Centre on Regulation in Europe
Improving network and digital industries regulation

Gas and the electrification of heating & transport: scenarios for 2050

A case study for France

Chloé Le Coq, CERRE & Stockholm School of Economics[*]

24 May 2018

[*] <chloe.lecoq@hhs.se>

Centre on Regulation in Europe (CERRE) a.s.b.l.
Avenue Louise 475 Box 10|B-1050 Brussels|Belgium
+32 2 230 83 60|info@cerre.eu|www.cerre.eu

Table of Contents

1. Introduction

This report presents a 2050 scenario study of the implications of a possible gradual electrification of road transportation and domestic heating and cooking in France. The study is intended to derive the consequences of electrification for the electricity and gas sectors, for the CO_2 emissions associated with the residential, transport and electricity sectors and for the overall social costs.

Specifically, the study explores three possible electrification paths:

1. *Fossil Fuel* scenario: a business-as-usual electrification path, where electrification remains quite limited and in line with current practices, even by 2050;
2. *Full Electrification* scenario: a full electrification path as an extreme benchmark in which the residential sector and the road transport sector (in particular passenger cars and motorbikes), are virtually fully electrified by 2050;
3. *Hybrid Electrification* scenario: a path in which the extent of electrification in 2050 is intermediate.

These scenarios are not forecasts, and which scenario turns out to be closer to reality will depend both on the policy goals of the government and developments in the market. Of course, these may vary over time.

Instead, we provide a framework for analysing the consequences that electrification (to a greater or lesser extent) will have for aggregate electricity demand and therefore for the energy mix needed for power generation. It should be noted that throughout this study, we treat gas as a residual fuel for power generation and Power-to-Gas (PtG) as the first source of flexibility.

This study is a data-driven, quantitative exercise. The starting point for the projections to 2050 is the year 2016, a year for which we can obtain most of the necessary data from public sources. Historical data are used to determine the parameters for the year-to-year projections. The analysis takes into account the policy commitments of the government (where they exist) regarding the expansion of renewable electricity sources (hydro, biomass, wind and solar) and the phasing-out of fossil fuel and nuclear sources of power production. The model also accounts for the effect of innovation by including yearly increases in the energy efficiency of housing and cars, decreases in the losses of battery charging devices and improvements in the efficiency of electricity production technologies.

With the necessary data and policy commitments in place, the study proceeds through a number of logical steps:

1. First, it derives the increase in the power demand resulting from electrification of the residential and transport sectors.

2. It then calculates the energy mix which will be required by the power sector to meet this demand. These calculations take into account government commitments/policy objectives and also take gas as the resource of last resort.
3. We then study the reliability of the electricity sector, using PtG as the primary source of flexibility and gas as the secondary source.
4. Following this, we compute the CO_2 emissions of the three sectors involved in the study (the housing, transport and electricity sectors) and compare them to 1990 levels.
5. Finally, we compute the social costs of electrification. In computing these costs, we include the costs of retrofitting houses, the price premia of heat pumps and electric cars, the costs of quick charging posts, the costs of electricity grid expansion, the costs of gas network expansion (if necessary), the cost of PtG technology, the costs of gas-fired power plant capacity expansion to guarantee reliability of the power sector, the savings in fossil fuels (gas in houses and gasoline and diesel in transport), and the savings in CO_2 emissions (outside the European emission trading system (ETS)) and the costs of CO_2 emissions inside the ETS.

Through these steps, the model derives the consequences of electrification for each scenario.

As is the case with all scenario studies, we model some features of the energy markets and purposely leave some aspects outside the analysis. We do not explicitly model the price dynamics of the energy markets, nor the development of the carbon price within the EU ETS. These two assumptions reflect our objective of placing the focus on the impact of government policy on the electricity supply curve. By doing this, we intentionally put the emphasis on a case in which the merit order for electricity production is primarily determined by policy.

These aspects would not significantly alter the main qualitative results of our study. For example, a higher price of natural gas might lead gas-fired power plants to opt for biogas for power production; this would merely affect our calculations of CO_2 emissions but not the other conclusions in our study. Likewise, an increase in the carbon price within the EU ETS might result in a reduction in government support for renewables, thus the share of renewables would remain primarily determined by policy as we assume in our model. Finally, while we have included PtG and gas as the primary sources of seasonal flexibility, we have not included other potential sources such as demand response.

The results of this report should not be seen as a recommendation for a specific policy option. More modestly, we try to shed light on the challenges and choices policymakers and the energy sector will have to manage depending on the extent to which electrification occurs.

1.1 Background

France is an interesting case to consider. First, electrification is relatively advanced in France with a relative high share of residential electric heating compared to many European countries (see Figure 1).

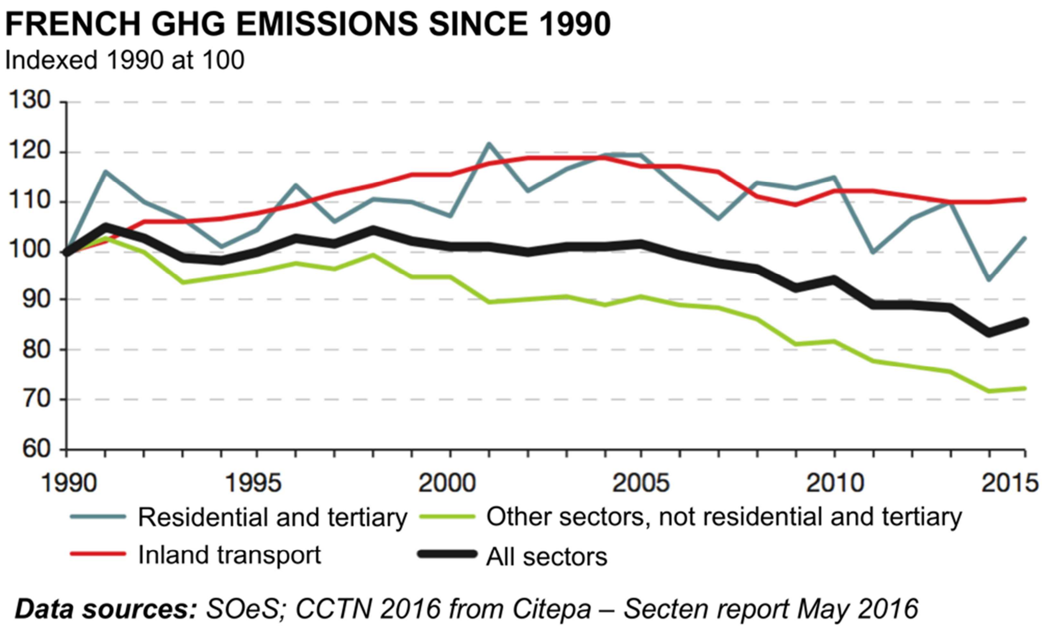
Second, the large share of nuclear power in total electricity generation contributes to the country's relatively low carbon emissions. It is also likely that nuclear production will remain a dominant technology, even after 2050, as the objective of lowering the nuclear share in total electricity production, not to mention the objective of phasing-out nuclear generation, has been postponed. In the 2015 Energy Transition Law, the initial target was to cut nuclear's share of electricity production from the high level of 75% to 50% by 2025. The plan was to close up to 17 of France's 58 reactors by 2025.[1] However, the current government is concerned that such a measure would seriously threaten France's security of power supply and increase CO_2 emissions.[2] The French grid operator warned about risks of supply shortages, in the event that 40-year-old nuclear reactors and all coal-fired plants were, as planned, shut-down simultaneously (RTE, 2016). On the other hand, France's ageing nuclear power plants also raise serious concerns that nuclear-reliant France could face supply shortages in the future. Supply shortages did in fact occur in 2016 when nuclear production was significantly reduced following the nuclear safety agency's order to EDF to delay the restart of several reactors for safety reasons.[3]

Third, because of its largely carbon-free electricity generation, France ranks among the developed economies with lowest GHG emissions, both in terms of emissions per capita and per unit of GDP. France has set very ambitious reduction targets; compared to 1990, GHG emissions should be reduced by 40% in 2030 and by as much as 75% in 2050 (see the Law on Energy Transition for Green Growth). Notwithstanding the ambitious nature of these objectives, it is far from obvious that these objectives will be reached. In fact, France's CO_2 emissions rose in 2016 by 3.6 percent, above the targeted 447 million tons of CO_2 emissions. And the government has recently announced that France will revise its CO_2 emissions targets at the end of 2018.

Fourth, the residential heating and transport sectors contribute heavily to France's CO_2 emissions (see Figure 1).

[1] Note that EDF is planning some investments ('Grand Carenage' program) because its fleet of 900 MW class reactors is aging and will reach 40-year-lifespan before 2025.
[2] Speech by the French Environment Minister, Nicolas Hulot (7th November 2017).
[3] It was announced that a national plan for hydrogen would be launched on June 1, 2018. This plan is not accounted for here.

Figure 1: Contribution to CO2 emissions by sectors



For all these reasons, it appears important to study the implications of electrification of France's heating and transport sectors.

1.2 Organisation of the report

The organisation of the report is as follows. Section 2 describes briefly the framework and the different scenarios adapted to the French case. The impact of road transport and residential buildings electrification on the electricity demand is discussed in sections 3, 4 and 5. How the degree of electrification of the economy in general affects electricity supply is discussed in sections 6 and 7, while section 8 focuses on the gas sector. Finally, the general consequences on the system's flexibility, the system costs and the Co_2 emissions are analysed in sections 9, 10, and 11 respectively.

