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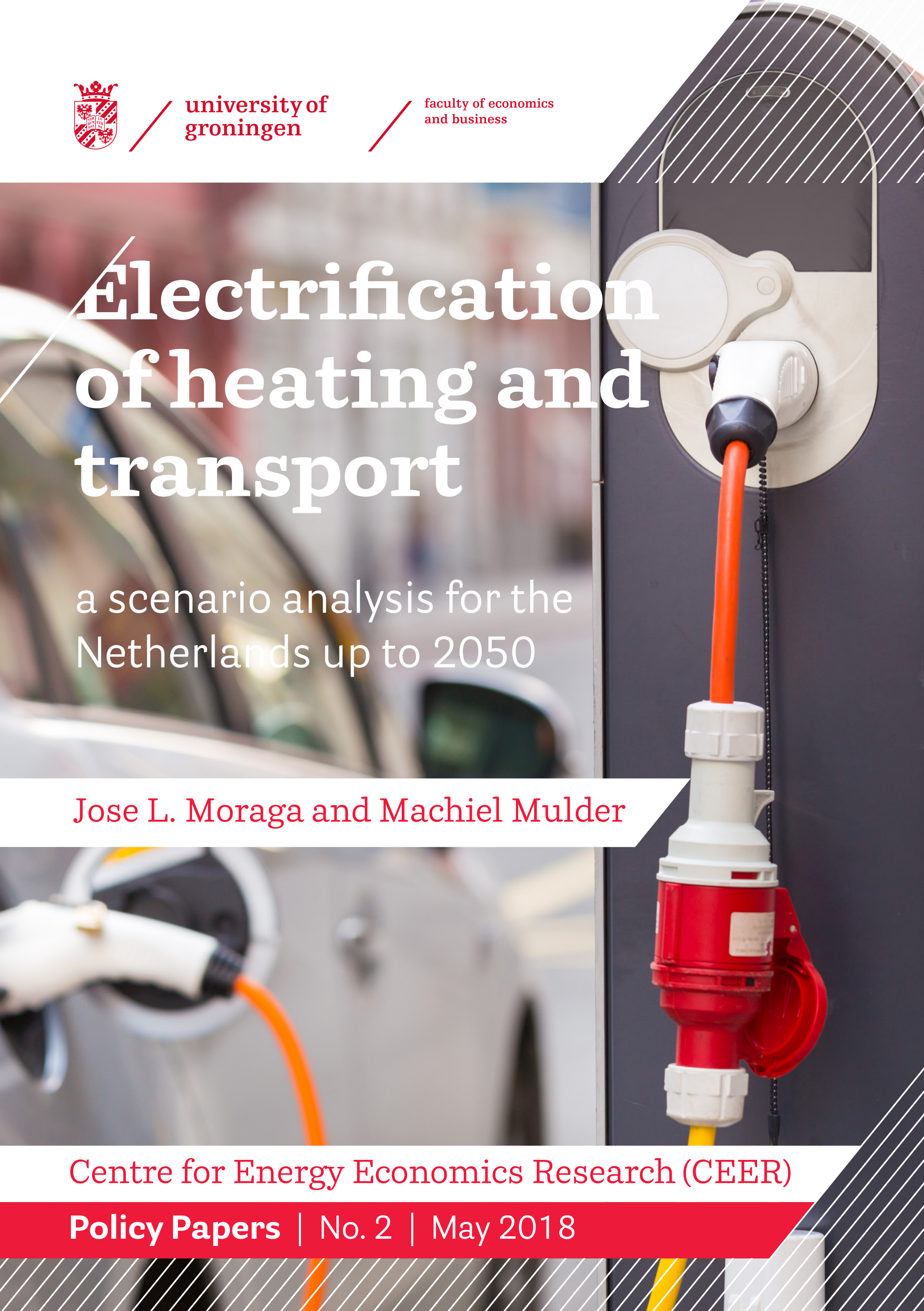

Electrification of heating and transport

a scenario analysis for the Netherlands up to 2050

Jose L. Moraga and Machiel Mulder

Centre for Energy Economics Research (CEER)

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1. Introduction

1.1 Background

In helping to prevent an increase in World temperature by two degrees Celsius compared to pre-industrial levels, the European Commission is committed to reduce EU greenhouse gas (GHG) emissions by 20% below 1990 levels by 2020, and by 40% below 1990 levels by 2030. It is expected that reaching such targets will pave the path to further reductions; in particular, by 60% below 1990 levels by 2040, and by 80% below 1990 levels by 2050.

Transport is one of the notable contributors to GHG emissions; as a matter of fact, in 1990 about 15% of the aggregate GHG emissions were attributed to transport, and this share has increased to 23% in 2015. Thus, in reaching the above-mentioned reduction targets, rethinking transport has a significant potential. In 2013, the EU launched the *European Alternative Fuels Strategy*[1], which is a technology neutral strategy for the replacement of conventional sources of energy for transport by a mix of alternatives including electricity, natural gas (LNG, CNG), hydrogen, biofuels, etc. Each of these alternative fuels suits the different types of transport in different degrees (EC, 2013). For example, the technology for the electrification of passenger cars is already quite well developed and probably suits the needs of millions of car drivers. The same could be said for city buses, and probably soon for light-duty transport vehicles and vans. However, for heavy-duty trucks and intercity bus transportation, perhaps solutions based on LNG and/or CNG are better positioned at this moment. Electrification of boat and plane transportation is expected to remain quite limited to short-distance operations (EC, 2013).

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[1] European Commission, Clean Power for Transport: A European Alternative Fuels Strategy, COM (2013) 17.

A second crucial contributor to GHG emissions in Europe is the stock of buildings. The building sector, which comprises commercial, public and residential buildings accounts for about a third of the GHG emissions in Europe (*ec.europa.eu*). However, because the weather has a major influence on energy consumption especially for heating, for some countries the building sector's share of GHG emissions reaches as high as 40%.[2] Residential dwellings account for about 60% of the emissions of the building sector in the EU (*ec.europa.eu*). This means that, the residential sector has a potential similar to that of the transport sector to reduce GHG emissions in Europe. In 2010 the EU reformed the *European Performance of Buildings Directive* (EPBD), which, among other things, introduced compulsory energy certification of buildings in the EU by 2006. The recast of the EPDB states that by the end of 2020 all new buildings in the EU should be "nearly zero-energy buildings", which refers to buildings with a very low energy consumption and whose energy needs are provided mostly by renewable sources, including energy from renewable sources produced on-site or nearby. Moreover, the 2012 *Energy Efficiency Directive* (EED) obliged member states to develop long-term actions for the investment in renovation of the stock of residential houses as well as the public and private non-residential buildings.

In both transport and buildings, electrification may help to reduce GHG emissions. Electrification does, however, not necessarily imply that the role of fossil fuels is reduced. This role depends on how the electricity will be generated in the future. In particular, natural gas may remain an important source of fossil energy. The potential role of gas in the future energy systems with electrification in transport and heating also depends on the developments on the supply side in the gas market. Europe still has a well-developed gas infrastructure for transporting, distributing as well as storing large gas volumes, which would enable a further increase in the demand for gas. This infrastructure can also be used for the transport and storage of green gas, such as biogas, hydrogen or synthetic methane. This implies that the gas infrastructure may also contribute to the business outlook of power-to-gas.

1.2 Scope

This study is concerned with the implications of a gradual electrification of *road transportation* and *domestic heating and cooking* for the electricity and the gas sectors in the Netherlands. By electrification of road transportation, we mean the gradual replacement of conventional gasoline and diesel cars, vans, buses, trucks, motorbikes, scooters and bicycles by the corresponding full electric versions. By electrification of domestic space and water heating and cooking we refer to the substitution of natural gas boilers and gas stoves in the residential sector by heat pumps and electric stoves.

The Dutch market is particularly relevant to analyse because the Netherlands is one of the major gas producing countries in Europe, with a highly developed gas infrastructure that is closely connected to neighbouring countries networks. Further, in the Netherlands heating is currently almost fully based on the use of natural gas, and gas-fired power plants play a key role in the Dutch power market as they produce about half of the electricity. Though the share of renewables is still low compared to most other European countries, the Dutch government has launched ambitious plans to strongly increase renewable energy in the power market. At the same time, the Dutch government wants to shut down all

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[2] In the UK, for example, in 2012 the emissions from buildings accounted for 37% of the total GHGs (Committee on Climate Change (*theccc.org.uk*)).

coal-fired power plants by 2030. This may imply that the role of gas-fired plants increase further.

Furthermore, there are some special features to the transport system in the Netherlands: one, the country possesses one of the most comprehensive systems of channels in the World and this allows for an economical shipping of goods using vessels and smaller boats; two, the train system is also very extensive and a large share of the population commutes by train; finally, the Netherlands is a flat country and the use of bicycles is prevalent.

The Dutch government responded to the *Alternative Fuels Strategy* of the European Commission with the *Energy Agreement* (*Energieakkoord*) of 2013 (SER, 2013). In this Agreement, the Dutch government set ambitious targets aiming at reducing GHG emissions in various sectors, including transport, buildings and the electricity sector. Particularly relevant for this project is the government's commitment to progressively electrify the mobility sector. In the building sector, the recast EPDB has been implemented in the Netherlands via the *Besluit en de Regeling Energie Prestaties Gebouwen*, which came into force in 2013. The newly formed cabinet has committed to abide to the most ambitious goals of the 2015 *Paris Agreement* for the period 2017-2021.[3]

In this paper we explore the consequences of the electrification in road transport and residential buildings for both the electricity and gas sectors, the total system costs and the emissions of CO_2. In order to systematically analyse the consequences of the policy ambitions regarding electrification, we have built a concise model of the Dutch energy system up to the year 2050.

Departing from actual annual data for 2016 and information on policy objectives regarding both electrification and the energy transition, this model simulates the yearly demand for energy from the residential housing and road transport sectors, the corresponding annual supply of electricity by type of generation technique, and the implied yearly consumption of natural gas. We allow the electrification degree to vary across transportation means: passenger cars, for example, are already in a path towards electrification, while this is not the case for heavy-duty vehicles. We do not include transportation by train, plane or boat. Train transportation is already mostly electric and the applications of electric powering of planes and boats are until now quite limited. Moreover, we leave heating of offices and industrial spaces outside of this study.

Using the outcomes concerning the demand for electricity and gas from these sectors, the model also calculates the investments needed for electrification of the housing and road transport sector, as well as the investments necessary to meet reasonable levels of reliability of supply of electricity, including investments in electricity generation capacity, in sources of flexibility to deal with the intermittency of the supply of renewable electricity, as well as in grid extensions. Finally, the model determines the impact of electrification on total system costs and the emissions of CO_2.

1.3 Organisation of the paper

In Section 2 we present our framework of analysis, putting it in the perspective of the literature, while we also describe the scenarios. In Section 3 and 4, we describe the impact of electrification on the electricity demand by road transport and residential buildings, respectively. Section 5 combines these results with estimations of the autonomous change in the electricity consumption in the rest of the economy in order to derive

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[3] *Vertrouwen in de Toekomst*, Regeerakkoord 2017 – 2021, VVD, CDA, D66 en ChristenUnie.

an estimate for the total level of electricity consumption. Section 6 provides an account of the future composition of the energy mix to meet the future demand for electricity. Section 7 is dedicated to the analysis of reliability of electricity production. Section 8 combines results from Sections 6 and 7 to provide an estimate of the future role of gas-fired power plants and power-to-gas within the Dutch electricity market. Section 9 focuses on the supply of gas, taking into account the recent commitment by the Dutch government to discontinue the extraction of natural gas from the Groningen field. In Section 10, we report on the implications of electrification for the electricity and gas infrastructure. Section 11 discusses the consequences of electrification for the carbon emissions. In Section 12, we provide an analysis of the costs of electrification resulting from investments in housing, electric vehicle charging infrastructure, power plants and electricity networks. Section 13 presents our concluding remarks and the consequences for policy.

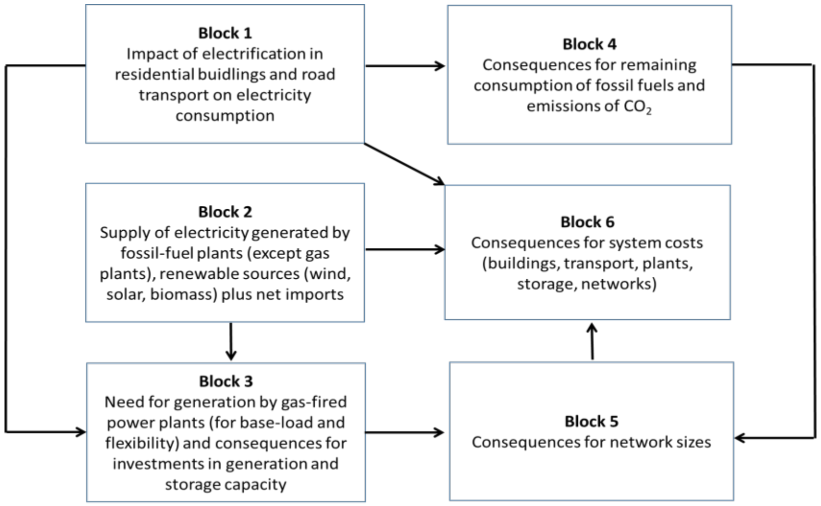
2. Method

2.1 Analytical framework

The analytical framework consists of 6 blocks (Figure 2.1). First, in Block 1, we determine the impact of electrifying the residential housing and road transport sectors on electricity consumption. In this analysis, we depart from three elements: 1) data on the actual number of houses and vehicles, their use of energy and the extent to which they are electrified, 2) assumptions on the future development in the number of houses and vehicles, and 3) information on current policy objectives with regard to the speed of electrification (see Figure 2.2 for the detailed framework). For the latter, we define a number of scenarios. For each scenario we calculate the annual demand for electricity as a result of the electrification. In order to arrive at an estimate for the total demand for electricity, we also make a forecast of the autonomous change in the remaining electricity consumption based on historical data.

Next, in Block 2, we determine how the electricity consumption is supplied by the different power generation technologies. In doing this, we assume that the supply from fossil-fuel power plants (except gas-fired power plants), nuclear, renewable sources of generation, and net imports is exogenously determined by both the existing installed capacity and the government policy commitments regarding the future development of this stock. Hence, the calculation of the annual supply of electricity generation by fossil-fuel based power plants (except gas-fired power plants) and that based on renewables technologies also relies on the above two elements: 1) data on the actual power generation per technology, and 2) information on policy objectives regarding the future development of these generation techniques (see Figure 2.2). These policy objectives refer to the future size of wind based generation capacity and the phasing out of coal-fired power plants, for instance.

