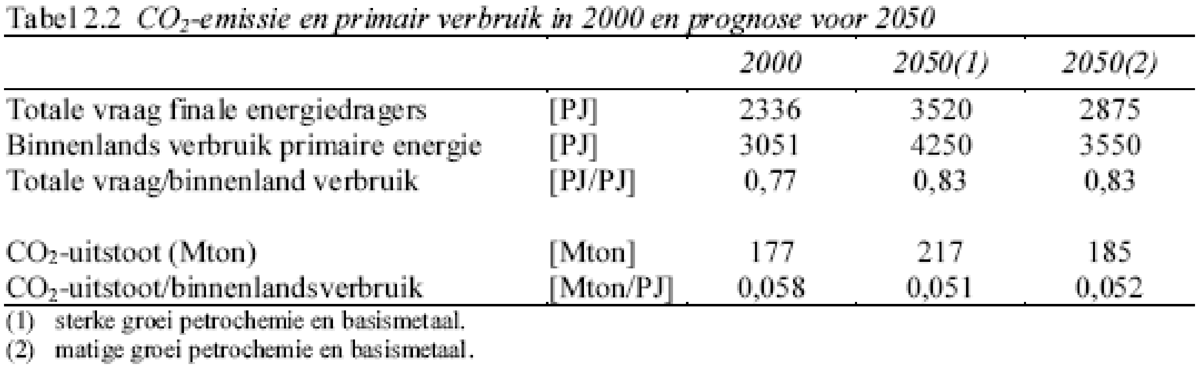
This Appendix contains the figures extracted from Jennings et al (2002) as used in this paper by showing the energy demand for all sectors in 2000 and 2050 for different types of energy carriers (Table 2.1) and the CO_2 emissions and primary energy use in 2000 and its estimates for 2050 (Table 2.2). In addition, both tables show a (1) high industrial growth and (2) moderate industrial growth scenario.



Tabel 2.1 *Energievraag voor sectoren in 2000 en 2050 per type energiedrager*

Sector	Zichtjaar	Elektriciteit [PJ]	Warmte (<100°C) [PJ]	Warmte (>100°C) [PJ]	Grondstof [PJ]	Olie voor brandstof [PJ]	Totale vraag per sector [PJ]
Huishoudens	2000	69	318	-	-	-	387
	2050(1)	180	330	-	-	-	510
	2050(2)	180	330	-	-	-	510
Diensten & Overheid	2000	102	154	-	-	-	256
	2050(1)	220	240	-	-	-	460
	2050(2)	220	240	-	-	-	460
Land & Tuinbouw	2000	20	146	-	-	-	166
	2050(1)	20	140	-	-	-	160
	2050(2)	20	140	-	-	-	160
Industrie	2000	147	68	409	412	-	1036
	2050(1)	290	106	644	570	-	1610
	2050(2)	200	86	404	285	-	975
Transport	2000	6	-	-	-	486	494
	2050(1)	10	-	-	-	770	780
	2050(2)	10	-	-	-	760	770
Totaal alle sectoren per type vraag	2000	344	686	409	412	486	2337
	2050(1)	720	816	644	570	770	3520
	2050(2)	630	796	404	285	760	2875

(1) sterke groei petrochemie en basismetaal.
(2) matige groei petrochemie en basismetaal.



Tabel 2.2 *CO_2-emissie en primair verbruik in 2000 en prognose voor 2050*

		2000	*2050(1)*	*2050(2)*
Totale vraag finale energiedragers	[PJ]	2336	3520	2875
Binnenlands verbruik primaire energie	[PJ]	3051	4250	3550
Totale vraag/binnenland verbruik	[PJ/PJ]	0,77	0,83	0,83
CO_2-uitstoot (Mton)	[Mton]	177	217	185
CO_2-uitstoot/binnenlandsverbruik	[Mton/PJ]	0,058	0,051	0,052

(1) sterke groei petrochemie en basismetaal.
(2) matige groei petrochemie en basismetaal.