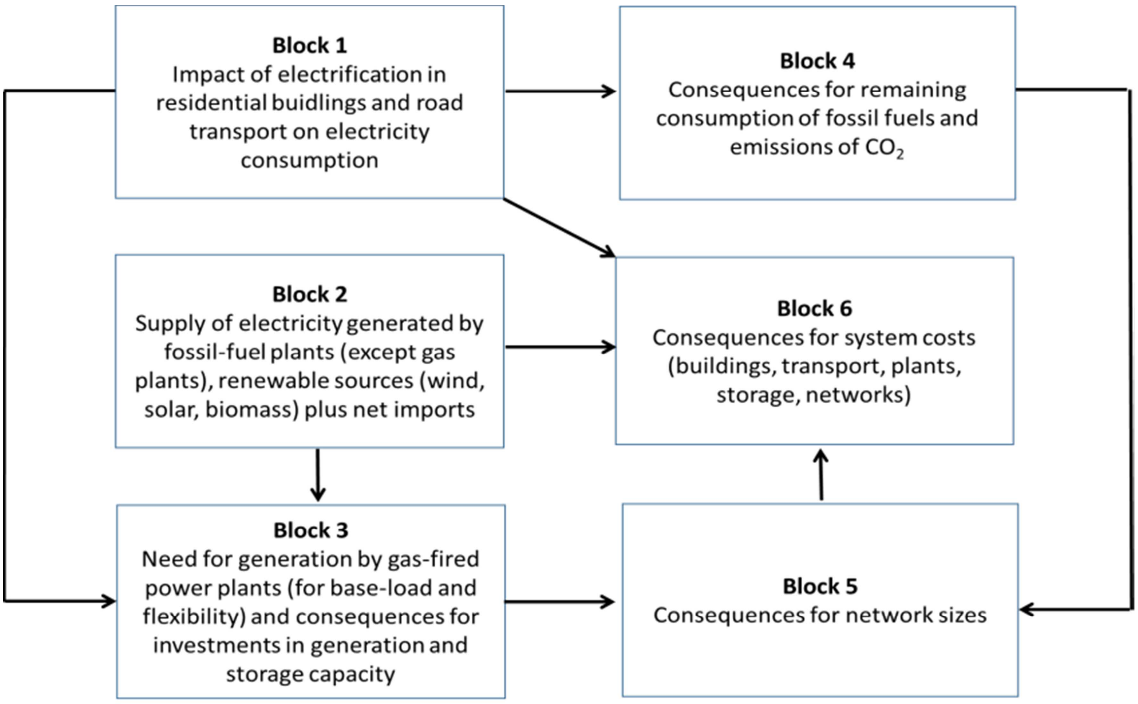
2. Method and scenarios

The objective of this report is to understand how electrification of the economy will impact the required electric and gas supply, the tension on the network and the impact on CO_2 emission.

2.1 The framework

The modelling framework developed for the Netherlands case study can be divided in four blocks, as illustrated in the following figure.

Figure 2: Main building blocks of analytical framework



Source: Moraga and Mulder (2018)

Block 1 of the model calculates the impact of electrification on power demand. The model requires input data on the current stock of vehicles and houses, and their respective energy needs when electrified. Using estimates on the future development of the housing and vehicle stock until 2050, along with assumptions on the increase in the share of electrified houses and vehicles, the model yields additional power demand arising from electrification of both sectors.

Block 2 derives needed electricity supply, taking into account the power demand modelled in the first block. More specifically, the model calculates the resulting generation mix on the supply side used to satisfy future power demand each year. The generation mix for each year is defined using a merit-order approach. Investment and market exit of technologies are exogenous and follow policy objectives, e.g. for reduction of nuclear plants' market share or increasing renewable generation.

Block 3 determines the resulting gas demand. The higher the degree of electrification becomes, the more gas demand stems from the power market, and the less from heating. This modelling block thus presents outcomes on the net impact on gas demand over the years.

Blocks 4 and **5** calculate the resulting net CO_2 emissions and infrastructure needs from electrification, respectively. Eventually, the last block of the model establishes a net present value approach to electrification.

Naturally, the speed of electrification, as the share of electrified houses and vehicles per year, is a crucial element of the analysis. Hence, this study considers three scenarios with varying degrees of the electrification: the business-as-usual, *Fossil Fuel scenario* (henceforth, FF scenario), and the *Full Electrification scenario* (henceforth, FE scenario) where transport and road sector are fully electrified. The intermediate situation, with the two sectors 50% electrified, is considered in the *hybrid scenario* (henceforth, HY scenario). Importantly, policy assumptions on the power market are kept constant in each scenario. In particular, renewable integration paths and lower nuclear share (50% of the total electricity generation) are identical across scenarios.

2.2 Scenario assumptions

We estimate the model (that was originally built for the case of Netherlands) using French data.

The model runs separately for each of the three scenarios. Table 1 summarises the parameters used in each scenario, in particular the assumptions on new houses and cars, and the degree of electrification.

Table 1: Assumptions on the speed of electrification, by scenario

	Scenarios		
	Fossil Fuel	**Hybrid**	**Electrification**
Annual degree of electrification			
Housing			
New	33%	50%	100%
Existing stock (x1000)	0	220	350
Houses connected to district heating (x 1000)	1	1	1
Transport (% of new cars)			
Passenger cars	2%	32%	62%
Vans	0%	15%	40%
Trucks	0%	1%	5%
Buses	0%	5%	40%
Motorbikes and scooters	0%	20%	40%
Bicycles	35%	35%	72%

The electrification trends considered are relatively similar for the residential building and transport sector.

The *FE scenario* corresponds to full electrification of the housing and transport sector.

Each new house built is assumed to be fully electrified, for instance via electric heating or, to a lesser extent, the use of heat pumps. In addition, 350,000 houses, out of the total stock of 28.4 million (principal residency) houses, are electrified every year.[4] This is indeed slightly less than the target of 500,000 major renovations per year that is considered by the French government in order to speed up the energy renovation of housing. The parameters are chosen to yield fully electrified housing in 2050. Similarly, in this scenario, almost the entire fleet in 2050 is composed of electric cars. It is assumed that 62% of the new cars are electrified. This share is 40% for vans but much lower for trucks (5%).

The *HY scenario* assumes parameters to roughly reach half of the parameters considered in FE scenario. In the *FF scenario*, the share of houses electrified is 33% while the percentage of electric vehicles each year are insignificant in 2050 (except for bikes).

[4] On one hand, because only "principal" residencies are considered, this exercise may give a lower bound of the estimates calculated in HY and FE scenarios. On the other hand, it is important to note that given the typical lifetime of heating systems and current market shares, every year roughly 1.5 million existing dwellings will have their heating system changed (see Ademe report, 2017). Among them, 600,000 are already equipped with electrical systems, and will probably replace them with an electrical system. But, among the remaining houses a significant share will not be electrified, because there is already another well-functioning system using gas, fuel oil, LPG, biomass or district heating.

3. Electrification in road transport

3.1 Policy objectives

The transport sector is the largest contributor to greenhouse gas emissions, accounting for 28% of France's total emissions in 2013, with a significant increased share since 1990 but with a relative stabilisation since 2010. It is also accounted for 32.6% of France's total energy consumption in 2014.

The Energy Transition Law does not state precise targets for the transport sector in general, only some specific rules for some subsectors.[5] For example, the French State and its public bodies are required to purchase a minimum of 50% vehicles with low CO_2 and air-polluting emissions, such as electric vehicles. All new buses and coaches purchased for public transport services from 2025 onwards must be low-emission vehicles. Moreover, 10% of vehicles acquired by companies operating taxis or car rental companies should be low-emission vehicles in 2020. Finally, at least seven million charging points should be installed by 2030.

3.2 Data and assumptions

All input data and assumptions are derived from statistics published by the French governmental agency Service de l'observation et des statistiques (SOeS) that provides annual reports regarding the transport sector. The data relates to the existing stock of cars, its yearly growth rate, and shares of electric vehicles of newly registered cars. The data entail statistics for a range of vehicle types: passenger cars, buses, trucks, and motorbikes and scooters. It also covers the annual average number of kilometers driven for each type of vehicle (that will be used to evaluate savings in emissions and gasoline in the case of electrification of the vehicle fleet).

Table 2 below summarises the data on the stock of cars for the starting year of our model, the year 2016. In that year, 32.2 million passenger cars were registered in France, plus 6 million vans (incl. light duty vehicles), and about 600,000 trucks and heavy-duty vehicles. In addition, our model takes account of 100,000 buses and 3.6 million motorbikes. The total of less than 81,000 electric vehicles is small compared to the total fleet. Due to a lack of data on the share of electric vans, trucks, buses and motorbikes, the model starts with zero electrification for these types. For calculating the electricity demand from transport, we also need to account for the kilometers driven and the efficiency of electric vehicles. On average, passenger cars drive around 14,000 km per year, while vans and trucks drive about 16,000 km and 49,000 km, respectively.

[5] The Energy Transition Law (published in August 2015) has mentioned that, for the transport sector, there is a target of 15% of energy demand met by renewable energy sources. However, there is no clear target regarding electric vehicle.

Tabe 2: Input data for road transport

Variable	Value
Number of (x million)	
passenger cars	32.17
vans	6.02
trucks	0.55
buses	0.09
motorbikes and scooters	3.62
bicycles	25
Of which electric (x 1000)	
passenger cars	47.508
vans	2.4
trucks	0.0985
buses	0.4045
motorbikes and scooters	0.7417
bicycles	0.5498
Average distance per year (km)	
passenger cars	11227
vans	25172
trucks	49564
buses	34438
motorbikes and scooters	3031
bicycles	800

The efficiency of new vehicles, including the number of new vehicles a year, are depicted in Table 3 below. While Table 2 reports historical data, Table 3 shows our key assumptions on the transport sector up to 2050. Based on data from recent years, it is assumed that more than 2 million new cars will be sold every year.

Data on the efficiency of electric vehicles and on losses when charging are published by the US Department of Energy.[6] 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/100kms, for trucks 70 kWh/100km, for buses 100kWh/100km, and for motorbikes and scooters 5 kWh/100km.

In this computation, we also take into account electricity losses that occur while charging batteries of about 16%. Finally, to account for cars becoming more fuel efficient, we assume

[6] See www.fueleconomy.gov

their fuel consumption decreases by 1% per year. In a similar vein, we assume that there will be an annual improvement in battery charging efficiency of 0.5%.