Figure 2.1. Main building blocks of analytical framework

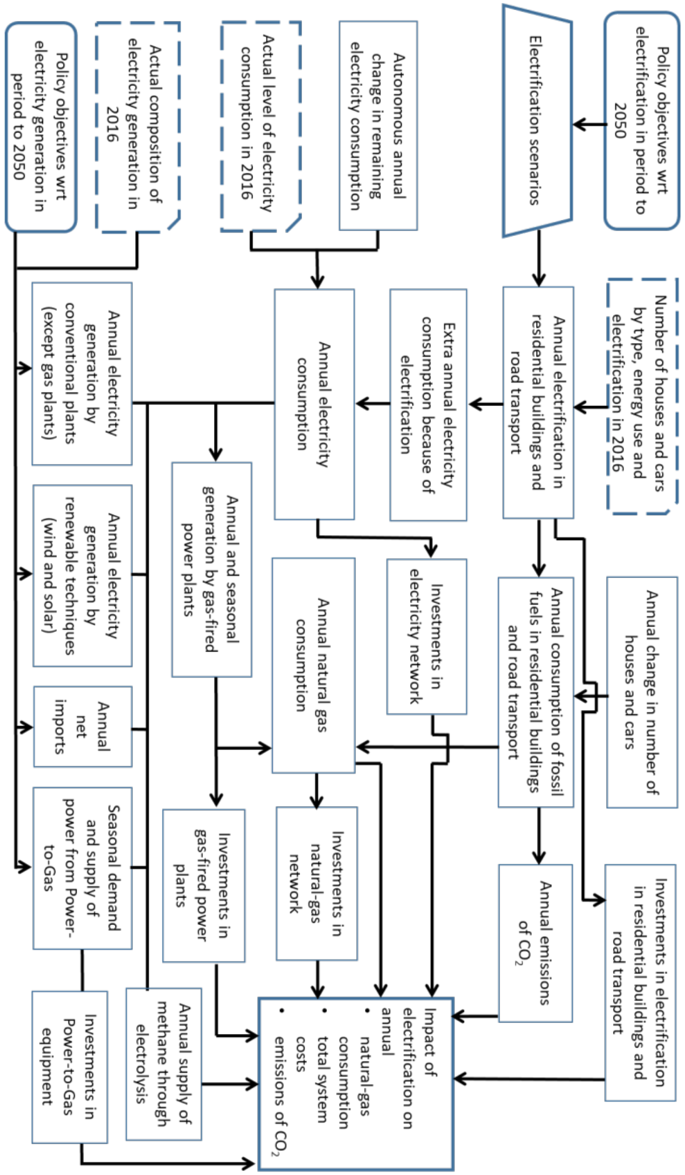


In Block 3, we derive the volume of electricity demand satisfied by gas-fired power plants. Gas-fired power plants are regarded as the source of last resort and therefore endogenously dispatched to meet the residual demand. Because the production of electricity by renewable sources is intermittent and may vary strongly from day to day, we explicitly take into account the need of flexible sources (see Figure 2.2). Power-to-gas plants are included to deal with seasonal storage, while gas-fired plants take control of all the remaining need of flexible supply. In this block, we also translate the necessary generation by gas-fired power plants into the investments needed to extend the generation capacity.

The results of the first three blocks are the input for the computation of the consequences of electrification for system infrastructure, emissions and costs. In Block 4, we determine the carbon emissions originating from the remaining use of fossil fuels in the housing, transport and electricity sector. The remaining annual consumption of fossil energy in the residential buildings and road transport is used to estimate the emissions of CO_2 (see Figure 2.2). Only these emissions are relevant, as the emissions caused by electricity generation fall within the European Emissions Trading Scheme (ETS).

Using the annual total consumption of electricity, we estimate by how much the electricity grid needs to expanded; we also check the extent to which the existing gas network is sufficient to deal with the change in the total demand for gas (Block 5). Finally, in Block 6, we calculate the impact on system costs by taking into account the annual cost of capital and depreciation related to investments for electrification, generation capacity, storage and networks.

Figure 2.2. Detailed analytical framework



2.2 Scenarios

Our study focuses on the effects of electrification of house heating and cooking and road transportation on electricity demand, gas demand, the implied carbon emissions and system costs. In order to do this, we have defined three scenarios for our projections towards 2050: the *Fossil Fuel (FF)* scenario, the *Hybrid* (HY) scenario, and the *Full Electrification* (FE) scenario. These scenarios mainly differ in the degree of electrification. The HY scenario also differs from the others in that district heating takes a much more prevalent role. The FF scenario is meant to capture the current prevalence of electrification (business-as-usual); the FE scenario is, by policy design (more on this below), meant to deliver very high levels of electrification, specifically, around 90% or more for passenger cars and houses. The HY scenario pictures a mixed situation where transport is halfway electrified and district heating is as widespread as electrification in the housing sector. The differences across scenarios are summarised in Table 2.1.

In the *FF scenario*, we assume, first, that 5% of the newly built dwellings constructed every year are electrified, while no houses belonging in the stock of existing houses are electrified. Each year, only 1000 extra houses are connected to district heating systems. Second, we assume that 5% of the newly bought passenger cars are electric; likewise, we assume that 35% of the new bicycles bought every year are electric. In this scenario, vans, trucks, buses, motorbikes and scooters remain not electrified at all.

In the *HY scenario*, we assume that 50% of the newly built houses and 100,000 of the stock of existing dwellings are electrified annually. In addition, 100,000 houses are annually connected to district heating systems. In the transportation sector, we assume that, every year, of the newly bought vehicles, 40% of the cars, 25% of vans, 5% of the trucks, 25%

of the buses, 50% of the motorbikes and scooters and 35% of the bicycles are electric. We assume that houses and vehicles which have been electrified remain electrified.

Table 2.1. Scenarios of electrification in terms of annual speed

	Scenarios		
	Fossil Fuel	Hybrid	Full Electrification
Degree of electrification per year			
Housing			
New	**5%**	**50%**	**100%**
Existing stock (x1000)	**0**	**100**	**200**
Number of extra houses connected to district heating (x 1000)	**1**	**100**	**1**
Transport			
Passenger cars	**5%**	**40%**	**80%**
Vans	**0%**	**25%**	**50%**
Trucks	**0%**	**5%**	**10%**
Buses	**0%**	**25%**	**50%**
Motorbikes and scooters	**0%**	**50%**	**80%**
Bicycles	**35%**	**35%**	**35%**

In FE *scenario*, we assume that all of the newly built houses plus 200,000 additional houses from the stock of existing ones are electrified yearly. Just as in the FF scenario, only 1000 additional houses are connected to district heating systems. Regarding transport, we assume that, every year, of the new vehicles, 80% of the cars, 50% of the vans, 10% of the trucks, 50% of buses, 80% of the motorbikes and scooters and 35% of the bicycles are electric.[4]

2.3 Related studies

In the recent past a number of relates studies have been published, including CPB (2015), Ecofys (2016) and ECN/PBL/CBS/RvO (2017). Here we only briefly summarize the first study, focussing on the differences with our method of research.

In their Climate and Energy chapter of CBP(2015), the Netherlands Bureau for Economic Policy Analysis develops scenarios based on environmental targets. In particular, they focus on the reduction in GHG emissions by 2030 and 2050. They distinguish between a Low Scenario, a High Scenario and a Two-Degrees Scenario. In the Low Scenario they assume that GHG emissions will be 30% lower compared to 1990 levels by 2030, and 45% lower by 2050. In the High Scenario they assume that GHG emissions will be 40% lower compared to 1990 levels by 2030, and 65% lower by 2050. In the Two-Degrees Scenario they assume that GHG emissions will be 45% lower compared to 1990 levels by 2030, and 80% lower by 2050.

The WLO 2015 approach is different from our approach in at least three regards. The first difference is that their scenarios have many more moving parts, while we have chosen to make the scenarios only different with respect to the extent of electrification. For example, their High scenario combines, among other things, a relatively high population growth with a high economic growth and a significant city growth. Their

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[4] According to the scenarios developed by the IEA, by 2050 the share of electric vehicles and hybrid electric vehicles will be around 60%. In our model, under the FF scenario the share of electric passenger cars by 2050 is only 6%, but increases to 44% under HY and to 88% under FE.

Low scenario, by contrast, has a moderate population growth combined with a modest economic growth and a limited city growth. In our simulations, by contrast, we keep demographic developments and economic growth constant across scenarios. Hence, our study is closer to the economics tradition of comparative statics analysis, where the focus is on the impact of one parameter *ceteris paribus*.

Another important difference is the scope of the study. While we focus on electrification of the residential housing and road transportation and basically keep everything else constant, the study of the CPB is much more comprehensive and general equilibrium oriented. They basically consider all the sectors together and rather than focusing on electrification they have emissions targets. Interestingly, our conclusion that the energy supply will continue to rely heavily on fossil energy for a long time is also borne by their study.

A third distinction is that while we depart from policy targets regarding electricity generation and electrification, the WLO study departs from emission targets. While our study asks to what extent the policy objectives result in lower carbon emissions, and derives the costs of the implied emission reduction, the WLO report fixes environmental targets in terms of emissions reductions compared to 1990 levels.

3. Electrification in residential buildings

3.1 Policy objectives

The EU launched a regulation of energy use of building (the EPDB) in 2002 to stimulate owners of houses to invest in energy saving measures. It was believed that labelling buildings in accordance to energy performance criteria (EPCs) would create a market for energy efficient buildings; by implication, a higher market value for energy efficient houses would incentivise house owners to improve their houses. The Dutch government has implemented the EPDB via the *Besluit en de Regeling Energie Prestaties Gebouwen* (*rvo.nl*). EPCs were introduced progressively as early as 2007, and by January 2016 around 3 million dwellings were certificated. Since January 1 2018, the EPC is obligatory for all house rental and sale house transactions. Some studies using data from the Netherlands, confirm the rationale for introducing the energy labels: energy efficient houses sold in 2008 and 2009 commanded a price premium of about 3.6% (Brounen and Kok, 2010).

Further, during the last few years, the Dutch government has made available about 60 million euro of direct subsidies to incentivise house owners to insulate their homes and switch from natural gas boilers to heat pumps (*rvo.nl*). Furthermore, the current cabinet, in its governmental agreement (*Regeerakkoord 2017-2021*), has promised to push this agenda harder: it has agreed that, by the end of its mandate, it will not be allowed for new houses and buildings to be connected to the gas network any more. Further, the ambition is that about 50,000 fully electric new houses will be built every year from now to 2021, and that in between 30,000 and 50,000 existing houses will be disconnected from gas, renovated and fully electrified in the same period. It is expected that soon after 2021, this number will reach 200,000 houses on an annual basis, which will pave the path to have a fully electrified stock of houses by 2050 (*Regeerakkoord 2017-2021*). These ambitions have inspired our full electrification scenario (Table 1).

As full electrification of houses may not be possible for all houses, for technical or economic reasons, the Dutch government also considers the further increase of district heating systems (EZK, 2018). Currently, 5.5% of Dutch houses is connected to a district heating system, but according to Ecofys (2016) this can be increased to 30% in 2050. This potential of district heating systems has been implemented in the Hybrid scenario.

3.2 Data and assumptions

Following the analytical framework described in Section 2, we first gather data on the number of residential dwellings in the Netherlands, as well as the annual average consumption of natural gas for cooking, water heating and space heating. Based on historical data, we also determine the rate at which new houses are built in the Netherlands and, in line with current government policy, assume that a fraction of these new houses are fully electric. The electricity necessary to cook in and heat newly built houses and in the existing dwellings that are renovated on an annual basis, constitute the increase in electricity demand due to electrification in the housing sector.

Table 3.1. Data on residential buildings, NL, 2016

Variable	Value
Number of houses (x million)	7,6
Number of houses electrified (x million)	0,02
Average size of houses in m2	119
Average gas consumption per house (m3)*	1400
share of gas used for cooking**	5%
share of gas used for hot water**	15%
Share of houses connected to district heating system	5.5%
CO_2 emissions by households in 1990 (Mton)	21

*Note: * source: RVO, Monitor Energiebesparing gebouwde omgeving, november 2017; **the source is milieucentraal.nl; the source for other data is CBS Statline.*

Table 3.1 describes the data we use for the residential housing sector. In 2016, there were 7,6 million dwellings occupied in the Netherlands; only about 20,000 of them were fully electrified. The average size of a typical dwelling is 119 m^2. The average household consumed 1400 m^3 of natural gas per year. About 80% is consumed for the purpose of heating space, 15% for warming water and the remaining 5% for cooking. Emissions attributed to houses in 1990 amounted to 21 Mton.

Table 3.2 describes the key assumptions for our projections to 2050. Based on the policy targets mentioned above, we assume that about 50,000 new houses will be built every year. This figure is in line with the average number of the past 10 years. Some of the new houses replace old houses. We assume that the net aggregate number of occupied houses increases annually by 0,5%. This figure should be regarded as somewhat conservative, because the data from CBS reveals that the number of occupied houses has increased annually by 0.9% on average in recent years.[5]

In line with the energy-efficiency policy in the Netherlands, the energy efficiency of houses has increased over time, as the data on natural gas consumption shows. For example, while the average house did consume 2,500 m^3 in 1980, in 2016 the average consumption was 1,400 m^3. Of course, differences in temperature can partly explain this decrease in consumption but factors such as better insulation, the use of high-performance gas boilers and the adoption of smart devices such as thermostats are also relevant. In this connection, for our simulations we assume that the average natural gas consumption of a new house is only 1,000 m^3 and we take the electricity equivalent to this consumption as a measure of demand for electricity of an electrified dwelling. In addition, we factor an annual increase in the efficiency of houses of 1%.

As mentioned above, electrification of houses means that gas boilers and cooking stoves are replaced by their electric equivalents. In the Netherlands, most gas boilers are replaced by air-source heat pumps. The coefficient of performance (CoP) of these devices is about 3 for heating space and 1 for heating water.[6] We assume that this CoP increases over time at the annual rate of 1%.

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[5] Historically, from 2005 to 2015, the number of houses has increased annually by approximately 0.9%. Note that this period includes the recent crisis, which signified an important decrease in the construction activity. CPB/PBL (2016) assumes that the number of houses in the Netherlands remains fairly constant in their Low scenario, while in their High scenario it increases by about 0.75% per year.

[6] See e.g. https://en.wikipedia.org/wiki/Heat_pump. A heat pump CoP of 3 means that the electricity consumption is 1/3 of the heat provided.

Table 3.2. Assumptions for simulation to 2050

Variable	Value
Annual increase in number of houses	0,5%
Annual number of new houses (x 1000)	50
Energy use for heating a new house (in m^3 gas)	1000
Annual increase in efficiency houses	1%
Coefficient of performance (COP) of heat pumps	
Space heating	3
Warm water	1
Annual increase in efficiency of heat pumps	1%

3.3 Results

In a given year, the demand for electricity stemming from the housing sector is computed by adding the electric power needed to heat space and water of the newly bought fully electrified houses as well as the existing renovated ones, as well as the power necessary to cook with electric stoves in those houses. In Figure 3.1, we show the outcome of the simulation model in terms of the number of electrified houses. As it can be appreciated, in the FE scenario the percentage of electrified houses already reaches 45% by 2030, while by 2050 the stock of houses is almost completely electrified (95%). The FF scenario shows very little electrification (1.2% by 2050), while the HY scenario is in between (48% by 2050).

Figure 3.2 shows the total number of houses in the Netherlands that use gas for heating, that are electrified as well houses that are connected to a district heating system, for each scenario from 2016 up to 2050. In the FF scenario the number of houses using gas increases from the current 7 million to about 8,5 million in 2050. In the HY scenario the number of houses connected to a district heating system increases to almost 4 million in 2050. In the FE scenario, almost all houses (8.4 million) are electrified in 2050.

Figure 3.3 depicts the predicted amount of electricity consumed by the housing sector in 2050. In the FE scenario, the total amount of electricity consumed by the housing sector would go up by 36.4 TWh, which is about 30% more than current total; 22.2 TWh for space heating, 11 TWh for warm water and 3.2 TWh for cooking. By 2030 (not shown in Figure), the total electricity consumption in this scenario would be 26.3 TWh, about 22% of current total. In the HY scenario, these increases are above half of what they are in the FE scenario. In the FF scenario, they are negligible.