Table 3: Assumptions on new vehicles

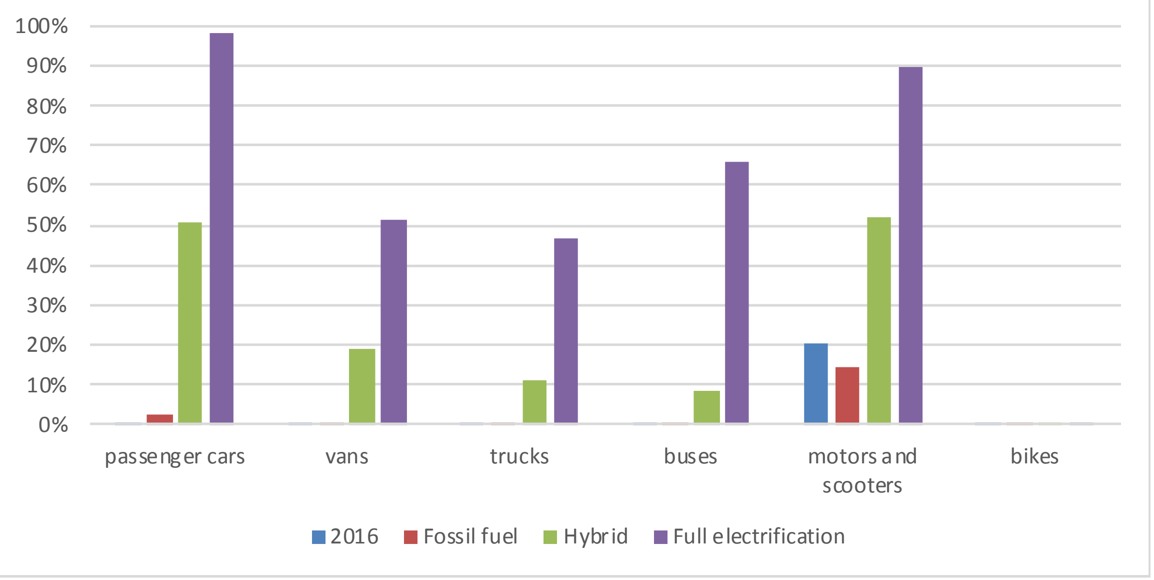
Variable	Value
Passenger cars	
Annual number of new cars (x 1000)	2093
Performance - electric (kWh/100km)	20
Vans	
Annual number of new vans (x 1000)	317
Performance - electric (kWh/100km)	35
Trucks	
Annual number of new trucks (x 1000)	213
Performance - electric (kWh/100km)	70
Buses	
Annual number of new buses (x 1000)	6.30
Performance - electric (kWh/100km)	100
Motorbikes and scooters	
Annual number of new M&S (x 1000)	279
Performance - electric (kWh/100km)	5
All vehicles	
Annual increase in number (%)	1%
Battery charging units	
Annual improvement in charging efficiency	0.5%

These input data in this block are used for projecting the overall share of electrified vehicles for each year until 2050.

3.3 Results

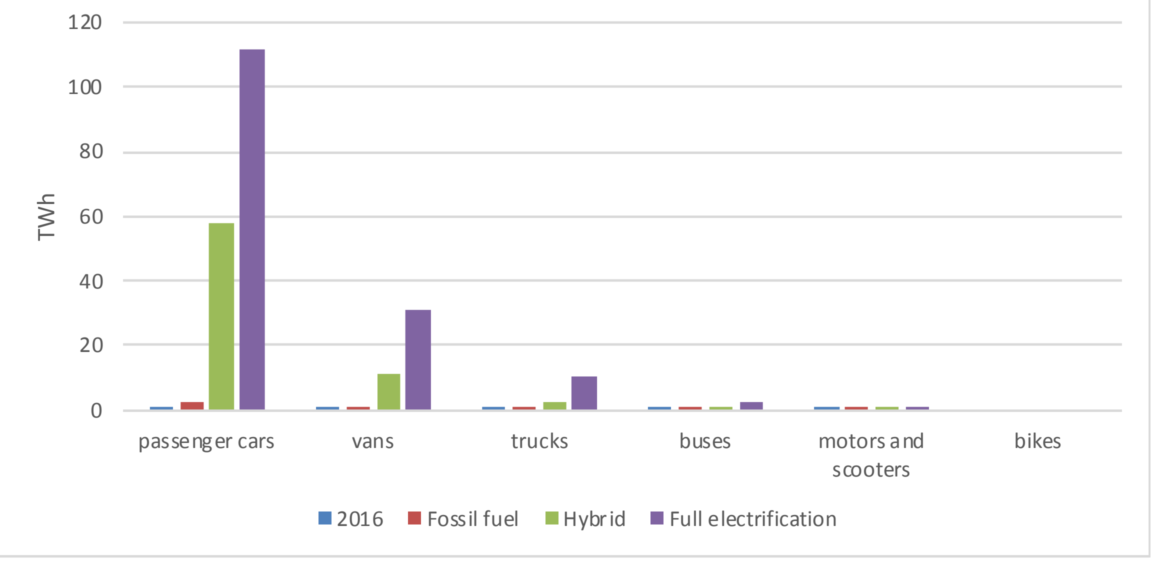
Figure 3 illustrates the shares of electric vehicles in each scenario in 2050. The share of electrification of passenger cars, the most important driver in transport, is constructed to reach almost full electrification on 2050 by design: the amount of passenger cars grows by 1% net, with more than 2 million new cars entering the stock every year. In the FE scenario, all new cars are fully electrified.

Figure 3: Shares of electrified vehicles in 2050



The impact of electrified transport on power demand is shown in Figure 4. Despite high shares of almost all types of electrified vehicles, the power demand generated is more concentrated on passenger cars. This is in line with the mass of kilometers driven by the high stock of passenger cars. The amount of additional electricity of 111 TWh amounts to about 23% of today's total electricity load in France of 482 TWh.

Figure 4: Power demand from electrified transport in 2050



4. Electrification in residential buildings

This section focuses on the additional power demand from electrification of residential buildings.

4.1 Data and assumptions

The approach is similar to section 3 on the electrification of the transport sector. Given the housing sector's characteristics, the net growth rate of the housing stock and assumptions on the share of electrified buildings among new houses, the extra power demand from the electrification of the residential heating sector is estimated.

Insee (2016) reports 28.4 million houses (principal residencies) where 33% of houses are already electrified (or to be precise, 9.51 million houses using electric heating). The average size of a house is 81.3 m^2. Further, in 2015, the total gas consumption equaled 1175 m^3 gas. Only 6% of gas is used for cooking and 1% for hot water. Note that this differentiation between the different gas usage types is relevant for deriving the extra power demand stemming from the different gas applications. These input data on the stock of houses and the corresponding energy usage are summarised in Table 4.

Table 4: Input data on residential buildings

Variable	Value
Number of houses (x million)	28.38
Number of houses electrified (x million)	9.51
Average size of houses in m2	81.3
Average gas consumption per house (m3)	1175
% of gas used for cooking	6%
% of gas used for hot water	12%
CO_2 emissions by households in 1990 (Mton)	57
% houses connected to district heating	4.2%

To determine how the stock develops up to 2050, we rely on historical trends. In the last 30 years, the stock of houses have grown 1% per year. Based on historical data, we assume that each year 390,000 houses will be added. Together with our assumptions on the share of electrification in the different scenarios (see Table 1 above) we then obtain an electrification path up to 2050.

The data on future energy usage (measured in m^3 gas) is set to 1000 m^3. The coefficients of performance for heat pumps are set to 3 and 1 for space heating and warm water, respectively. In addition, we assume an autonomous increase in electricity usage, for instance, from an increased use in electric appliances.

Table 5: Parameters for residential buildings

Variable	Value
Annual increase in number of houses (%)	1.0%
Annual number of new houses (x 1000)	390
Energy use for heating a new house (in m3 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%
Autonomous increase in electricity use	0.5%

4.2 Results

The additional demand for electricity is constructed as the sum of power needed for space heating, water and cooking – both in newly built and renovated fully electrified houses.

Figure 5 illustrates the resulting power demand from electrification of the housing sector under different scenarios.

The flat curve in FF scenario is a direct consequence of our business-as usual assumption, where we assume that the rate of 33% of electrified houses is kept constant and is applied to old and newly built houses. Note also that the rate of 91% (or 62%) electrified houses in 2050 in the FE (or HY) scenario is constructed by design, given the 33% of electrified houses in 2016.

Figure 5: Share of electrified houses by scenario, 2016 to 2050

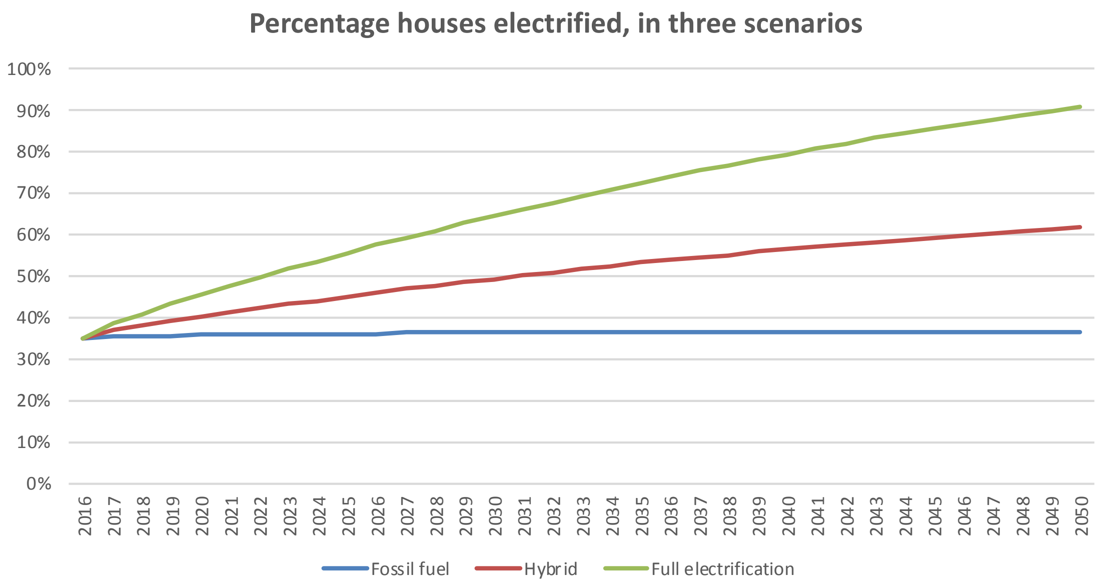
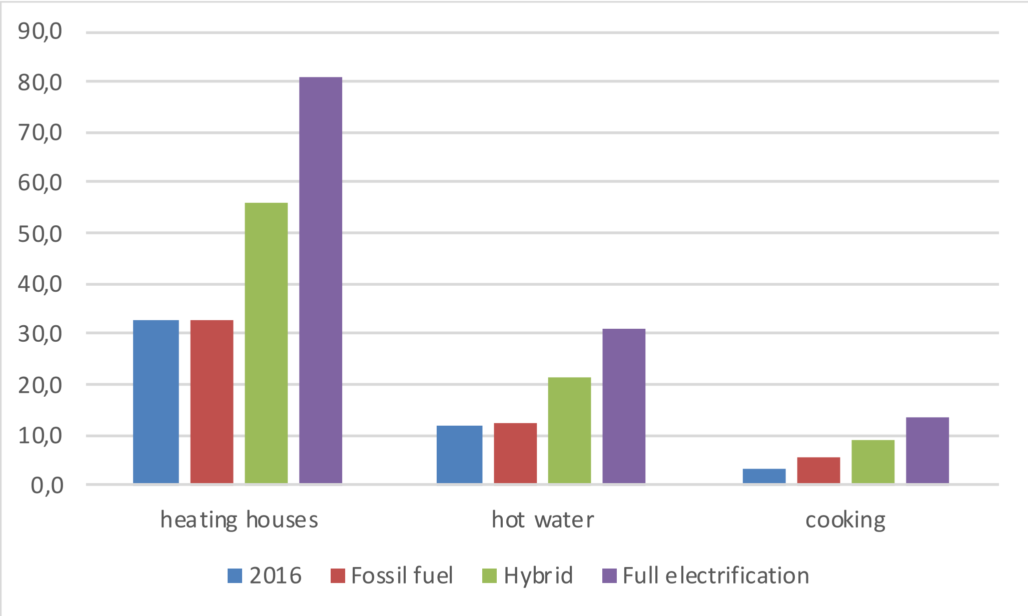


Figure 6 shows the projected electricity consumption by the housing sector in 2050. Most strikingly, under full electrification, the total amount of electricity consumed by the housing sector increases to nearly 90 TWh. This projected increase from electrification represents an increase of 30% relative to today's total electricity demand of French households. The increase is roughly halved in the HY scenario, and insignificant in the business as usual FF scenario.

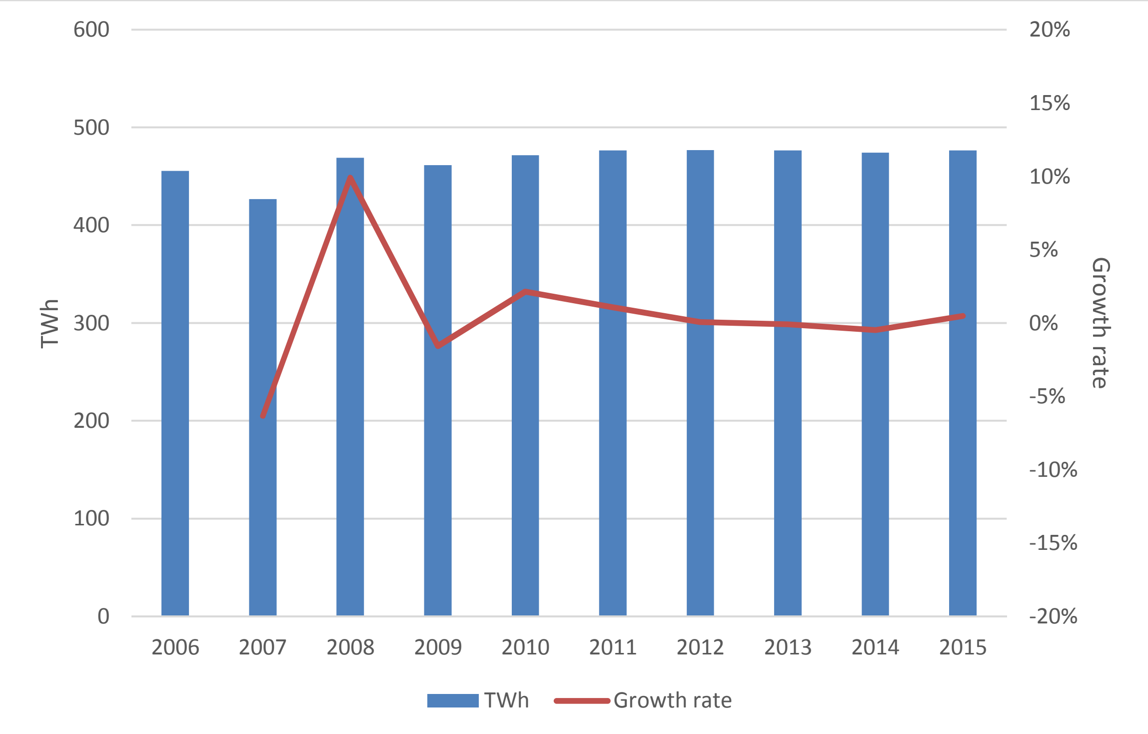
Figure 6: Household electricity demand (Twh) by scenario in 2050



5. Total electricity consumption

The total energy consumption in France has fluctuated over the period 2006-2015 (see Figure 7 below).[7]

Figure 7: Energy consumption and Growth rate



Source: RTE, 2015

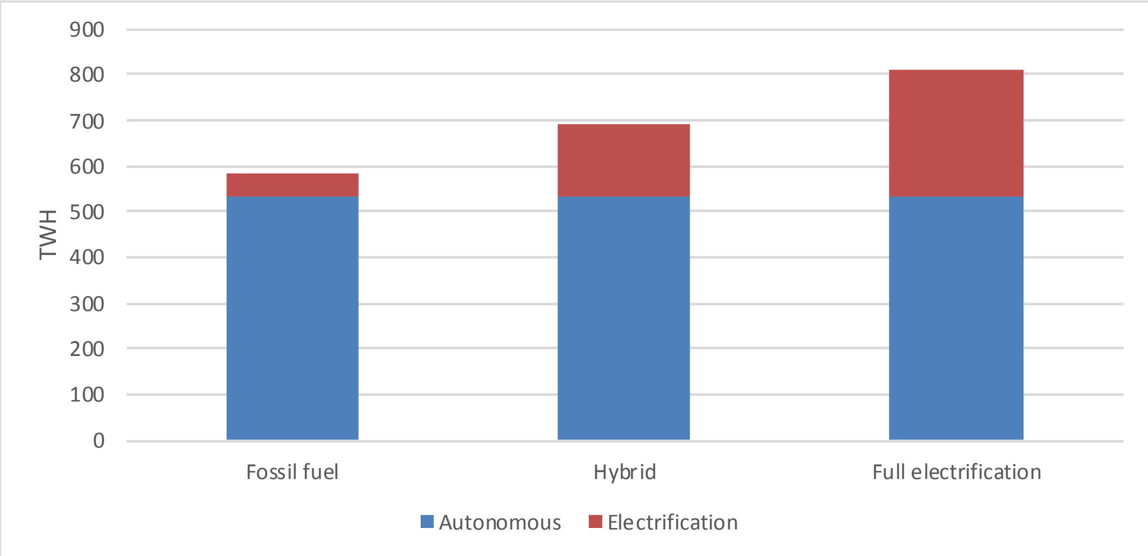
Note that total electricity consumption is not only altered by electrification but also by GDP, energy efficiency, type of electrical appliances, etc. It is therefore challenging to assess the interlink between all these factors. We assume a low, positive growth rate in autonomous electricity usage of 0.5% per year.[8] As such, the impact of electrification is only one factor that leads to an overall rise in consumption. Figure 8 displays the absolute demand levels in 2050 broken down to autonomous growth and the growth due to electrification of housing and transport.

In the FF scenario, the autonomous growth leads to a significant increase in consumption as compared to the 482 TWh in France in 2016. The impact of electrification is negligible in this scenario.

[7] This figure illustrates the aggregate energy consumption adjusted for weather and the 29th day in February, excluding energy withdrawn by the energy sector.
[8] Interestingly, as mentioned in the RTE report (2015), "as the amount of renewable power connected to distribution grids rises, energy withdrawn from the RTE network, adjusted for weather, does not necessarily trend in line with consumption anymore, and has been declining since 2011 (-0.6% between 2014 and 2015)".

In contrast, in the FE scenario, the absolute consumption reaches more than 800 TWh, of which electrification accounts for about 280 TWh. The latter splits up into roughly 110 TWh electric demand from fully electrified passenger cars and about 80 TWh from electrified buildings, plus some additional demand from the transport sector (vans, trucks, buses) and water heating. The part of electricity consumption from housing and transport in the full electrification scenario thus accounts for roughly 30% of consumption in our 2050 projections.

Figure 8: Electricity consumption in 2050, broken down to autonomous growth and electrification



6. Generation of electricity

Given the additional demand from electrifying housing and transportation estimated in section 5 and France's policy objectives regarding energy mix, this section investigates the evolving power supply needed to satisfy this demand.

6.1 Policy objectives

The policy objectives are laid out in the Energy Transition for Green Growth Act, adopted in August 2015. The main objectives can be summarised as follows:

- 40% less greenhouse gas emissions in 2030 compared to 1990;
- 30% less fossil fuel consumption in 2030, compared to 2012;
- increased share of renewable energies to 32% of final energy consumption by 2030 and to 40% of electricity production;
- reduction of final energy consumption by 50% in 2050 (compared to 2012);
- diversified electricity production and reduction of the share of nuclear energy to 50% (but as mentioned already in the introduction, no deadline has been specified). Operating licenses will no longer be granted for nuclear power plants that would raise total authorised capacity above 63.2 GW (the current nuclear electricity generation capacity).[9]

The French government has a target of one ton of carbon valued at €56 in 2020 and €100 in 2030, for the carbon component of the domestic tax on the consumption of energy products (*Taxe Intérieure de Consommation sur les Produits Energétiques* – TICPE).