Figure 3.1. Percentage of residential buildings electrified, per scenario, 2016-2050

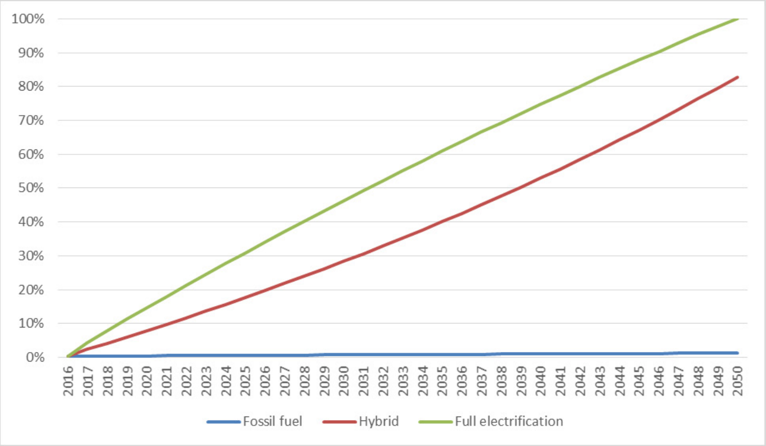
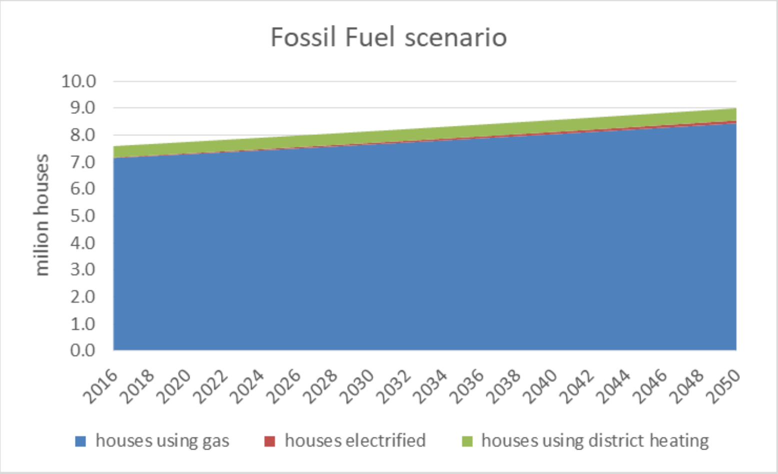
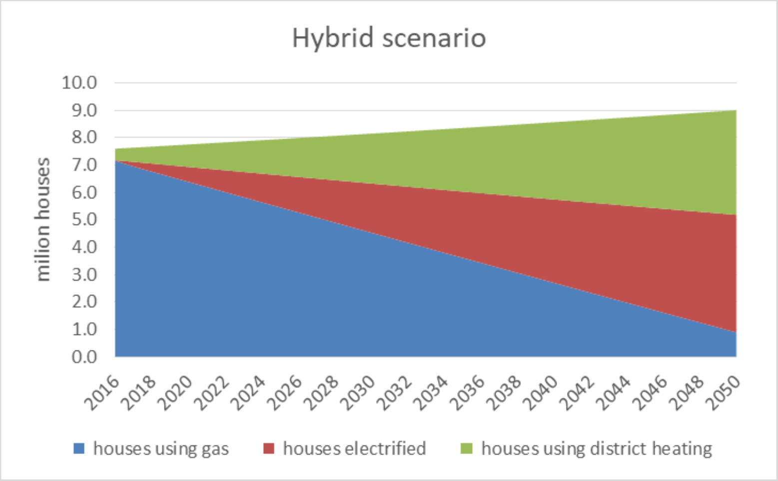


Figure 3.2. Annual number of houses per type of heating, per scenario, 2016-2050





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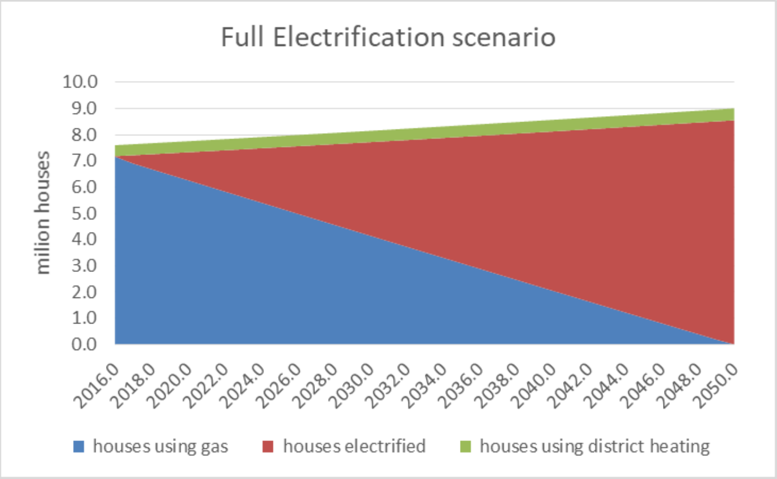
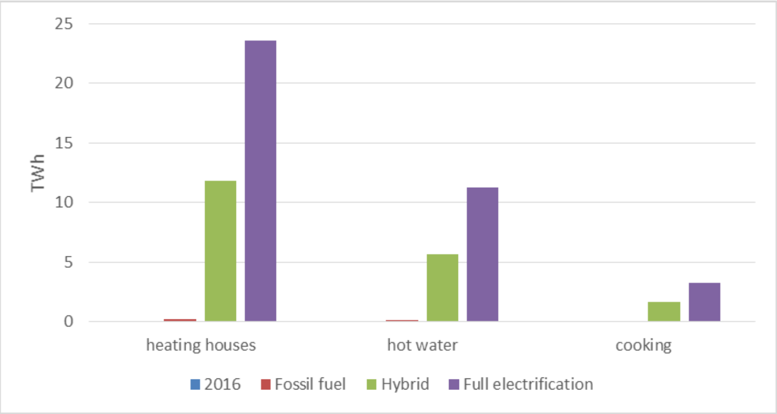


Figure 3.3. Electricity use by residential buildings, per type of use, in 2016 and per scenario in 2050



4. Electrification of road transportation

4.1 Policy objectives

In 2016, a consortium of public (including the Dutch government) and private institutions signed the 2016-2020 *Electric Transport Green Deal*. The 'Deal' is an agreement to stimulate electric mobility. The ambition is that by 2020 about 10% of all newly sold passenger cars will have an electric powertrain and a plug. Moreover, by 2020 the expectation is that private individuals will own about 75,000 electric automobiles, of which 50,000 second-hand and 25,000 new. Finally, by 2025 the ambition is that 50% of the newly sold cars have an electric powertrain, and that at least 30% of them are fully electric.[7] The policy also has ambitions concerning public buses: by 2025 all new buses should be electric.

To realise these goals, in 2016 the Dutch government made funding available to actively promote (via co-payments) the installation of public charging stations, as well as the acquisition of electric vehicles (via deductions of special vehicle taxes and road taxes). The subsidy schemes, after reform, continued into 2017 but the expectation is that the government will withdraw the subsidies once electrification in the transport sector gets sufficient momentum.

For freight transport, solutions based on combining electricity, sustainable biofuels and renewable gas are seen as more realistic. In the Energy Agreement, concluded between the Dutch government and several societal stakeholders, attention is also paid to efficiency measures and a progressive switch to sustainable fuels like bio-kerosene for aviation and biogas for the shipping sector, with a more important use of LNG in the transition period. In the train sector, though most of the trains are electric

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[7] Source: *www.rvo.nl*, website of the Netherlands Enterprise Agency.

in the Netherlands, the government has committed to switch the remaining from diesel to LNG or biogas powered trains.

4.2 Data and assumptions

The first step in the analysis of electrification of road transport is to collect data on the number of passenger cars, vans, buses, trucks, motorbikes, scooters and bicycles, as well as the annual average number of kilometres driven per year.[8] Based on data from the recent past, we determine the number of new vehicles sold every year and we assume that a certain fraction of these new vehicles are fully electric. The electricity necessary to power these vehicles thus represents the increase in electricity demand due to electrification in the transportation sector.

Table 4.1 describes the data we use for the transportation sector.[9] In 2016, there were 8.9 million passenger cars registered in the Netherlands; in addition, there were 835,000 vans, 152,000 trucks, 11,000 buses and 1.15 million motorbikes and scooters and 22.7 million bicycles. As reported by the *Association of Car Dealers and Garages* (*bovag.nl*), by 2016 the number of electric vehicles was relatively low.

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[8] The number of passenger cars in the Netherlands has increased from 2005 to 2016 by 1,30% on average, reaching 8.9 million in 2016, while the average number of kilometers has remained fairly constant (Statistics Netherlands). Regarding vans, the number has decreased by approximately 1% from 2005 to 2013, while the average number of kilometers has remained relatively stable. With respect to trucks, the number has remained fairly constant from 2009 to 2012, while the number of km per truck has decreased slightly. In connection with buses, the number has remained relatively constant while the average number of km has increased by 1.13% annually from 2005 to 2012.

[9] The source for most of our data is *Statistics Netherlands* (CBS). Their data are freely accessible at their website http://statline.cbs.nl/Statweb/. In what follows we will only mention the source of data other than CBS data.

Table 4.1. Data on transport sector, NL, 2016

Variable	Value
Number of (x million)	
passenger cars	8,9
vans	0,84
trucks	0,15
buses	0,01
motorbikes and scooters	1,15
bicycles	22,7
Of which electric (x 1000)	
passenger cars	60
vans	0
trucks	0
buses	0,1
motorbikes and scooters	0
bicycles	1500
Average distance per year (km)	
passenger cars	13022
vans	18896
trucks	59228
buses	61461
motorbikes and scooters	2000
bicycles	1000

Source: CBS Statline; BOVAG/RAI

Because some cars are fully electric (FEV) and some are just partially electric (plug-in hybrid cars, PHEV), we compute the number of electric cars by summing the number of FEV passenger cars and half of the PHEV cars; this gives us 60,000 cars. The number of electric vans and trucks is set to zero. The number of electric buses is set to 100. For motorbikes and scooters we do not have precise data, so we also set the corresponding numbers of electric units to zero, while the number of electric bicycles in 2016 was 1.5 million. The table also gives the yearly average distance covered by the distinct vehicles. On average, cars drive around 13,000 km a year, while vans and trucks drive about 19,000 and 60,000.

Table 4.2 describes the key assumptions on the transport sector for our simulations to 2050. Based on data from recent years, we take it as given that 400,000 new cars will be sold every year; for vans this figure is 60,000, for trucks 10,000, and for buses 7,500. For motorbikes and bicycles 75,000 and 1 million, respectively. Because some cars are taken out of circulation (mainly because of age, export and accidents), we assume that the net number of cars increases annually by 1%. We note that this estimate is somewhat lower than the 1.3% annual increase in recent years (see footnote 10). Regarding the stocks of vans, trucks and buses, we assume that they remain constant. The number of km driven by the vehicles is also assumed to remain constant.

To derive the additional electricity demand stemming from electrification of transport, we need estimates of the performance of electric engines. For this calculation, we use data on the performance of electric cars published by the *US Department of Energy* (*fueleconomy.gov*). The average performance of electric passenger cars in 2017 was 20kWh/100km. For the case of vans, trucks and buses we have less reliable data. Using the consumption of electricity for cars, we impute vans, trucks and buses consumption levels that are in proportion to what they consume of fossil fuels. For the case of vans, we factor an electricity consumption of 35 kWh/100km, for trucks 70 kWh/100km, for buses 100kWh/100km, for motorbikes and scooters 5 kWh/100km and for bicycles 1 kWh/100km. In this computation, we also take into account the electricity losses that occur while charging batteries. These are about 16% (*US Department of Energy*).

Table 4.2. Assumptions for simulation to 2050

Variable	Value
Passenger cars	
Annual number of new cars (x 1000)	400
Performance electric (kWh/100km)	20
Vans	
Annual number of new vans (x 1000)	60
Performance electric (kWh/100km)	35
Trucks	
Annual number of new trucks (x 1000)	10
Performance electric (kWh/100km)	70
Buses	
Annual number of new buses (x 1000)	0,75
Performance electric (kWh/100km)	100
Motorbikes and scooters	
Annual number of new M&S (x 1000)	75
Performance electric (kWh/100km)	5
Bicycles	
Annual number of new bicycles (x 1000)	1000
Performance electric (kWh/100km)	1
All vehicles	
Annual increase in number	1%
Annual increase in efficiency	1%
Annual increase in average distance per vehicle	0%
Battery charging units	
Annual improvement in charging efficiency	0,5%

Regarding energy efficiency in the transport sector, because cars are becoming steadily more fuel efficient, we assume their fuel consumption decreases by 1% per year. Likewise, we assume that there will be an annual improvement in battery charging efficiency of 0.5%.

4.3 Results

Figure 4.1 shows the outcome of our simulation model in regards to the percentage of passenger cars electrified by 2050. In the FE scenario, 88% of all cars are electric, while for vans this share is 87%, for trucks 16%, for buses 84%, for motorbikes 82% and for bicycles 42%. In the HY scenario, these shares are about half of those in the FE scenario. By 2030 (not shown in Figure), the percentages of electrified vehicles are as follows: 44% of passenger cars, 44% of vans, 8% of trucks, 43% of buses, 41% of motorbikes and scooters, and 25% of bicycles. Figure 3 also shows that the percentages of the various vehicles electrified by 2050 in the FF scenario and very low.

Figure 4.2 shows the implied electricity demand from the transport sector. In the FE scenario, the total electricity necessary to power the electric vehicles by 2050 is 39,4 TWh. This new electricity demand by 2050, which represents about 33% of current total demand in the Netherlands, is divided as follows: 32 TWh for cars, 5,4 TWh for vans, 1,1 TWh for trucks, 0,6 TWh for buses, 0,16 TWh for motorbikes, and 0,11 TWh for bicycles. By 2030 (not shown in Figure), under the same scenario the electricity necessary would be 17,3 TWh, about 14% of the current total demand. In the HY scenario, the increase in the electricity demand by 2050 is about half. In the FF scenario, except for cars, it is negligible.