Finally, the objectives related to the development of renewable energies are published in France's multiannual program of energy (PPP, 2016). The installed on- and off-shore wind capacity is predicted to be 15500 MW by 31 December 2018 and 29,000 MW by 31 December 2023. Taking into account this trend, we assume an investment of 2700 MW per year in our estimations. Similarly, the solar energy capacity is predicted to be 10.2 GW by the end of 2018 and 20.2 GW by 2023, which implies 2000 MW solar investment per year. Finally note that we consider a constant renewable energies' investment trend after 2023, even though this is not explicitly stated in the Energy Transition for Green Growth Act. This implies an increased wind investment of 72,900 MW between 2023 and 2050, with a total capacity of 101,900 MW in 2050. The solar energy capacity is assumed to increase by 46,440 MW between 2023 and 2050, leading to a total capacity of 66,640 MW in 2050.

[9] There is also a €50 billion program (the "*Carenage program*") to upgrade almost the entire fleet of EDF's 900 MW class reactors that will reach their 40-year-lifespan before 2025. The French government should decide, at the end of 2018, whether the reactors' age limit can be increased.

6.2 Data and assumptions

The generation technology mix used to supply future demand depends significantly on national policy, and the way it steers investment in different technologies.

We assume that in the short run, demand will be covered according to marginal cost, i.e. we use a merit order approach to determine the supply mix year by year. However, market entry and exit across years is instead determined exogenously according to policy decisions. [10] Table 5 gives an overview on the modelling assumptions.[11]

Table 6: Modelling choices for market exit and entry of different generation technologies

Variable	Assumption	Background		
coal-fired plants	-20%	phasing out in	2021	
other fossil fuel plants	-4%	phasing out in	2040	
nuclear plants	-2%	phasing out in	NO	
hydro plants	0%	remains constant		
wind (annual increase in TWh)	8.1	policy target in 2030 is	29000	MW
wind in period after policy target (increase in TWh)	7.1	annual investments after 2030	2700	MW
solar (annual increase in TWh)	2.0	policy target in 2030 is	20200	MW
solar in period after policy target (annual increase in TWh)	1.8	annual investments after 2030	2000	MW
biomass	2%	gradual increase based on past		
other	1%	gradual increase based on past		
net import (if negative, this refers to export)	0%	increase in cross-border capacity		

The projection of yearly generation mix (until 2050) is relative to the year 2016, with Table 7 summarizing the generation mix for this year. Note that, as opposed to the other country's cases, nuclear is not assumed to be phased-out. Instead, it is assumed that the yearly nuclear power is always 50% of the total 2016's electricity generation. This allows us to take into account the current target for nuclear power, that is the reduction of the share of nuclear energy to 50% current load. Note that, because electrification will lead to an increase of electricity consumption, the share of nuclear power will eventually be less than 50% in 2050.

[10] France has set an objective of 75% reduction in its carbon dioxide emissions by 2050 in the framework of the Environment Round Table (Grenelle).
[11] Further modelling details are discussed in Moraga and Mulder (2018).

Table 7: Generation mix in 2016

Variable	Value (TWh)
gas-fired plants	22
coal-fired plants	9
other fossil fuel plants	1
nuclear	403
hydro	64
wind	19
solar	4
biomass	1
other	1
net import	-42
total load	482

6.3 Results

Results for the supply mix are illustrated in Figure 9. Such results, of course, are strongly driven by the assumptions mentioned earlier (in particular Section 6.2).

Figure 9: Generation per scenario, 2016 to 2050

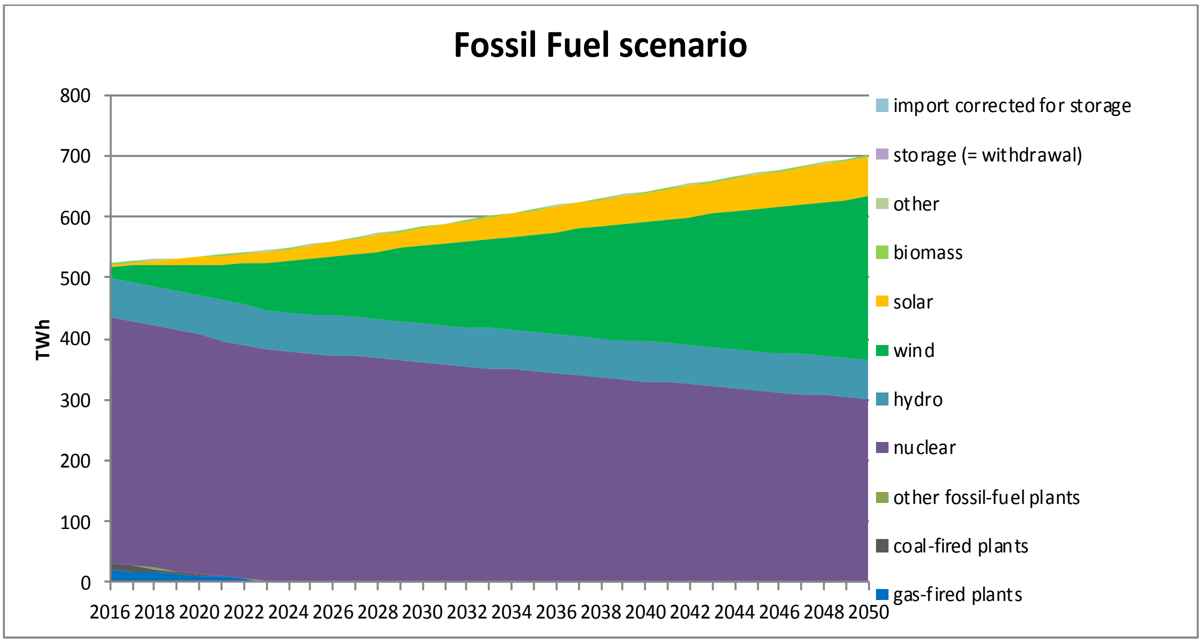
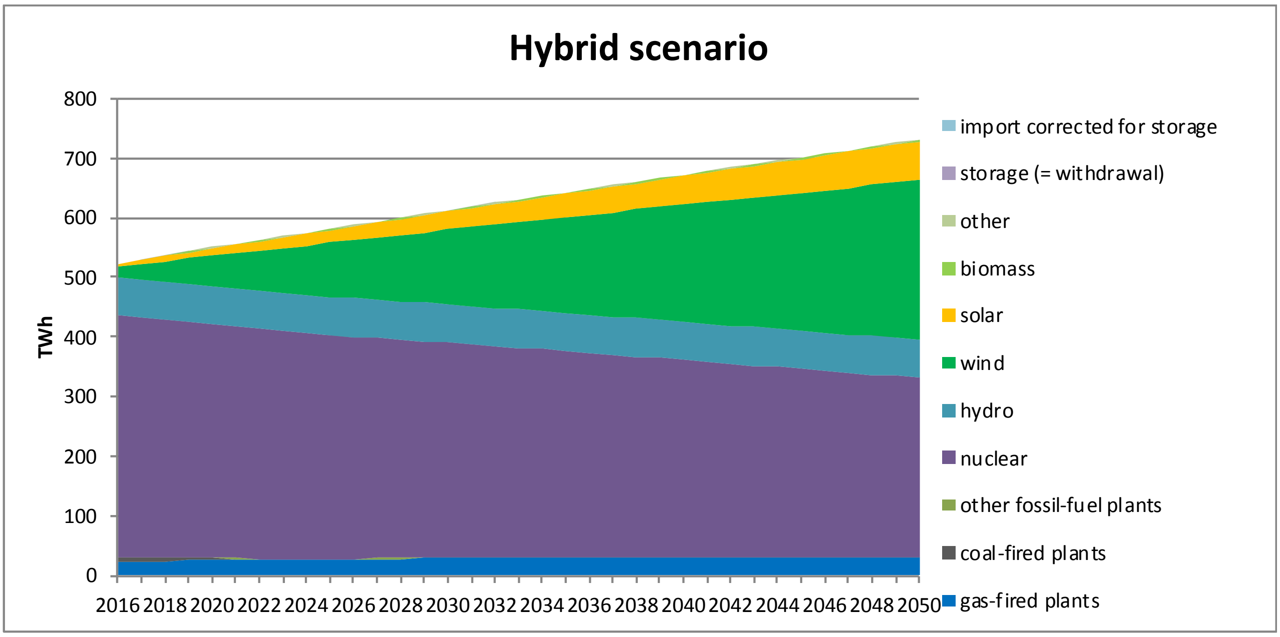
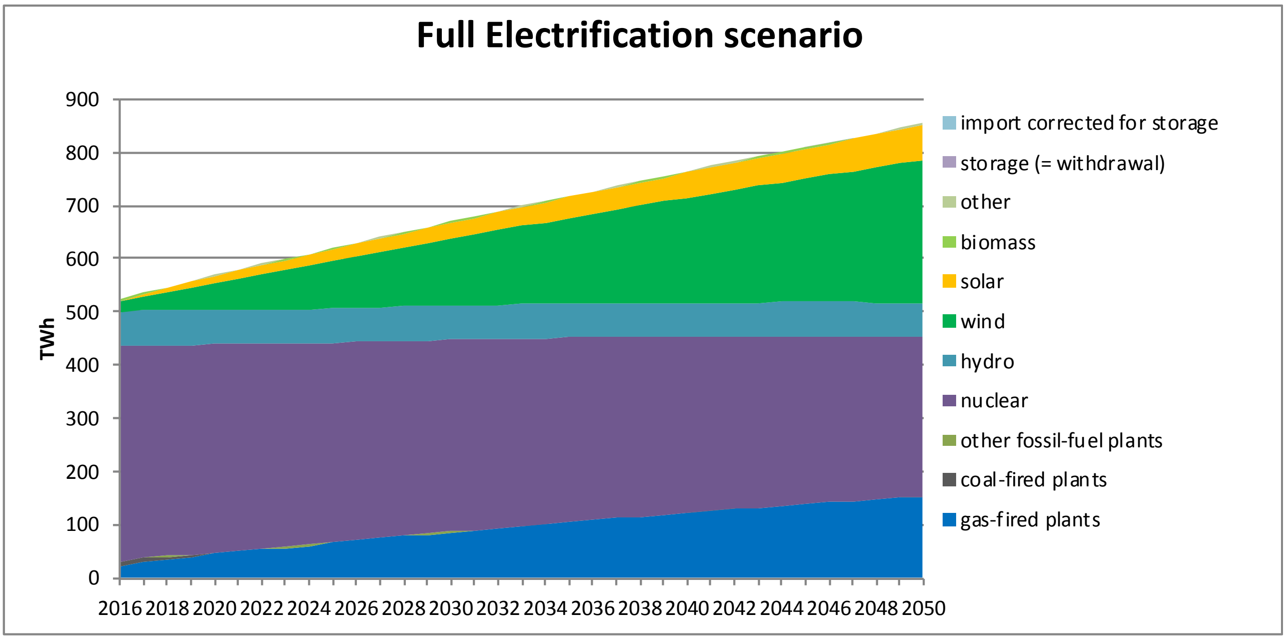