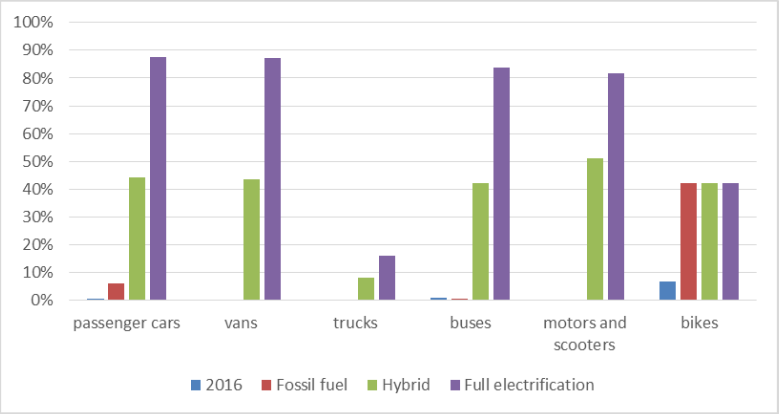
Figure 4.1. Electrification in road transport (in %), by type of vehicle in 2016 and per scenario in 2050

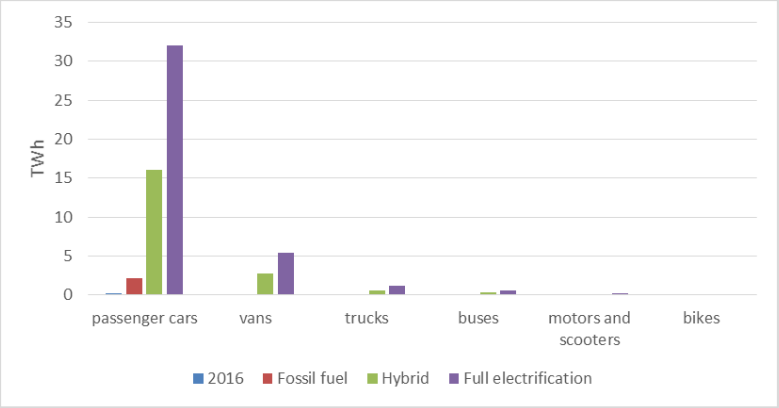
Figure 4.2. Electricity use in transport by vehicle type, in 2016 and per scenario in 2050

5. Total electricity consumption

5.1 Autonomous change in electricity consumption

Electricity consumption also changes over time independently from the process of electrification in the transport and housing sectors.[10] Data from the CBS reveals that the annual change in the aggregate level of electricity consumption is strongly related to the changes in the macroeconomic business cycle (Figure 5.1). Over the past 15 years, the average annual change in the level of electricity consumption was 0.6%. As we observe a slightly declining trend in this annual change, we assume that the autonomous annual change in the future electricity consumption will be 0,5% (Table 5.1). The starting point for this study is the actual level of total electricity consumption in the Netherlands in 2016, which is 120 TWh (see Table 6.1).

Table 5.1: Assumption on autonomous electricity consumption

Variable	Value
Autonomous annual change in electricity demand (%)	0,5%

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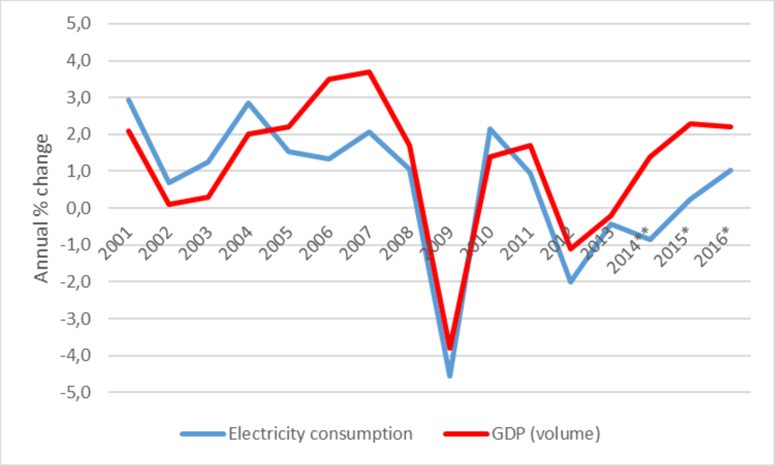
[10] Note, however, that households are likely to further increase the use of electrical appliances in the future, think for example of cleaning, cooking and gardening robots.

Figure 5.1. Annual changes in electricity consumption and volume of GDP in the Netherlands, 2001 – 2016

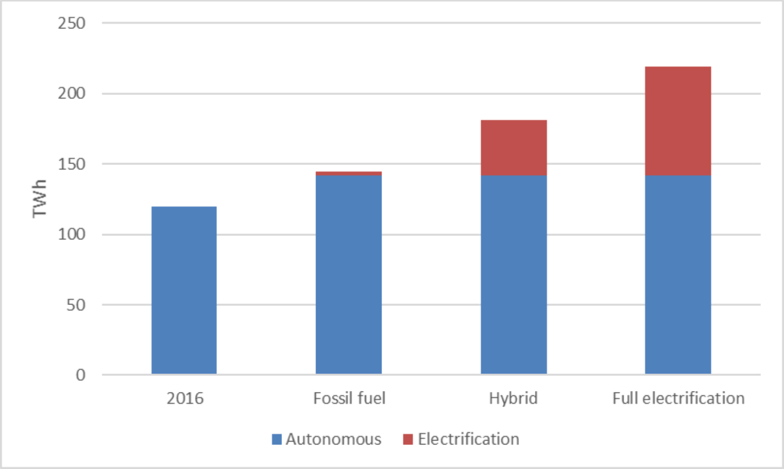


Source: CBS

5.2 Results

The total change in electricity consumption is equal to the change arising from the autonomous increase in the level of electricity consumption and the change caused by electrification. In the FF scenario the electricity consumption increases from the current 120 TWh to almost 150 TWh by 2050. The 30 TWh increase compared to 2016 stems almost completely from the increase in autonomous demand. In the HY scenario, electrification of road transport and residential buildings create an additional demand for electricity of about 40 TWh in 2050, while in the FE scenario, this extra demand amounts to 75 TWh. In the latter scenario, the total electricity demand in the Netherlands is projected to be about 100 TWh higher than the current level of electricity demand (Figure 5.2).

Figure 5.2. Aggregated Dutch electricity consumption by origin, in 2016 and per scenario in 2050



6. Generation of electricity

6.1 Policy Objectives

After determining the increase in electricity demand jointly stemming from the autonomous increase and the electrification of the transport and housing sectors, we move to examine the composition of the supply of electricity necessary to meet demand. The first step is to analyse the recent policy targets of the Dutch government, which are gathered in the so-called *Energy Agreement* ("*Energieakkoord voor duurzame groei*").

First, the government has committed to cease all coal-based power generation by 2030. Second, the authorities have agreed to discontinue the production of electricity based on nuclear and other fossil fuels by 2025.[11] Third, there are ongoing expansions in the export/import capacity with neighbouring countries such as Belgium, Denmark and Germany. The government also wants to increase the connections with Great Britain and Norway (ECN, 2017). Last by not least, there are ambitious plans regarding the deployment of renewable electricity production. Currently, the on- and off-shore wind capacity is about 3,400 MW (2015). The Energy Agenda of the Dutch government includes plans to increase the installed on-shore capacity to 6000 MW by 2020. There are also plans to build new off-shore wind parks. The plans aim at an installed capacity of 4,450 MW by 2023 (3450 MW over and above the current 1,000 MW). In total, on- and off-shore wind capacity is expected to increase to 10,450 MW by 2023. By 2030, the policy target is an installed wind capacity of 13,000 MW. Solar power represents only about 1.6% of electricity consumption. The Dutch government has, however, also ambitious plans here. It is expected

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[11] Nuclear power is not very important in the Netherlands and currently represents only about 3% of the electricity consumption. The discontinuation of nuclear power has been a matter of debate for already a good number of years.

that solar, wind and biomass together will represent about half of the electricity production by 2025, and about two thirds by 2030.

6.2 Data and assumptions

In the Netherlands, the total domestic generation was 115 TWh in 2016, while 5 TWh was the net import (Table 6.1). Natural gas has traditionally had a share of about 50-60% in generation, but has decreased in recent years (to about 40% in 2015) in favour of coal, which currently represents approximately 33% of electricity production.

Table 6.1: Data on electricity supply in the Netherlands, 2016

Variable	Value (TWh)
gas-fired plants	52
coal-fired plants	37
other fossil-fuel plants	4
nuclear	4
hydro	0
wind	8
solar	2
biomass	5
other	3
net import	5
total load	120

Source: CBS

For the development of the future Dutch generation portfolio, we make a number of assumptions (Table 6.2) that are based on the policy objectives discussed above. The commitment to gradually face out all coal-fired power plants by 2030 translates into an annual reduction in the electricity production of these plants of 7%. Other fossil plants (except gas-fired plants) have to gradually diminish electricity production and shut down by 2025, which translates into an annual reduction of 11%. In regard to the (single) nuclear power plant in the Netherlands, whose production has to be discontinued by 2025, we make the same assumption of an annual decrease of 11%.

As mentioned before, for wind and solar energy, the government has formulated targets in terms of installed capacity for the year 2030. We have translated these targets into annual increases in production by wind and solar in terms of TWh (Table 6.2).[12] For the period after 2030, because no further targets regarding installed capacity have been formulated by the government, we have set assumptions on annual investments in wind and solar in MW. For biomass we assume that there will be a 2% gradual increase in production. As the cross-border capacity will be further extended in the future, we assume that net imports may increase by 2%.

The sharp increase in wind and solar production capacity has the disadvantage that electricity generation will gradually become more volatile. As a consequence, the short-term dynamics in the electricity sector will change. In the next section we will pay attention to this issue and the implications it has for the security and reliability of supply; in particular, we will derive the investments in gas-fired power plants that are needed to meet demand under unfavourable weather conditions for the production of wind and solar energy.

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[12] Using a capacity factor for wind turbines of 30% and for solar panels of 10%. These capacity factors are based on actual data on renewable production and installed capacity in the Netherlands (see the monthly reports of *en-tran-ce.org*).

Table 6.2: Assumptions on annual change in electricity supply to 2050

Variable	Assumption	Background		
coal-fired plants	-7%	phasing out in	2030	
other fossil fuel plants	-11%	phasing out in	2025	
nuclear plants	-11%	phasing out in	2025	
hydro plants	0%	remains constant		
wind (annual increase in TWh)	1,9	policy target in 2030 is	13000	MW
wind in period after policy target (increase in TWh)	1,6	annual investments after 2030	600	MW
solar (annual increase in TWh)	0,6	policy target in 2030 is	12000	MW
solar in period after policy target (annual increase in TWh)	0,5	annual investments after 2030	600	MW
biomass	2%	gradual increase based on past		
other	1%	gradual increase based on past		
net import	2%	increase in cross-border capacity		

6.3 Results

The future composition of the supply of electricity is mainly driven by the policy objectives to close the conventional power plants, except the gas-fired plants. This holds for all scenarios (see Figure 6.1). In 2030, the major remaining sources of electricity are natural gas, renewables and imports. In the longer term, the policies to stimulate wind and solar have a major impact on the electricity supply. In the FF scenario, the share of renewables increases to almost 70% in 2050. In the HY scenario, this share reaches 50%, while in the FE scenario, it stays below 40% due to the relatively high level of electricity consumption (216 TWh). In the FE scenario, gas-fired plants are responsible for about 50% of total supply by 2050.

Figure 6.1: Supply of electricity, per scenario, 2016-2050

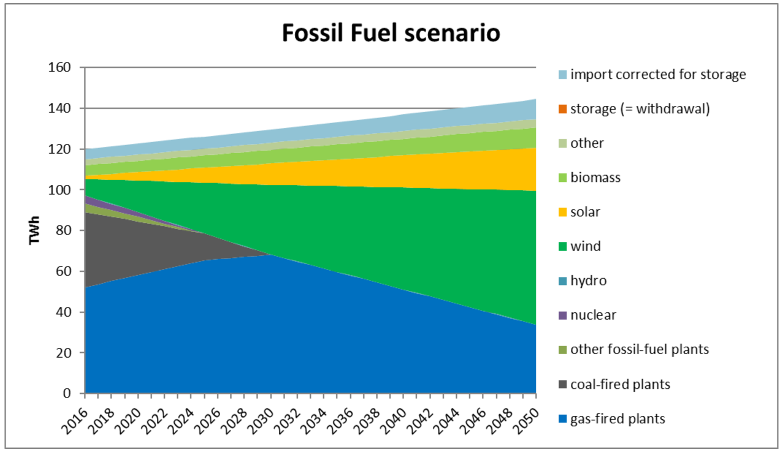
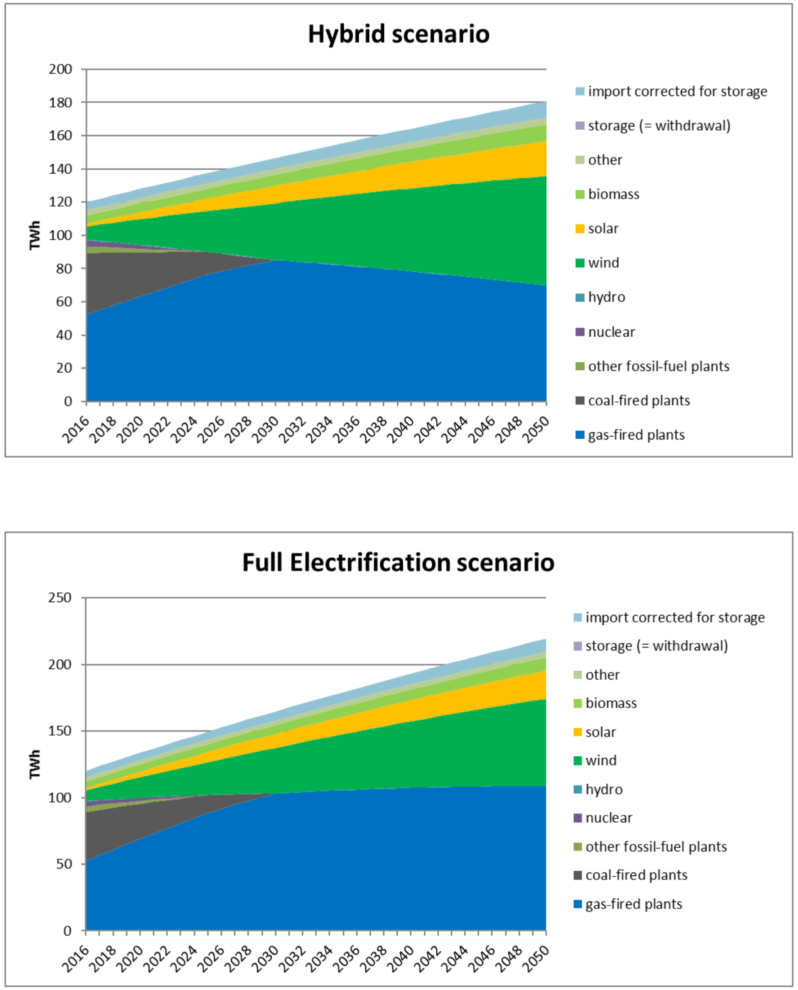


Figure 6.1. (continued)



7. Demand and supply of flexibility

7.1 Method, data and assumptions

In the previous sections, we have analysed the aggregate annual demand and supply of electricity without paying much attention to a key characteristic of electricity systems, namely, that the networks need to be in balance every second. The total supply needs to be permanently equal to the total load in order to keep the system working. Because generation by renewable sources is intimately linked to the weather conditions, the supply of electricity will become increasingly volatile as the share of renewables in power generation increases over time. The impact of the weather on the power supply from renewable sources is not straightforward because the amount of wind and solar generation depends on different aspects of the weather. Sometimes a lack of wind may be compensated by a high intensity of daylight, or the other way around. On other occasions, wind speed and sunlight may have the same positive or negative effect on total renewable generation: on windy and sunny days production is relatively high, while on windless cloudy days there may hardly be any production by renewable sources.

Besides the supply of renewable power, the demand for power is also volatile. First, the demand is closely linked to the weather. For instance, it is relatively high during the winter because the days are shorter and more electricity is needed for lighting purposes. Moreover, as the electrification of houses progresses towards 2050, the demand for electricity for heating purposes becomes more and more related to the outside temperature. Second, demand also fluctuates over the week: during weekends the demand for electricity is generally lower than during weekdays.

In order to assess the influence of these exogenous factors on both the generation by renewables and the demand for electricity to later on take them into account when computing system needs to secure a reliable supply, we proceed by first defining extreme environmental circumstances. These circumstances refer to the joint occurrence of specific wind speeds, intensities of sunlight, outside temperature (measured by heating degree days, HDD) and structural day patterns in demand levels. We define these extreme circumstances by first ranking each (historical) day for each dimension from the perspective of electricity use and supply. For wind and sunshine, we rank the days from lowest to highest level; for HDD and the structural volatility in demand levels, we rank from highest to lowest level. Using the position of each day on each of these dimensions, we are able to classify each day on a set of aggregate weather classes. The weather of a specific day is classified into "Worse" if the average wind speed and sunshine are low, while HDD and demand levels are high. Such a day is likely to be a windless, cloudy and cold day. On such a "Worse" day, the electricity system needs a lot of additional supply from flexible sources to meet all demand. By contrast, on a windy and sunny day with relatively low levels of demand for heating (which we refer to "Best" days), the system may need flexibility to take care of potential oversupply.

In order to incorporate this volatility into our model, we define two extreme weather classes based on the historical distribution of actual weather circumstances from 2006 to 2014 (Figure 7.1). In the 5% Worse days, the average wind energy was 17% of the annual average, while sunshine was at a 24% level, average temperature was low, resulting in a HDD of 205% of the annual average, while demand was 18% higher than average. For the 5% Best days, the respective percentages are 189%, 193%, 26% and 85%.[13]

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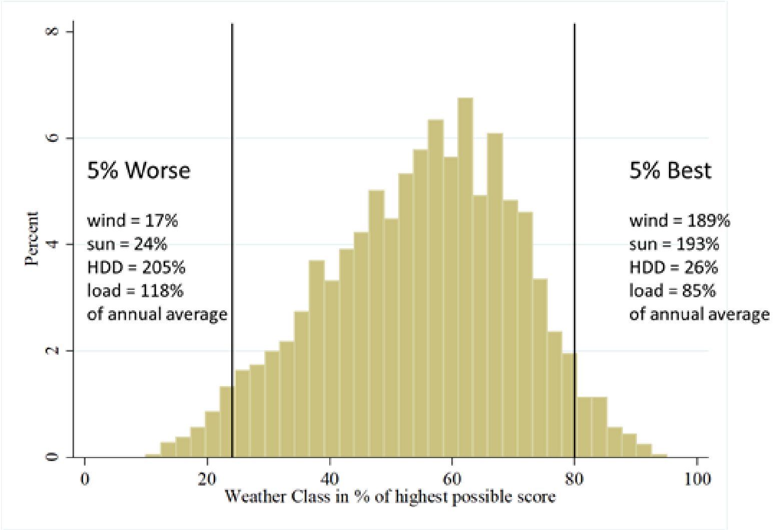
[13] We express these circumstances in terms of the average day, as our model is based on annual data. The average daily value is simply defined as 1/365 of the annual value. For instance, the annual value of wind generation in the Netherlands in 2016 was 8 TWh (see Table 6.1). Hence, on an average day the generation was 0.02 TWh. On the 5% Worse days, the average wind generation was 0.004 TWh, while on the 5% Best days, the average wind generation was 0.04 TWh.

Figure 7.1: Definition of 5% Worse and 5% Best days for electricity system (based on actual data on Dutch market over 2006-2014)



The flexible sources of supply to deal with the exogenous fluctuations in renewable supply and demand are, in order, imports, seasonal storage and gas-fired power plants. If the domestic generation exceeds the domestic demand, which is more likely to happen in a Best day, the first option considered is to reduce imports. The economic rationale behind this is that in case of an oversupply, domestic prices will fall, which will trigger traders to reduce imports or increase exports. The next option considered is to make use of seasonal storage, which can be provided after the appropriate deployment of Power-to-Gas infrastructure. Although this technique is still quite expensive, it will become more economical over time. The flexibility offered by this source is best understood as seasonal: oversupply during Best days can be stored and used later on Worse days. The flexibility source of last resort is generation by gas-fired plants.

We have included this in our model as follows. First, we simulate demand and supply of electricity in a Best day. If there is an excess supply, net import is reduced first. If there is still an oversupply, this electricity is converted into hydrogen and stored (see Table 7.2 for efficiency). Next, we simulate demand and supply of electricity in a Worse day. If all conventional sources, excluding gas plants, are insufficient to meet demand, hydrogen from storages is used to generate electricity. If this additional supply is still insufficient to satisfy demand, gas-fired power plants are dispatched as supplier as last resort.

Table 7.2. Assumptions on efficiency of Power-to-Gas, seasonal storage

Variable	Value (%)
Efficiency electrolyser	75%
Efficiency power plants	42%
Resulting efficiency Power-to-Gas	31%

7.3 Results

In the FF scenario, on a Best day, all domestic demand can be met by renewable sources of supply as of 2031 (Figure 7.2) and gas plants are not dispatched on such good weather circumstances. In the first years thereafter, reducing net imports is sufficient to supply flexibility but as from 2035 electricity is overproduced and has to be stored. The capacity needed to store electricity increases over time, reaching a capacity of about 6 GW in 2050 (Figure 7.3).

In the FE scenario, even on a Best day, there is hardly any oversupply because the demand for electricity is so much higher due to electrification. In this scenario, and on such good weather circumstances, gas-fired plants will no longer be dispatched to produce electricity as from 2042. Reduction of imports is sufficient to balance the electricity system. Hence, there is no need for seasonal storage.

Figure 7.2: Supply of electricity on a 5% Best day, FF and FE scenario

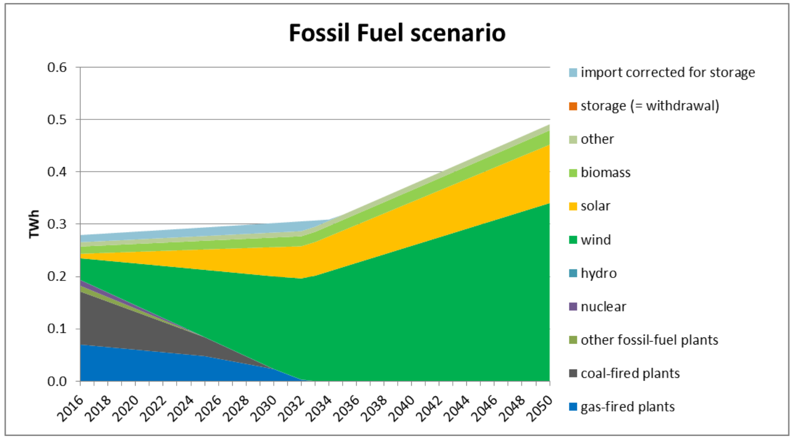


Figure 7.2. (continued)

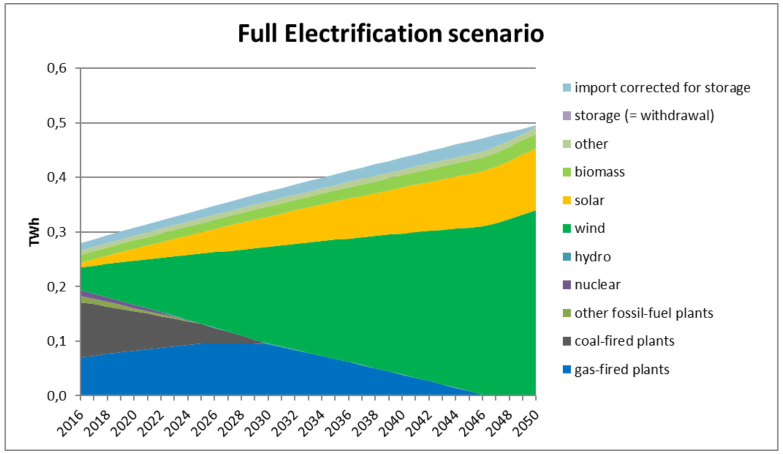
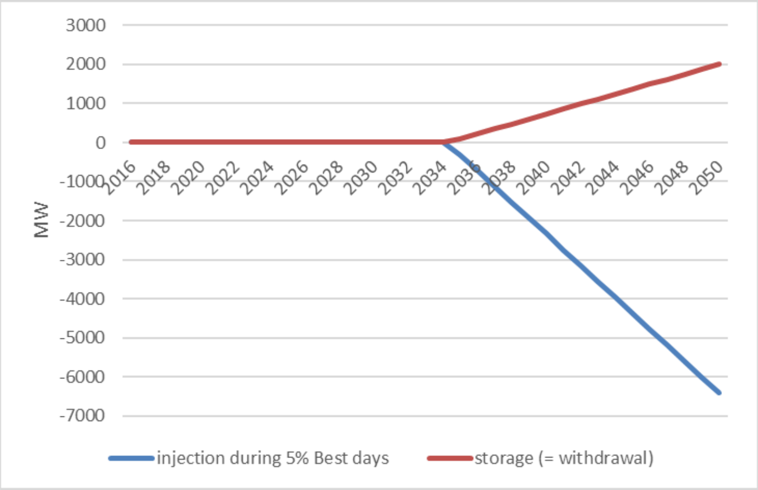


Figure 7.3. Use of seasonal storage (Power-to-Gas), in terms of maximum capacity needed, FF scenario



We now consider the Worse days. The supply of electricity under such bad weather circumstances can be seen in Figure 7.4. In the FF scenario, because of the storage of hydrogen as from 2035 during Best days, Power-to-Gas can be used as source of flexibility during Worse days. Because this is not sufficient, the major source of flexibility, however, remains gas-fired generation. In the FE scenario, extra supply during the Worse days can only delivered by gas-fired plants. It appears that on such relatively cold days with hardly any wind and sunshine almost all demand is met by gas-fired plants.

Figure 7.4. Supply of electricity on a 5% Worse day, FF and FE scenario

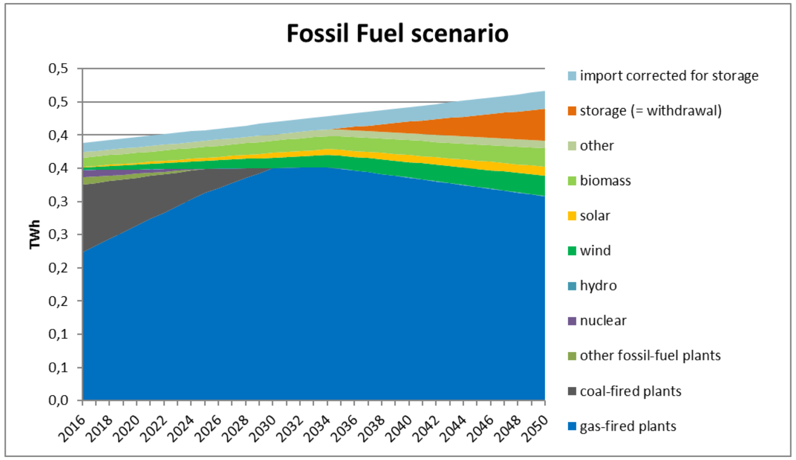
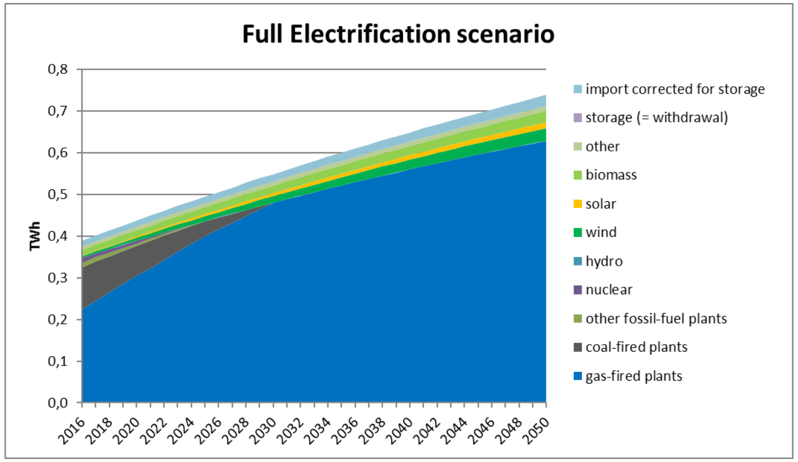


Figure 7.4. (continued)



The capacity of gas-fired plants needed to keep the electricity system in balance is depicted in Figure 7.5.[14] In the FF scenario, the required capacity increases slightly till 2030 and then decreases to a slightly higher level than the current 9 GW capacity. In the FE scenario, significant investments have to be made in order to have sufficient generation capacity to secure supply on high-demand days with hardly any supply from wind and solar. In fact, in 2050, there should be about 25 GW of gas-fired plants, almost a three-fold increase compared to current installed capacity.

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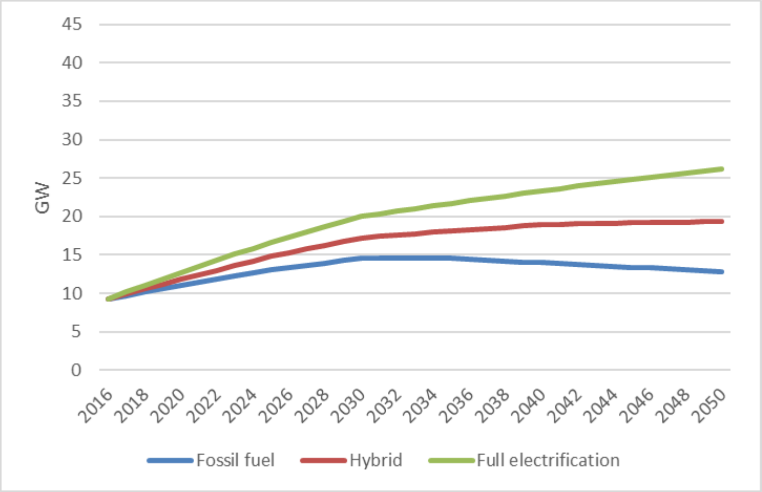
[14] The required generation capacity is calculated as the required generation (in MWh) by gas-fired plants on an average Worse day (see Figure 7.4) divided by 24 (i.e. the daily number of hours).

Figure 7.5. Extra gas generation capacity needed on an average 5% Worse day (taking into account PtG)



8. Consumption of gas

8.1 Data and assumptions

The effect of electrification of road transportation and domestic heating and cooking on the natural gas sector is estimated by computing the demand for gas stemming from the dispatch of gas-fired power plants and the demand originating from the non-electrified dwellings. The assumptions made in order to calculate the gas consumption of gas-fired power plants are given in Table 8.1. The assumptions made to calculate the remaining gas consumption in residential buildings, such as number of houses and efficiency of houses, have been already presented in Section 6. In order to calculate the total gas consumption in the Netherlands, we also need to make an assumption on the gas consumption in the other sectors. In 2016 the total level of this gas demand was 16 bcm. We assume that this demand will annually reduce by 1% due to efficiency measures.

Table 8.1. Assumptions regarding efficiency of gas-fired power plants

Variable	Value
efficiency gas-fired power plants	42%
annual improvement in efficiency gas-fired power plants	1%
annual change in gas demand by other sectors	-1%

Note: efficiency gas-fired power plant is based on actual electricity production per unit of gas consumption by these plants in the Netherlands, ignoring the production of heat (CBS).