Figure 9 (cont.): Generation per scenario, 2016 to 2050





The share of gas-fired plants' generation is the adjustment variable across the scenarios, where a higher level of electrification automatically translates into a higher natural gas share.

The share of renewable generation across the three electrification scenarios is, by assumption, constant. In all scenarios, the current target of 50% of 2016's electricity generation coming from nuclear is also taken into account. Note however that after 2035, the share of nuclear decreases as the generation of electricity increases in FE scenario, reaching 25% of 2050's level of production. This last result depends on the policy goals regarding the future of nuclear in France.

7. Demand and Supply of Flexibility

The generation mix estimated in section 6 is based on average capacity factors for wind and solar. This approach is relevant for a full-year analysis but does not take into account the volatility of the generation by renewable sources. To do this, this section analyses how extreme weather and load conditions impact the flexibility of the system.

7.1 Data and assumptions

Notion of Best and Worst day

The model characterises representative "best" and "worst" days. A day among the best days may be, for instance, a summer day with low demand but high PV and wind output. In contrast, a day among the worst, may be a winter day with high demand but low renewable output. As in the Netherlands case study, the analysis below considers data on daily averages of load, temperature, wind, and solar generation and classifies days into best and worst days. Specifically, temperature, wind and solar generation are ranked from lowest (worst) to highest (best), whereas load is ranked from highest (worst) to lowest (best). Worst and best cases are then the 5th and the 95th percentiles within each distribution.

This results in a hypothetical worst day being characterised by PV output of less than 35% of what is generated on an average day, wind output of less than 20%, demand above 132% of the average day, and a low temperature, measured in heating degrees, of higher than 234% of the average day. A day among the best days is characterised by PV output of more than 188% of the daily average, wind output of more than 164% of the daily average, load below 78%, and heating degree of 10% of the daily average. Note that the analysis excludes a range of flexibility sources such as pooling effects of cross-border trade or demand response.

Data on wind, load, temperature at the local level

The temperature data for France are from the European Climate Assessment and Dataset (ECAD). In total ECAD has made available daily observations of mean, minimum and maximum temperatures for 44 French stations, somewhat evenly spread out over the country. Wind and sunshine data are from Météo-France. Due to time and cost restrictions, this data is restricted to two weather stations (Nantes-Bougenais and Millau) and for a slightly shorter period (01/01/2007-31/06/2014) than the other data.[12] Finally, the half-hourly load data is accessed from RTE's website and that data is used to create daily means.

[12] The locations of the two weather stations were chosen to be representative of the French mean weather conditions. The stations Nantes-Bougenais and Millau are placed in what until 2015 were the regions of Pays-de-la-Loire and Languedoc-Roussillon respectively. According to the Windustry document from 2014, these respective regions were in the middle of the arithmetic mean of regions in terms of wind power generation. The mean altitude of our two stations (369 meters) is also close to the national mean of 375 meters. The population density around the weather stations is around 100 people/km^2 while the average population density for France is 130 people/km^2.

Seasonal storage

The volatility of the generation by renewable sources can be managed in different ways: change in electricity export level, seasonal storage and gas-fired power plants. The potential of seasonal storage is calculated by assuming that oversupply during Best days is converted into hydrogen, stored and used on Worst days (see Table 8 for efficiency). The gas-fired power plants are considered here as the last resort technology (i.e. only dispatched if additional supply from hydrogen is still insufficient to satisfy demand).

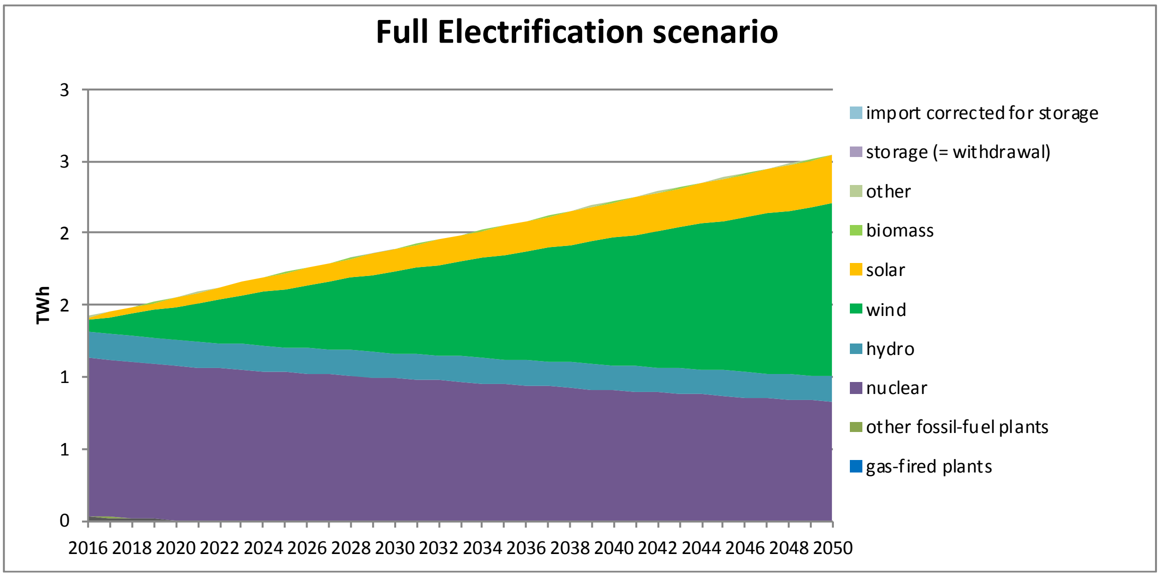
Table 8: Assumptions on efficiency of Power-to-Gas, seasonal storage

Variable	Value (%)
Efficiency electrolyser	75%
Efficiency power plants	42%
Resulting efficiency PtG	31%

7.2 Results

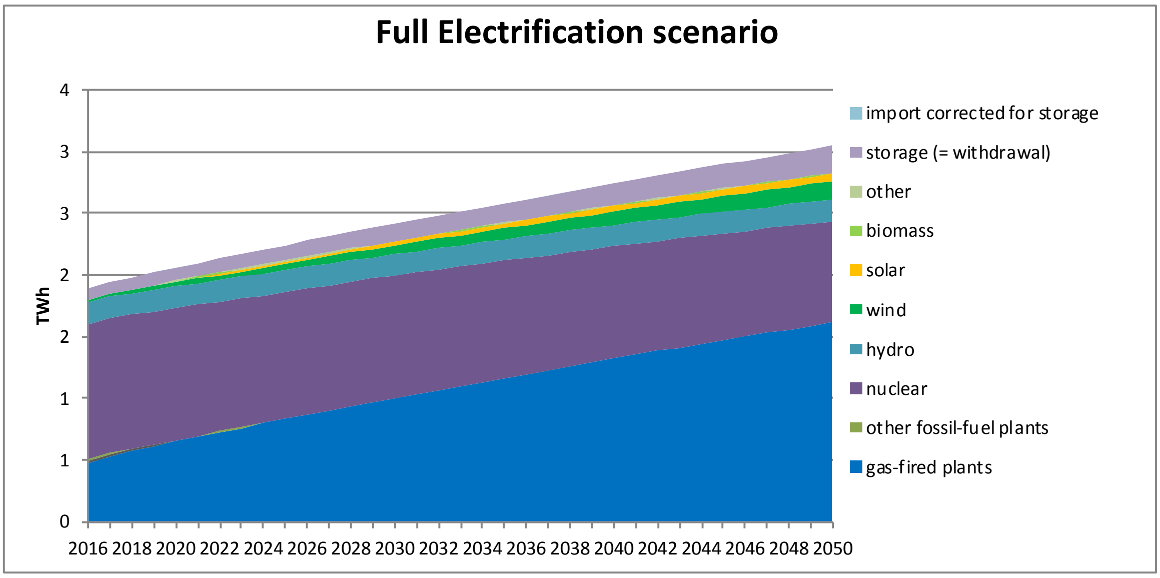
During a 5% best day with extreme levels of solar PV, wind, high temperatures and resulting low heating demand, as well as low load levels, demand can be fully met by nuclear, hydro and renewables, even in the full electrified scenario, as illustrated in Figure 10a.

Figure 10a: Power supply on a hypothetical best day under full electrification



The picture is very different on a winter day with extremely low levels of renewable generation, low temperature, and extremely high demand. In this case, the major back-up technology will be gas-fired (see in Figure 11b). Note that generation on the y-axis is scaled as TWh by day. Further note that because other flexibility sources are excluded, the shares of gas-fired generation can only be interpreted as upper bound and will be lower if trade and demand response would be included.