8.2 Results

We have seen that in the three scenarios the share of gas in power generation increases significantly up to 2030 due to the discontinuation of coal- and other oil-based generation and nuclear (Figure 10). Gas consumption from the housing sector decreases gradually as the houses are electrified. Up to 2030, the increase in gas demand from the power sector more than compensates the decrease in demand from the housing sector and total consumption of gas increases (Figure 8.1). After 2030, we have seen that in the three scenarios gas-fired power plants decrease their weight in the energy mix because of the increase in generation by renewable sources. However, by no means gas disappears from the energy mix. Most importantly, we observe that as the extent of electrification increases, more gas is needed in the electricity system.

For example, in the FE scenario, gas-fired power plants increase production from 52 TWh by 2016 to 96 TWh by 2030 and then only decrease to 79 TWh by 2050. In this scenario, gas will be gradually fully removed from the residential buildings but by 2050 the gas consumption in the electricity sector will be higher than today’s gas consumption in the electricity sector.

In the FE scenario, the aggregate gas consumption by residential buildings and the electricity sector will exceed the aggregate consumption in the other two scenarios (Figure 8.2). The demand composition of gas consumption differs significantly across scenarios of electrification (Figure 8.3). While in the FF scenario, the aggregate gas consumption in the residential sector remains more or less on the current level of about 10 bcm per year, in the FE scenario this demand almost completely disappears.

As a result of the electrification in heating and transport and the autonomous (assumed) reduction in gas demand in the other sectors, the total Dutch gas demand increases until 2030, while it gradually decreases further on in the Full Electrification scenario. In 2050, the total Dutch gas demand is estimated to be about 33 bcm (Figure 8.4).

Figure 8.1. Gas consumption in residential buildings and electricity sector, FE scenario, 2016-2050

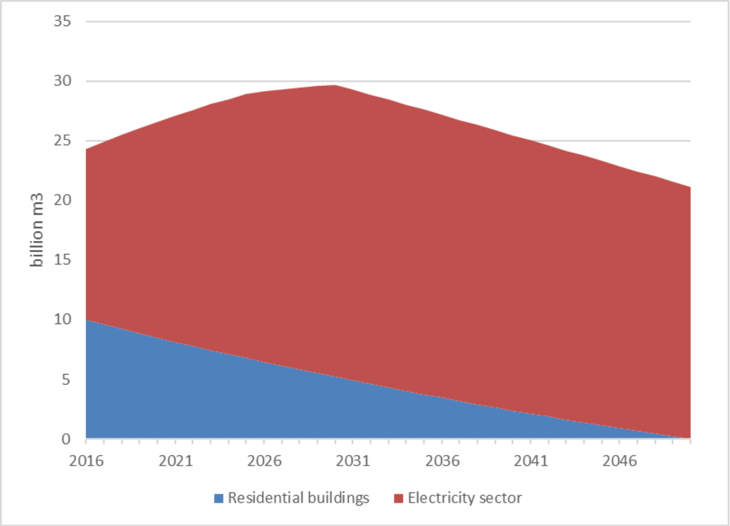


Figure 8.2. Total consumption of gas in residential buildings and electricity section, per scenario, 2016-2050

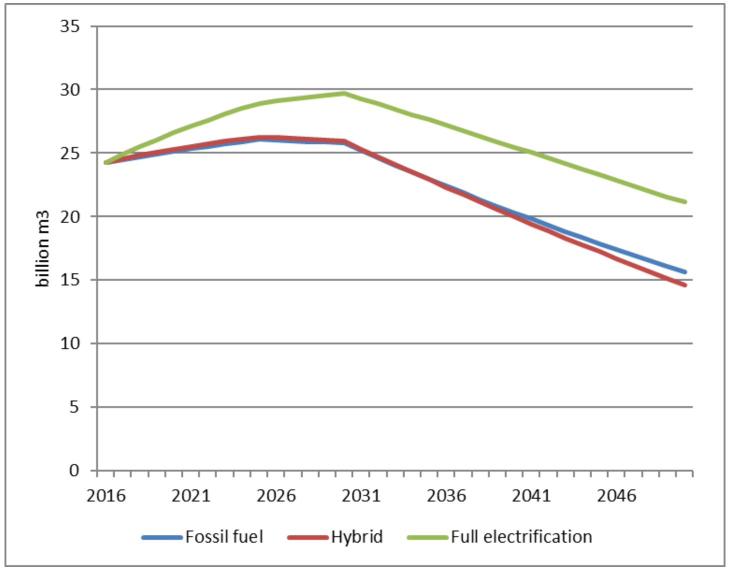


Figure 8.3. Consumption of gas in residential buildings and electricity sector, per scenario in 2050

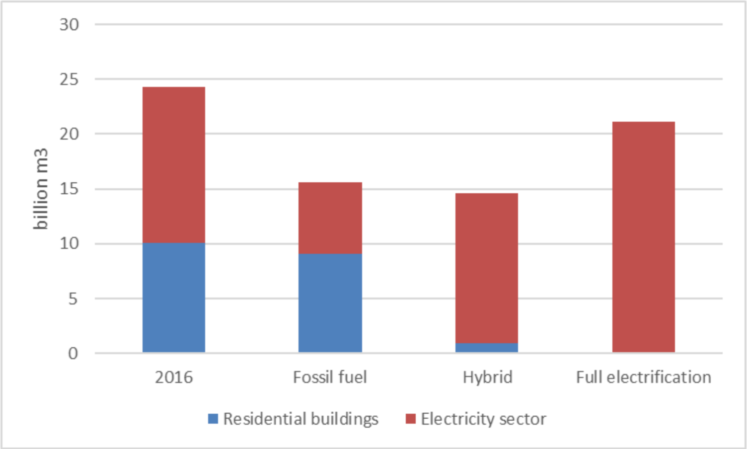
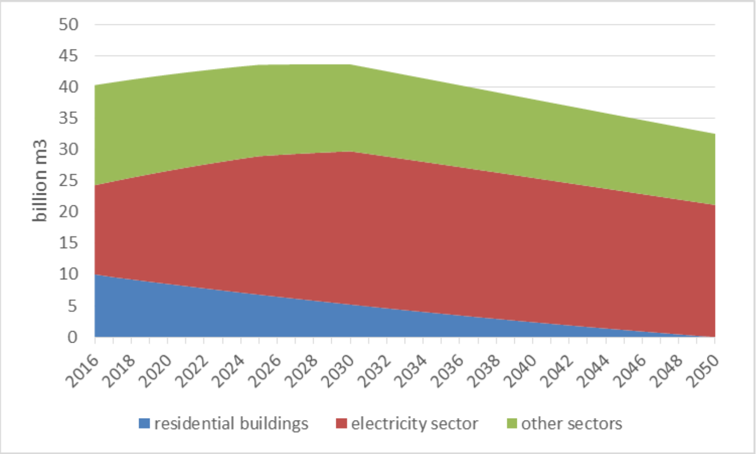


Figure 8.4. Total gas consumption in the Netherlands, per sector, FE scenario, 2016-2050



9. Supply of gas

9.1 Method

The Netherlands have been a major net exporter of natural gas over the past decades because of the huge Groningen gas field. In response to the earthquakes resulting from the gas production from this field, the Dutch government has imposed an annual production cap (Table 9.2). Recently, the government decided to fully stop the production in 2030. The other domestic source of natural gas is the so-called “small fields” (both onshore and offshore). Because these fields are gradually getting depleted, the domestic gas production is bound to reduce in the coming decade. The production of green gas is currently negligible: in 2016 the total production was 0.08 bcm (Table 9.1). We assume that this supply will increase by 5% per year up to 2050. In addition, gas may be produced synthetically first converting electricity into hydrogen via electrolysis and in turn obtaining methane from the hydrogen. We assume that this will only be done when there is an oversupply of electricity on an annual basis, that is, when some amount of the production of electricity is not needed to meet the electricity demand. Note that we have assumed that seasonal oversupply of electricity supply will be stored and used during other seasons within the same year (see Chapter 7). The efficiency of transforming the annual oversupply of electricity into synthetic gas is assumed to be 60% (=80% * 75%) (Table 9.2).

Table 9.1. Data on supply of gas (situation 2016)

Variable	Value
remaining reserves Groningen gas field (bcm)	663
remaining reserves small fields (bcm)	247
annual net export (bcm)	10
annual production of green gas (bcm)	0.08
production small fields in 2016 (bcm)	26

Sources: CBS and http://www.nlog.nl/olie-en-gas-overzicht

Table 9.2. Assumptions on future supply of gas

Variable	Value
production cap Groningen gas field (bcm):	
- 2017 - 2021	21.6
- 2022	12
2023-2030	gradual decline to 0 bcm in 2030
annual reduction in production small fields	2%
annual increase in production of green gas	5%
efficiency of electrolysis	75%
efficiency of converting H_2 into CH_4	80%

9.2 Results

Because the total domestic demand for gas remains at a level close to the current consumption (Figure 8.4), while the domestic production (Groningen and small fields) will decline, other sources of supply of gas will be needed. It appears that the supply of green gas remains very small, despite the assumption of a 5% annual growth. As there will be no oversupply of electricity on an annual basis (i.e. total annual electricity demand exceeds the total production by renewables and the conventional power plants, except natural-gas fired plants) (see chapter 6), there is no reason to produce synthetic gas (as that would mean that more electricity has to be generated by gas-fired plants). Hence, the import of gas has to increase strongly, in all three scenarios (Figure 9.1).

Figure 9.1. Supply of gas by origin, per scenario, 2016-2050

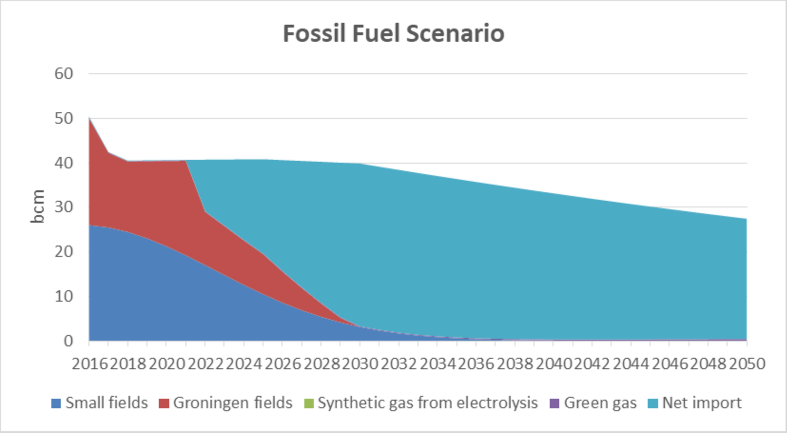
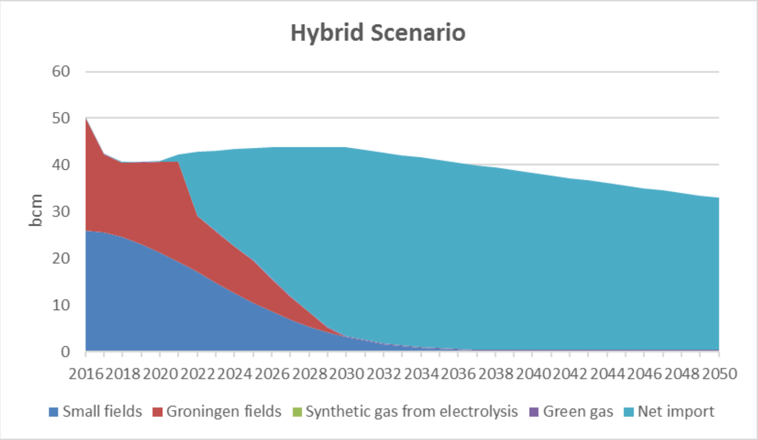
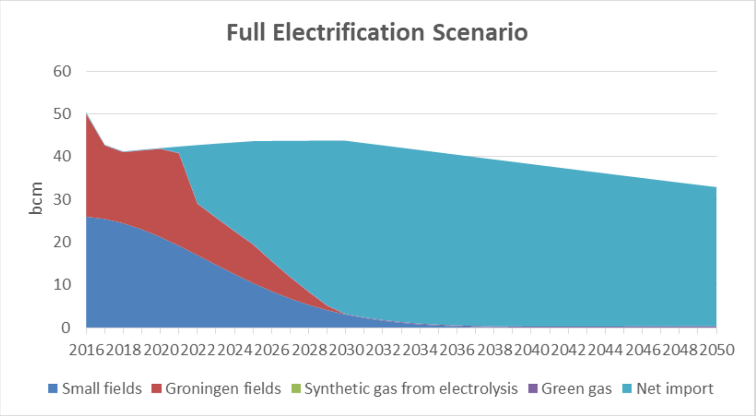


Figure 9.1. (continued)





10. Electricity and gas distribution networks

10.1 Method

As electricity and gas provision relies heavily on the use of distribution networks, an increase in power generation and/or in gas consumption requires a possibly costly resizing of the distribution networks. In this section we compute the network capacities that are needed for the future provision of electricity and gas.

To do this, we depart from the assumption that the present networks in the Netherlands are optimised to deal with current volumes of demand. Because demand is highly volatile (Section 7), this means particularly that the networks do have sufficient spare capacity to be able to handle peak usage. Hence, we argue, an increase in power demand has to be accompanied by a corresponding increase in the capacity of the networks in order to maintain the current level of network quality.

Consequently, because electricity networks need to be adapted to deal with the maximal level of load within a year, we compute the amount of power generated under the most favourable weather conditions for electricity production, which we defined as the 5% Best days in Section 7. Under those favourable conditions, electricity production will be at its maximum. For the gas networks, it is the opposite. We run the model for the 5% Worse days, because it is during those days that temperature is lowest and gas consumption is highest to meet the demand from both the residential housing and electricity sectors. In order to determine the impact of electrification on the network sizes, we express the total load for the HY and FE scenario in percentages of the total load in the baseline FF scenario.

10.2 Results

In the FE scenario, the electricity grid has to increase gradually over the years in order to deal with the increase in peak demand (Figure 10.1). In 2050, the electricity network capacity should be almost 50% larger than the current size. As gas consumption in the FE scenario is higher than in the FF scenario, the gas network should be larger as well (Figure 10.2). In the FE scenario, the gas network should be almost 20% larger than in the FF scenario by 2050. Note that this does not mean that the gas network needs to be expanded compared to the current size; this is because in the FF scenario the network is oversized, as gas consumption is declining. In the HY scenario, the gas network can be reduced because of the lower level of gas consumption during cold winter days (i.e. lower peak consumption).

Figure 10.1 Size of electricity grid compared to the FF scenario (in%), 2016-2050

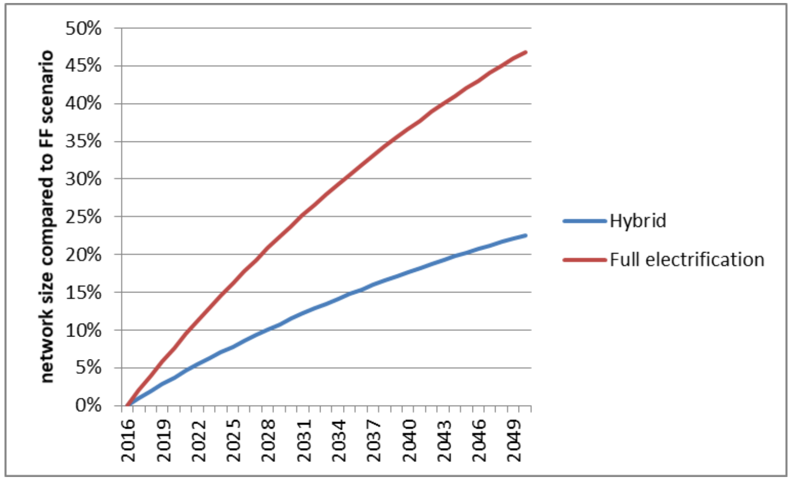
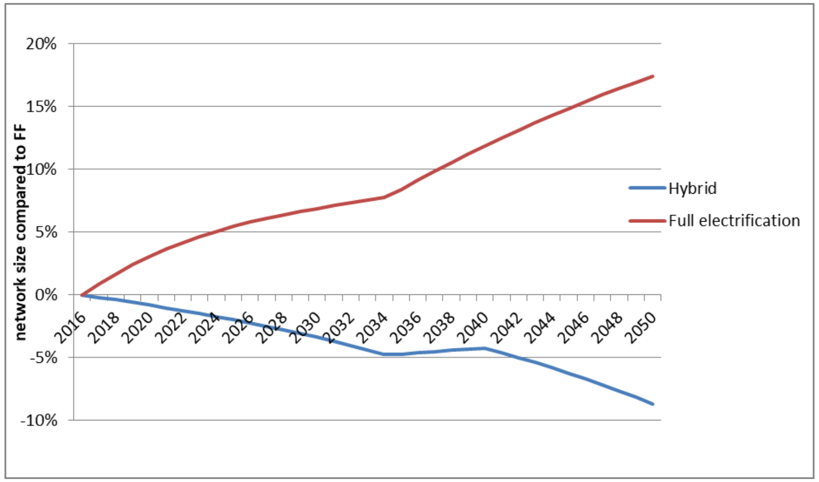


Figure 10.2. Size of gas network compared to FF scenario (in %)



11. Carbon Emission

11.1 Policy objectives

At the end of the day, the objective of electrification is to reduce carbon emissions. The European Union aims at reducing carbon emissions by 40% by 2030 compared to the levels in 1990. The newly formed Dutch government is pushing a more ambitious agenda: it has committed to a 49% cut in carbon emissions by 2030 (*Regeerakkoord* 2017-2020) and has agreed to advocate a 55% reduction in Europe by 2030 during the upcoming review of the Paris agreements this year. It is expected that reaching such targets will pave the path to further reductions; in particular, by 60% below 1990 levels by 2040, and by 80% below 1990 levels by 2050.

11.2 Method

As the policy objectives are expressed in terms of reductions of carbon emissions relative to 1990 levels, our starting input for assessing the impact of electrification on carbon emissions is the data about CO_2 emissions levels in 1990. According to CBS data, the Dutch households emitted in 1990 about 21 Mton of CO_2, the road transport emitted about 25 Mton of CO_2, and the electricity sector about twice as much as road transport (52 Mton) (Table 11.1).

Table 11.1. Data on emissions of CO_2 in the Netherlands, 1990

Variable	Value
CO2 emissions in 1990 (x Mton)	
residential buildings	21
road transport	
- passenger cars	15,5
- vans	2,2
- trucks	5,0
- buses	0,6
- motors	0,3
electricity sector	52

Source: CBS

In order to calculate the carbon emissions during the scenario period, we simply determine the consumption of fossil energy per sector and multiply this consumption with the carbon intensity per unit of fossil energy. For the case of road transportation, two factors are relevant: the quantity of fuel used per unit of distance and the carbon intensity of the fuel. Table 11.2 gives the assumptions we make regarding these factors. We assume that (non-electrified) cars and two-wheelers use gasoline, while vans, trucks and buses use diesel. The total distance driven per type of vehicle was presented in Section 3.

Regarding the gas consumption by (non-electrified) residential households, the calculation is more straightforward: we multiply the total gas consumption in residential buildings in m^3 by the CO_2 content per m^3. The CO2 emissions per m^3 of natural gas are taken to be 2.2 kg (*wikipedia*).

Table 11.2. Assumptions on emissions in road transport

Variable	Fuel efficiency (lt/100 km)	Carbon intensity (ton/lt fuel)
passenger cars	6,7	0,0024
vans	10	0,0027
trucks	22	0,0027
buses	29	0,0027
motors	5	0,0024

Source: gemiddelden.nl

Finally, we compute the carbon emissions caused by the electricity sector. For this, we sum the CO_2 emissions stemming from the power plants running on fossil fuels. For coal-fired plants, we factor CO_2 emissions per ton of coal equal to 3,66 tons; for gas-fired plants, as mentioned above, emissions are 2,2 kg/m^3; finally, for oil-based power generation we factor 2,6 tons of CO_2 per ton of oil.

For the electricity sector, however, it is important to note that electrification signifies a shift from non-ETS carbon emissions (originating from the combustion of fossil fuels to power the transport sector and the burning of natural gas to cook in and heat dwellings) to ETS carbon emissions (stemming from the burning of fossil fuels to produce electricity). This distinction is quite relevant because of the cap-and-trade nature of the ETS: decreases in the volume of emissions of the electricity sector will not imply a net decrease in carbon emissions because emissions will increase in other sectors of the economy.

11.3 Results

In the FF scenario, the carbon emissions originating from all three sectors together decrease by 50% by 2050, from the current level of 120 Mton to about 60 Mton (Figure 11.1). This reduction is mainly due to emissions cuts in the electricity sector because of the shutdown of the coal- and oil-fired power plants and the gradual replacement of gas-fired plants by wind and solar power. The carbon emissions by the residential buildings, however, are more or less stable in this scenario: efficiency improvements per house are compensated by an increase in the number of houses.

In the FE scenario the total reduction in carbon emissions is even stronger, to about 50 Mton in 2050. This results from the strong reduction in the emissions of the residential buildings and the passenger cars, though this effect is partly offset by a higher level of emissions by the electricity sector. Figure 11.2 shows that in the FE scenario the carbon emissions in the road transport sector go down by more than 50% by 2050, CO2 emissions of residential buildings are reduced by almost 100%, but the emissions from the electricity sector are reduced only modestly (around 20%) and remain much higher than in the FF scenario.

Looking at the three sectors together, carbon emissions fall by about 10% by 2030 relative to 1990 levels in the three scenarios (Figure 11.3). If we leave the electricity sector out, because of the existence of the EU ETS, it appears that in the FF scenario in 2030 the carbon emissions are about 20% higher than in 1990, while in the FE scenario a reduction of about 25% is realised in that year.

Figure 11.1. Emissions of CO_2 by road transport, residential buildings and electricity sector, in FF and FE scenario, 2016-2050

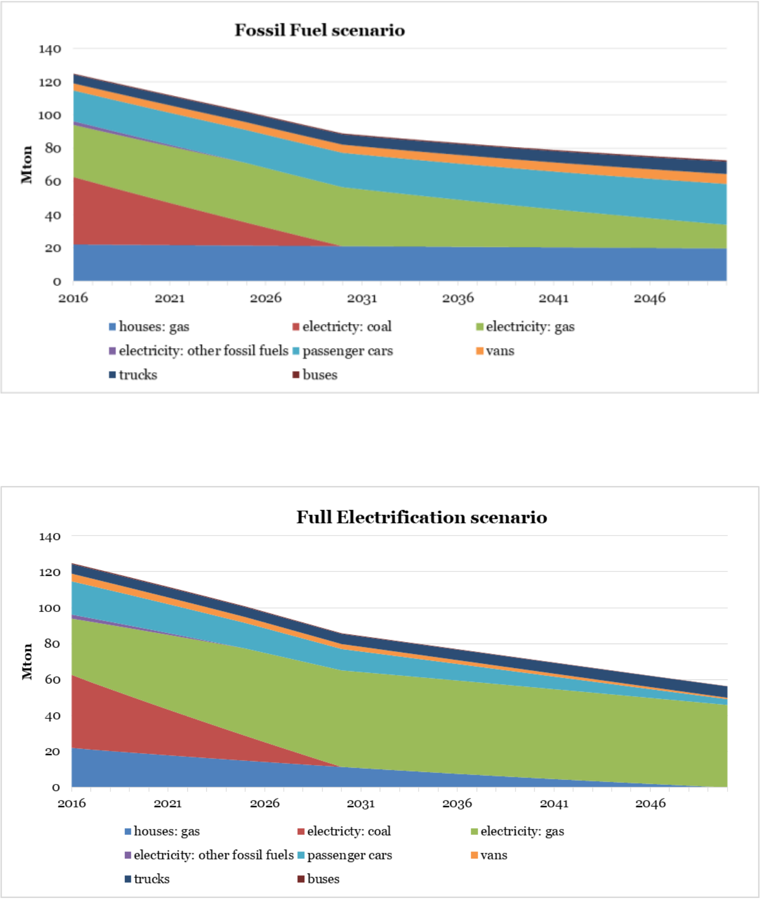
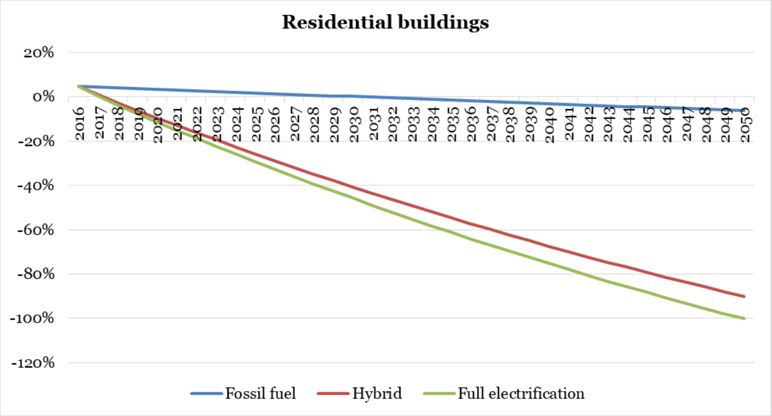


Figure 11.2. CO2 emissions in road transport and residential buildings, per scenario, 2016-2050 (in % of 1990 levels)



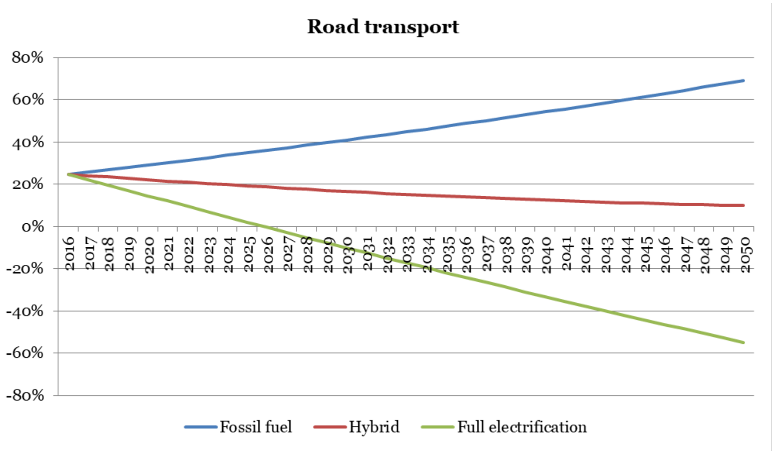


Figure 11.2. (continued)

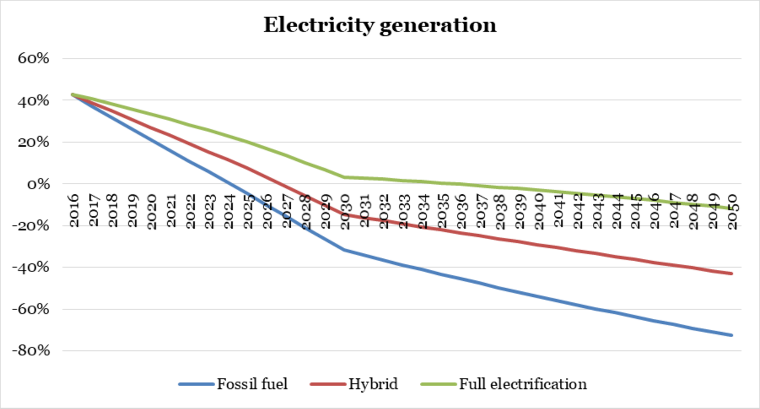
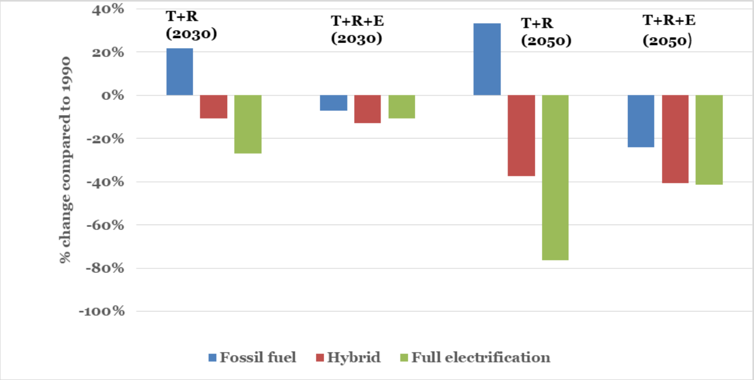


Figure 11.3. Carbon emission reduction per group of sectors, per scenario, in 2030 and 2050 (in % of 1990)



Note: T= Transport; R=Residential buildings; E = Electricity generation

12. System costs

12.1 Method

In the final step of our work, we compute the total costs of electrification of transport and housing. By costs of electrification we mean the investments (net of the savings, if any) necessary to realise the electrification targets laid down in the scenarios HY and FE. These investments relate to the three sectors that are affected by electrification: the housing sector and the mobility sector, which are affected directly, and the electricity sector, which is affected indirectly.

In residential buildings we compute the costs of insulating old houses (insulation of walls and roofs, floor heating systems, double glazing of windows, etc.) and the excess costs of installing heat pumps relative to gas boilers. In road transport, we take into account the excess price of electric cars relative to conventional ones, and the costs of deploying the necessary battery quick-charging infrastructure. We also include the savings of conventional fuels due to electrification as a negative cost. The estimates of these costs are reported in Table 12.1.

For the electricity and gas sectors, we include the costs of expanding the capacity of gas-fired generation for flexibility purposes, the costs of Power-to-Gas facilities for storage, and the costs of upsizing the electricity and, if needed, gas networks. In the previous sections, we derived the impact of electrification for the required capacity of gas-fired power plants and Power-to-Gas (Section 7), the capacity of electricity and gas networks (Section 10) and the emissions of CO2 (Section 11). The estimates of the costs of building gas-fired plants, and deploying Power-to-Gas infrastructure are reported in Table 12.1. We factor the savings in gas consumption due to the use of storage as a negative cost. The costs of expanding the networks are computed by assuming that the current asset bases have to be enlarged in a way proportional to the necessary upsizing of the facilities. For this, we calculate the annual costs using a value for the cost of capital (WACC) and an assumption regarding the depreciation period of the various types of assets (Table 12.1). As the assets depreciate over time thereby reducing the book value, we assume that on average the book value is equal to 50% of investments. This book value is used to determine the costs of capital. The WACC is based on the value that is currently generally used by regulators in the regulation of energy networks. This value (5%) is higher than the value that we use to calculate the present value of all costs as the latter only refers to the societal costs of time preference.