Figure 10b: Power supply on a hypothetical worst day under full electrification



Let's now turn to the supply flexibility and the use of seasonable storage. The capacity needed to store electricity increases over time, reaching a capacity of about 50 GW in 2050 in FF scenario and 25 GW in FE scenario (Figures 11a and 11b, respectively).[13]

[13] The difference in size between injection and withdrawal is due to energy losses during electrolysis, storage and electricity generation (see above parameters)

Figure 11a: Use of seasonal storage (Power-to-Gas), in terms of maximum capacity needed, FE scenario

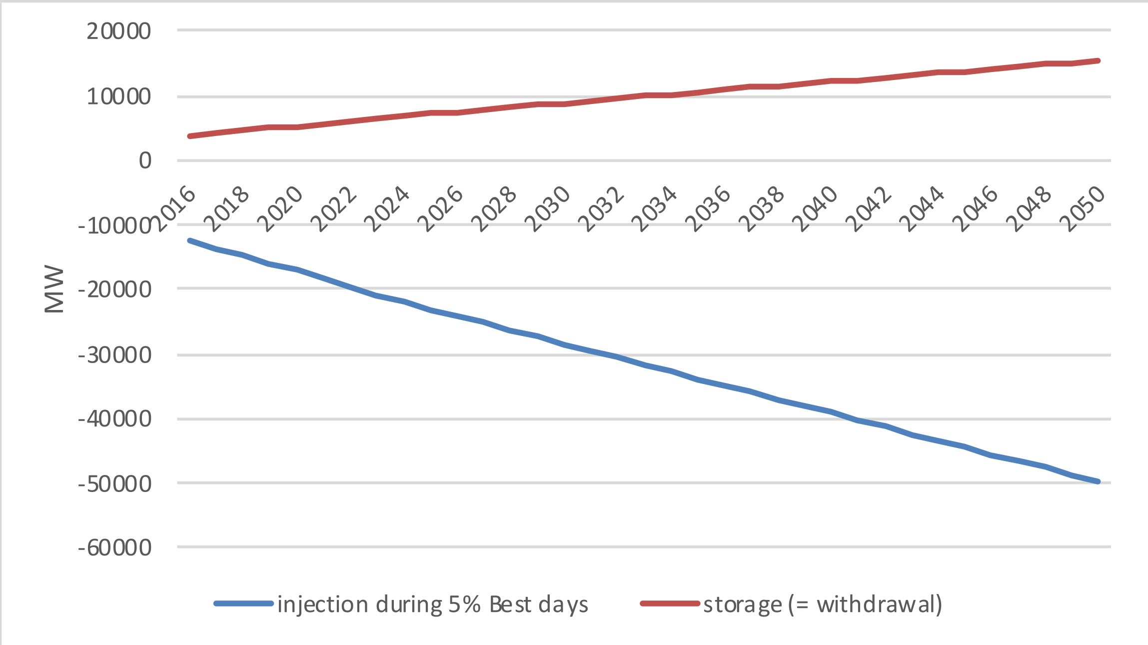
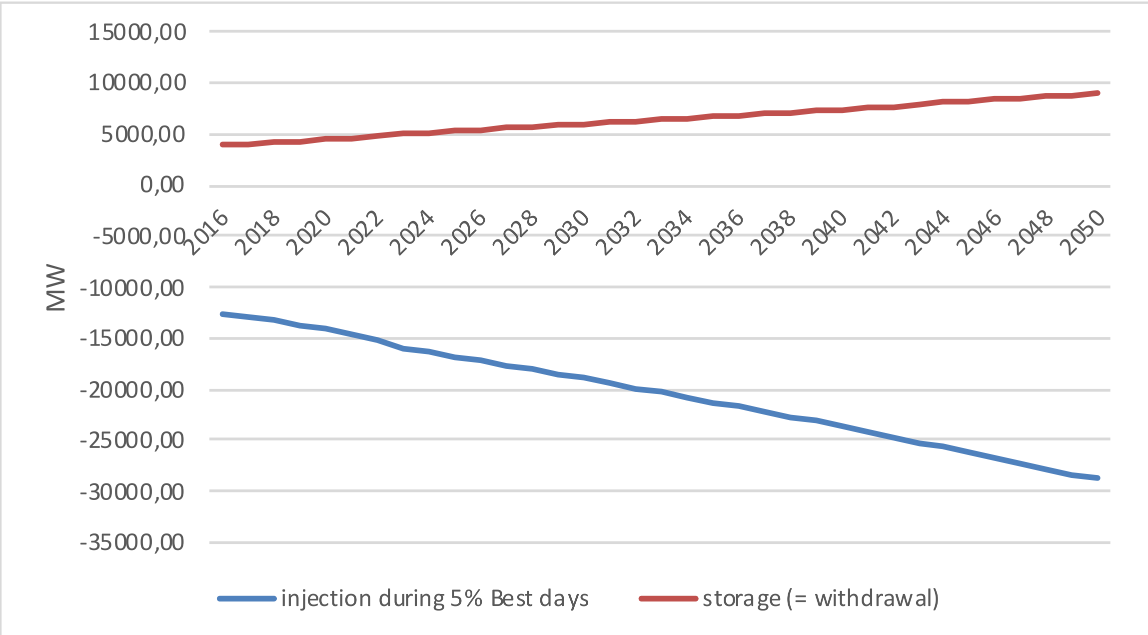
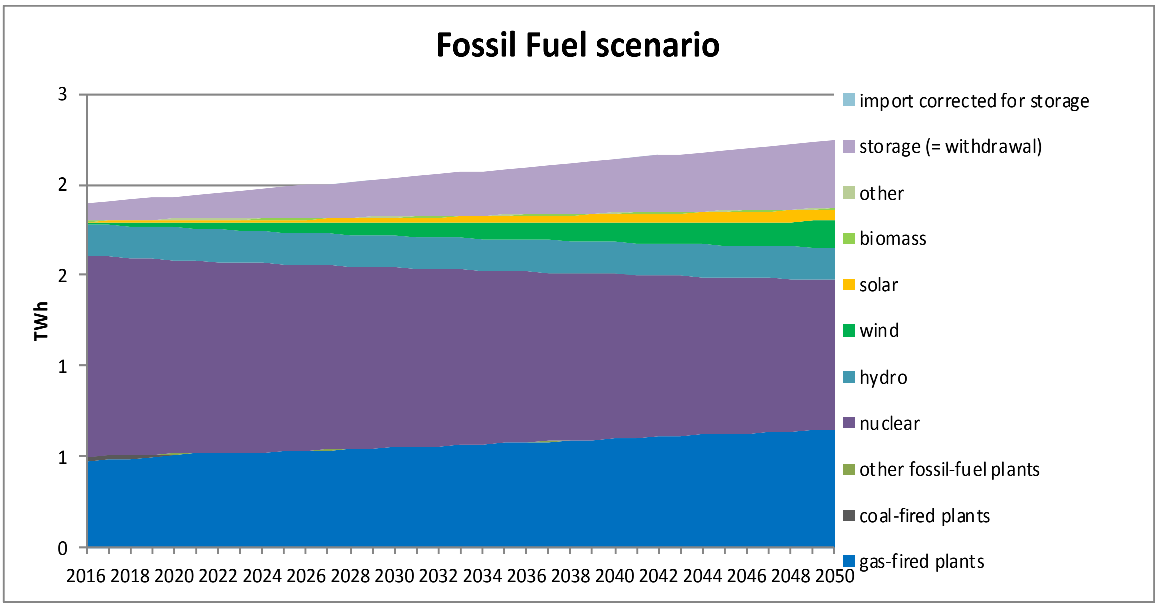


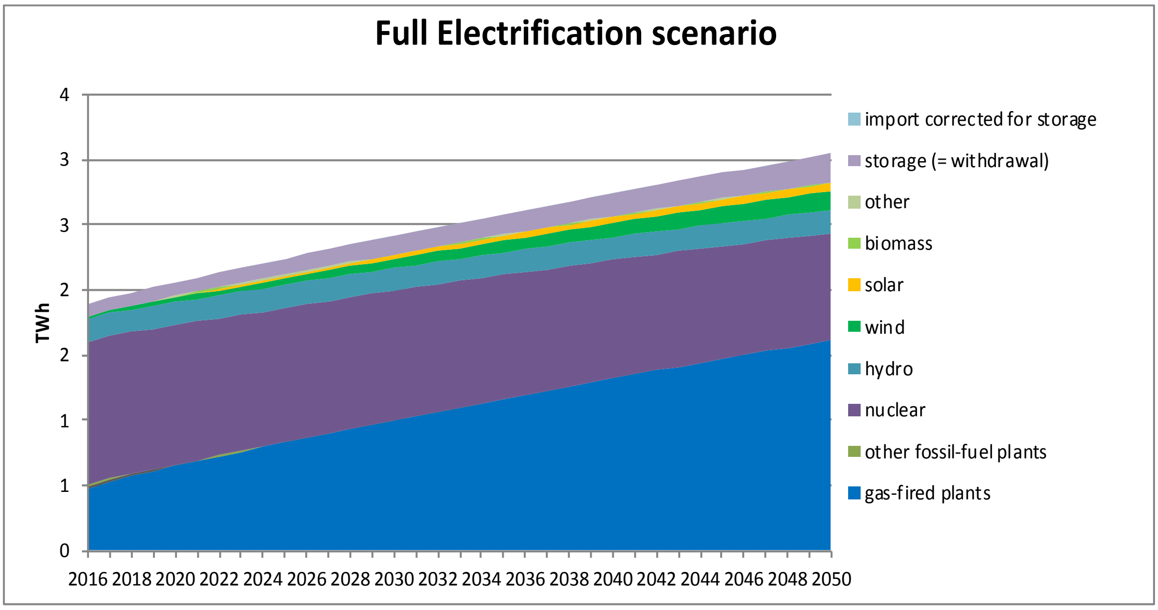
Figure 11b: Use of seasonal storage (Power-to-Gas), in terms of maximum capacity needed, FE scenario



We now consider the Worst days, where the Power-to-Gas can be used as a source of flexibility. As evident in Figure 12, storage plays a role but much more in the business-as-usual FE scenario than the FF scenario. Nevertheless, despite the use of seasonal storage in both scenarios gas-fired generation is still the major source of flexibility.