Finally, in the computation of the system costs we also include a shadow price for carbon emissions reductions, which should be viewed as a cost saving to society. To monetise the impact on the emissions of CO_2, we use two different shadow prices. For the emissions within the ETS, we use the ETS carbon price, while for other emissions we take the marginal costs of other reduction measures.

We report the costs of electrification by comparing total system costs in the HY and the FE scenario with the FF scenario. As the degree of electrification is the only factor that is different across scenarios, any difference in costs can be fully attributed to differences in the degree of electrification.

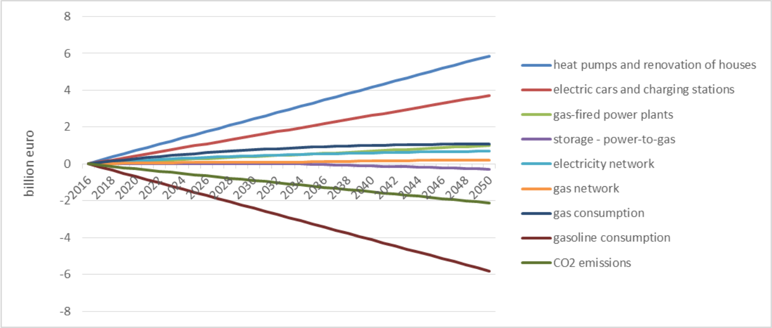
Table 12.1. Assumptions to calculate system costs

Variable	Value
Weighted Average Costs of Capital (WACC)	5%
Discount rate (for NPV calculations)	3%
Depreciation periods (years)	
- grid	20
- power plants	20
- houses	40
- cars	10
Investments costs:	
- gas-fired power plants (mln euro/MW)	0,75
- electrolyser (mln euro/MW)	0,5
- storage (caverne)	30
Asset value electricity grid (billion euro)	28
Investment costs residential buildings	
- heat pump (euro / house)	6000
- renovating house (euro/m2/house)	105
Investments costs road transport	
- quick charging stations (per unit)	35000
- ratio charging stations / cars	0,08
- extra costs of electric cars (euro/car)	7500
Gas price (Euro/MWh)	20
annual change in gas price	0%
Price motor fuels (Euro/lt, excl taxes)	0,5
annual change in price motor fuels	0%
shadow price of CO2 (euro/ton)	50
CO2 price in ETS (euro/ton)	10

12.1 Results

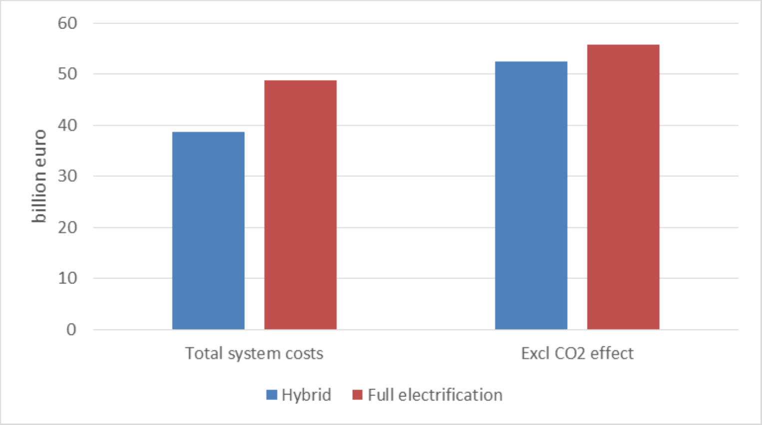
The major component of the costs of electrification is the investment necessary to renovate and insulate houses and to install heat pumps. In 2050 these costs are estimated at about 6 billion euro (Figure 12.1). The other major component of the total system costs refer to electrifying transport. Besides these costs, there are also benefits of electrification: savings on gas and gasoline as well as lower level of carbon emissions.

Figure 12.1. Costs of electrification per type, in billion euros per year, FE scenario, 2016-2050



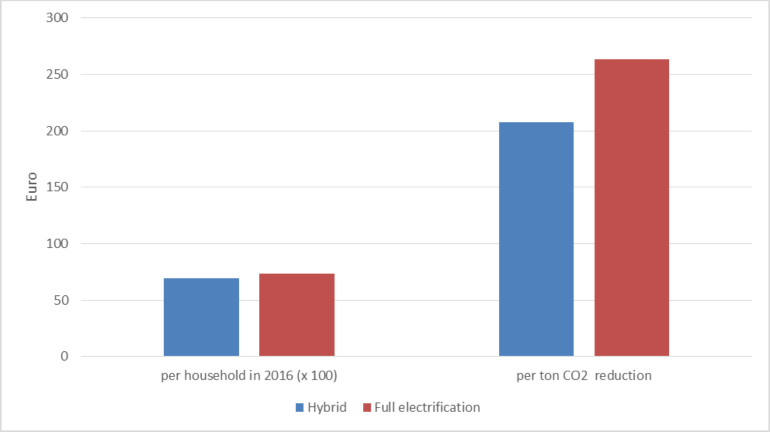
Finally, we calculate the net present value of the total system costs. As said above, these costs include all investments in residential buildings, road transport and energy sector needed for electrification, net of all savings in the consumption of fossil fuels and reductions of carbon emissions. The net present value of these costs are estimated at about 40 billion euro for the HY scenario and almost 50 billion euro in the FE scenario (Figure 12.2). If we exclude the monetary value of the reduced carbon emissions, the NPV of the total costs amount to more than 50 billion euro.

Figure 12.2. Net Present Value of total system costs, in HY and FE scenario, in billion euros



When we express the net present value in the number of households in 2016, then both the HY and the FE Scenario result in an average costs of about 7000 euro (Figure 12.3). As the cumulative reduction in carbon emissions in HY scenario exceeds the cumulative reduction in the FE scenario, the latter results in a higher costs per ton of reduction: 250 euro/ton in FE compared to 200 euro/ton in HY.

Figure 12.3. NPV of total system costs of electrification, per household (2016) and per ton reduction of CO_2, per scenario



13. Conclusions

13.1 Objective and method

In this paper we have performed a quantitative scenario analysis of the implications of electrification of the residential housing and road transport sectors in the Netherlands. While doing this, we have taken into account the current governmental policy plans regarding the closure of coal-fired power plants and the significant expansion of renewable generation. The main motivation for doing this analysis is the current policy agenda in the Netherlands to gradually “disconnect” from gas, an agenda that has precipitated due to the environmental agenda of the EU and the recent national crisis caused by the earthquakes in Groningen province.

The impact of electrification of the residential housing and road transport sectors on gas consumption is not easy to compute. In the Netherlands, because most house heating stems from the burning of natural gas, the direct effect of electrification of the residential housing sector is to lower gas demand. However, because electrifying houses implies a higher demand for electricity, depending on the amount of renewable generation available, this higher demand for electricity may be translated into a higher demand for gas as an input for electricity generation. To this indirect effect, we have to add the electrification of road transport, which, by the same token, may signify a higher demand for gas to generate the necessary electricity to power the vehicles.

13.2 Sensitivity analysis

Before presenting the final conclusions of this study, we first present the results of a sensitivity analysis. As in any study exploring future scenarios, the results are of course highly sensitive to the assumptions made. Table 14 presents the results of a number of scenario variants concerning crucial assumptions in our analysis. Specifically, these scenario variants refer to the assumptions made about the future improvement in the energy efficiency of households, transport and the electricity (‘Higher efficiency’), the assumptions on the future growth in the supply of renewable energy (‘More renewables’) and the assumptions on the future energy demand by households and transport (‘Stable demand’).

Table 13.1 shows that in all of these three variants on the Full Electrification Scenario, there is still a role for gas-fired generation in 2050. Only when we combine these three variants into a single variant (which we call ‘All 3’), then gas-fired generation is no longer needed to meet the total level of demand in 2050, although it is still necessary to deal with the seasonal flexibility. Only in this variant, we see that there will be oversupply of electricity at an annual level, which can then be converted into synthetic gas to be used in the industry, but this share will still be very limited in 2050.

From this sensitivity analysis, we conclude that our findings regarding the impact of electrification on the role of gas are fairly robust. Only if we make rather extreme assumptions on the future changes in energy efficiency (much higher that what we have seen in the past), the future deployment of renewables (much faster than in the current policy objectives) and the future demand from houses and transport (much lower than we have seen in the past), then gas-fired generation will be fully displaced from the energy system.

Table 13.1. Results sensitivity analysis

	Variants on Full Electrification Scenario				
Outcome model	**Baseline**	**Higher efficiency**	**More renewables**	**Stable demand**	**All 3**
Extra electricity demand due to electrification in 2050 (in % of 2016)	65%	57%	65%	59%	52%
Share of gas generation in total generation in 2050	49%	47%	10%	42%	0%
Gas consumption in electricity and residential sector in 2050 (in % of 2016)	87%	79%	17%	64%	0%
Share of synthetic gas in total gas supply in 2050	0%	0%	0%	0%	3%
Carbon emissions in electricity, residential and transport in 2050 (in % of 1990)	-41%	-46%	-80%	-66%	-100%

notes: 'higher efficiency': annual improvement in the energy efficiency of houses, vehicles and electricity generation is 2 times baseline; 'more renewables': annual increase in wind turbines and solar panels is 2 times baseline; 'stable demand': no increase in number of houses and cars and autonomous electricity demand remains constant; 'all 3': all the above 3 variants combined

13.3 Main findings

Going back to the baseline definitions of the Hybrid scenario and the Full Electrification scenario, we can formulate the following conclusions.

- Electrification of the road transport sector (mainly passenger cars and vans) would increase electricity consumption by 40 TWh by 2050, which is about 50% of total current Dutch consumption. The increase stemming from passenger cars would only be about 30TWh. Electrification of houses (heating space, warm water and cooking) would increase electricity production by 35TWh. Together, electrification of the residential housing and road transport sectors in the Netherlands would raise electricity consumption by 75TWh in 2050, which is about 50% more than currently.
- Despite the planned sharp increase in renewable generation in the Netherlands, we will still need 100 TWh of production of electricity from gas-fired power plants in case of full electrification. This is the outcome of the interaction of four variables, namely, the projected autonomous increase in electricity demand as the economy progresses, the electrification of houses and vehicles, the planned shutting down of other fossil-fuel (coal and oil) and nuclear plants and the ambitious but still limited increase in renewable power generation. Therefore, the electrification of households results in an important shift in the use of natural gas. The use of gas for cooking and heating houses progressively decreases, but the extra electricity demand stemming from electrified houses and vehicles requires the use of a lot of gas in electricity generation.
- Because of the strong increase in electricity demand, there won't be episodes of excess supply, even on windy and sunny days, and therefore it won't be necessary to make large investments in storage

infrastructure. Hence, there is also no excess supply of electricity on an annual basis which can be converted into synthetic gas.

- However, because of the strong increase in electricity demand coupled with the significant but limited growth of renewable power production, a substantial amount of gas-fired power plant capacity will be necessary for reliability of supply. This capacity is needed to keep the electricity system working on cold days without much wind and sunshine when the electricity demand is high and there is hardly any renewable power production. The capacity of gas-fired power plants need to increase from the current 9 GW to about 25 GW in order to be able to deal with fluctuations in electricity demand as well as renewable generation.
- Therefore, although the EU and its Member States have the ambition to move towards an electricity sector with low carbon emissions, gas-fired power plants will still be needed in order to meet the growing demand for electricity arising from electrification of, particularly, transport and heating as well as the growing need for providers of flexibility. Seasonal storage of electricity can partly help to solve this problem, but this help will be limited as only on really exceptional days there will be an oversupply of electricity. After all, electrification implies that the likelihood of oversupply of electricity decreases.
- Total gas consumption from the electricity and residential sector will increase in the next 10 to 15 years from 24 to 30bcm and then it will decrease to about 20bcm by 2050. The initial increase is due to the closure of the other fossil-fuel power plants, which favours gas-fired power plants, and the later decrease is mainly due to the gradual deployment of renewable generation. The composition of gas demand, though, changes importantly. By 2050, gas demand from household disappears due to electrification and the bulk of gas demand stems from the electricity sector.

- Because the total domestic demand for gas remains at a level close to the current consumption, while the domestic production from the Groningen and the small fields will decline, other sources of supply of gas will be needed. As the supply of green gas remains very small, while there is also no excess supply of electricity to produce synthetic gas, the import of gas has to increase strongly, in all three scenarios. In the Full Electrification scenario, the Netherlands will still import about 30bcm in 2050.
- To cope with the additional demand from electrified houses and vehicles, electricity networks in the Netherlands need to be expanded by about 50% in 2050. The gas networks need not become greater than they are right now but the capacity used will be much higher than in the absence of electrification. This is because electrification makes gas demand much more weather dependent.
- Compared to 1990 levels, by 2050 CO_2 emissions completely disappear from the housing sector due to electrification, while the transport sector lowers CO_2 emissions by almost 60%. However, in the electricity sector, the reduction in emissions is much more moderate, slightly above a 10% cut below 1990 levels. Together, emissions from the three sectors go down by only 10% by 2030, a reduction that falls quite short of the 49% reduction target of the Dutch government. By 2050, this reduction is 41%. Ignoring the electricity sector, the joint reduction of the housing and transport sector by 2030 is 27% compared to 1990 levels and by 2050 it is 76%. Note, however, that because the electricity sector is part of the ETS, the increase in the emissions originating from power production will have a corresponding decrease somewhere else in the ETS sectors.

- Finally, the net costs of electrification of the housing and transport sectors are positive and sizable. That they are positive implies that the benefits (in terms of CO_2 emissions reductions and savings in the use of gas and gasoline) fall too short relative to the costs. The costs are also sizable: the net present value of the net costs for the period up to 2050 are about 50 billion euros, which is about 2 billion euro per year (in real terms). Note that these costs only refer to the electrification and do not include the transition on the supply side of the energy system (i.e. replacing fossil fuels by renewables).
- The distribution of these costs shows that the bulk of them have to do with two elements, the renovation of houses and installation of heat pumps, and the excess price of electric cars and the cost of battery charging points. Relative to those costs, the costs of reliability of the electricity system and the additional gas-fired capacity are quite moderate.
- The total system costs excluding the benefits of lower carbon emissions over the full period 2016-2050 expressed in NPV per household in 2016 gives a number of about 7,000 euro. These are the net costs of electrifying heating and transport. When we express the same total system costs in the total tons of reductions in carbon emissions, we find a cost per ton reduction of about 200 euros in case of a hybrid scenario of both electrification and district heating and about 250 euros in case of full electrification of heating and transport.

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The residential and road transport sectors are both major contributors to the emissions of greenhouse gases. In both sectors, electrification may help reduce these emissions. Electrification, however, need not imply that the role of fossil fuels in the economy is reduced. This role is intimately linked to how the electricity will be generated in the future. In particular, natural gas may remain an important source of fossil energy. To what extent this will be the case closely depends on the transition of the electricity sector towards renewable energy sources. In this paper the authors explore the future energy system of the Netherlands, departing from actual data on the current situation and the policy objectives regarding both electrification and energy transition. The paper derives the consequences of electrification of heating and transport for the gas and electricity sectors, greenhouse gas emissions and the total social costs.

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