Figure 12: Supply of electricity on a 5% Worst in FF and FE scenarios



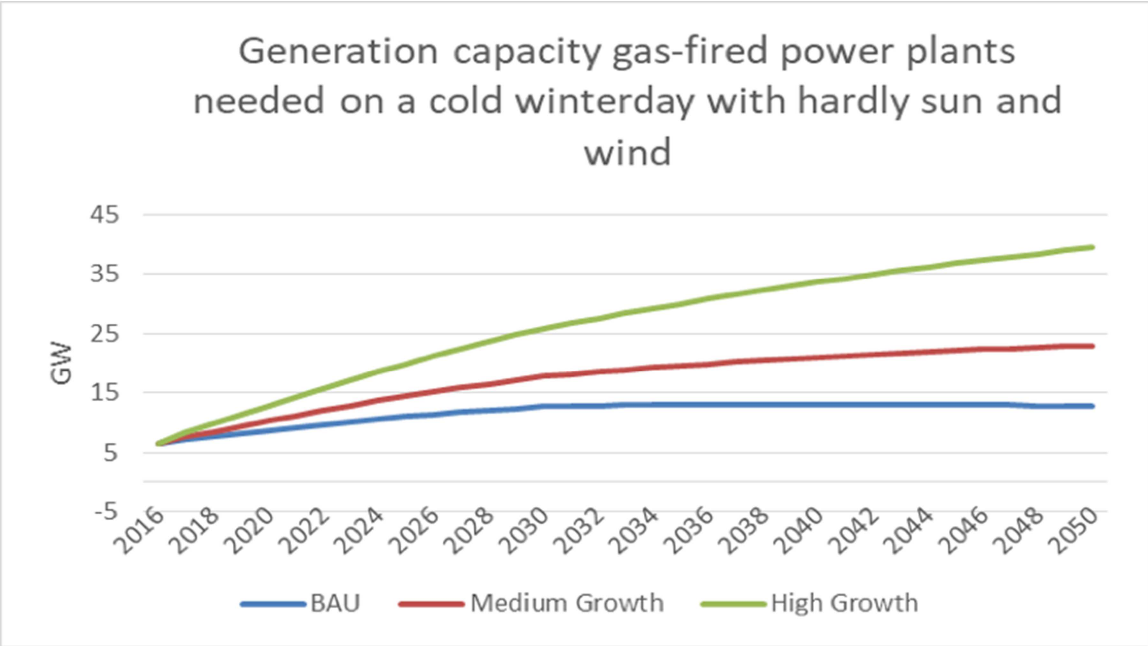


Finally, in all scenarios, the capacity of gas-fired plants needed to keep the electricity system in balance is increasing until 2050 (see Figure 13).[14] In FF scenario, the required capacity increases slightly till 2050 than the current 20 GW capacity. In FE scenario, 67 GW of gas-fired plants should be available in 2050. Hence, to secure supply on high-demand days with almost no wind

[14] The required generation capacity is calculated as the required generation (in MWh) by gas-fired plants on an average Worst day (see Figure 11.b) divided by 24 (i.e. the daily number of hours).

or solar power supply, would require significant investments (i.e. a multiple of more than three times the current generation capacity).

Figure 13: Extra gas generation capacity needed on an average 5% Worst day (taking into account PtG)



8. Consumption of natural gas

This section discusses the impact of the transport and heating sectors' electrification on natural gas consumption. The net impact is obtained from, on the one hand, the reduction of gas usage in residential buildings as electrification of houses increases (see Figure 3), and, on the other hand, the increase of gas consumption in the power sector (see Figure 9).

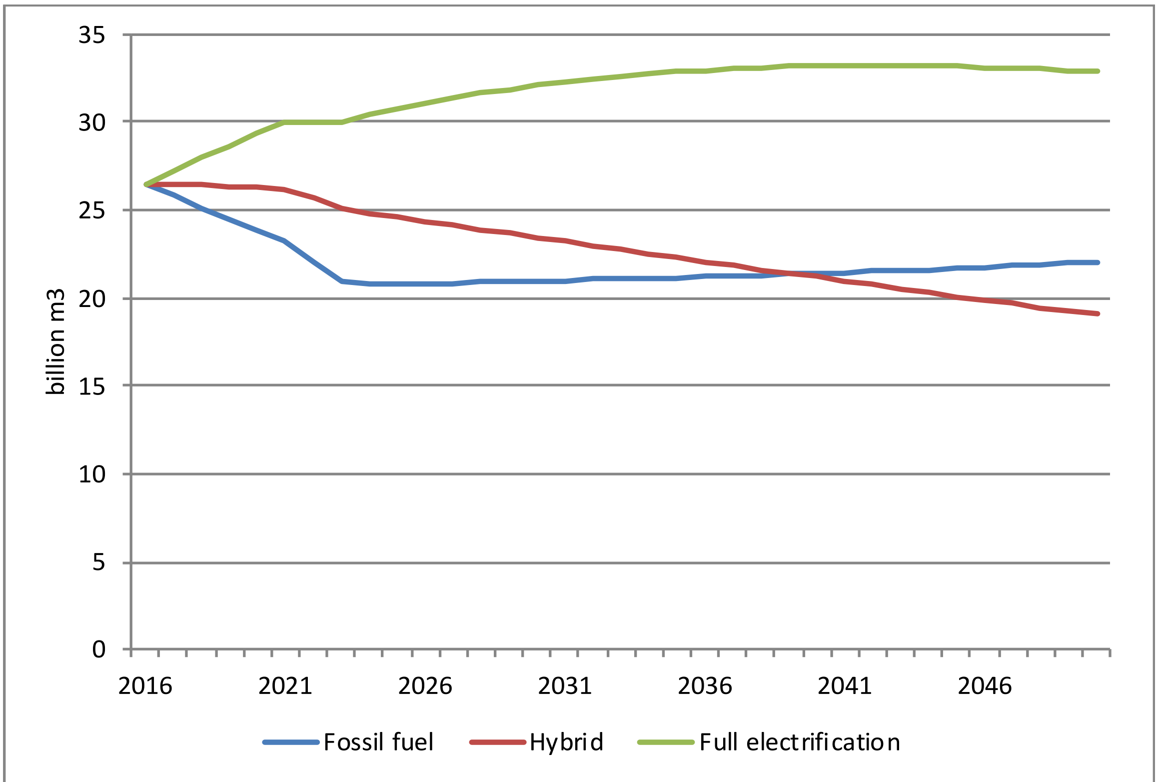
8.1 Data and assumptions

For calculating the gas consumption of gas-fired power plants we assume an efficiency of gas-fired power plants of 40%, and an annual increase in efficiency of 1%. The assumptions made to calculate the remaining gas consumption in residential buildings have been discussed above, see also Tables 4 and 5.

8.2 Results

The net impact on gas demand differs across scenarios, as illustrated in Figure 14.

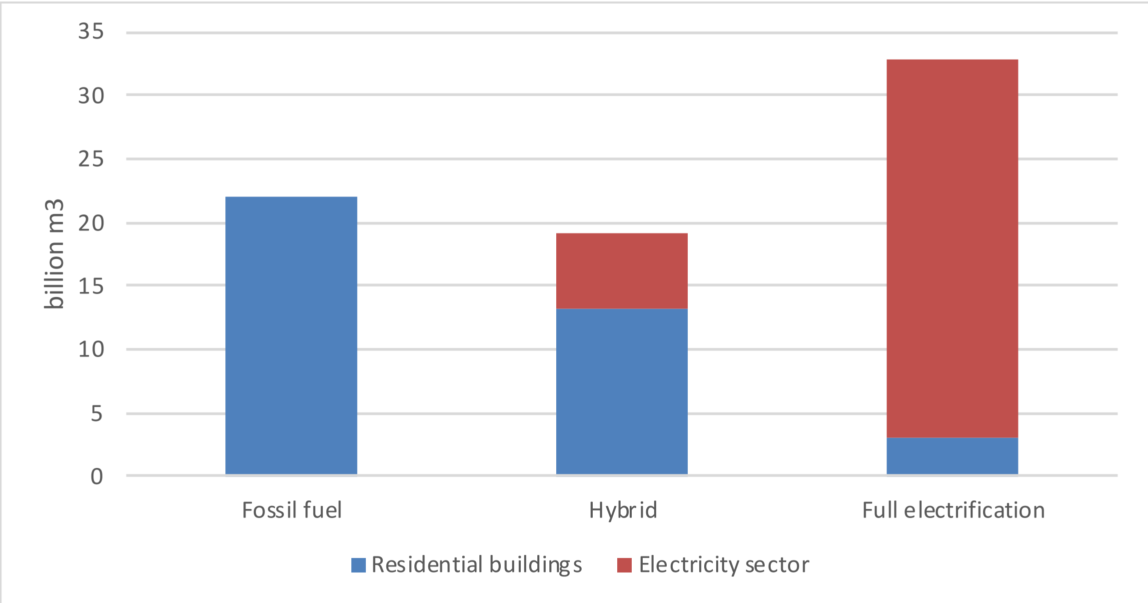
Figure 14: Gas demand from residential buildings and power, 2016-2050, by scenario



In FF and HY scenarios, gas consumption from the housing sector decreases gradually as the houses are electrified. Such a decrease is not fully compensated by the increase in gas demand from the power sector, leading to an overall decrease of aggregate gas consumption. In the FE scenario, because of the full electrification of housing and transport sectors, the gas demand increases constantly until 2050.

Figure 15 illustrates how gas demand is shifted from the residential sector to the power market. In particular, while in the FF scenario in 2050 gas demand stems from the housing sector, in the FE scenario gas demand shifts to the power market.

Figure 15: Gas demand in 2050, by origin



Later in Section 10 where we calculate the emissions associated to the housing, transport and electricity sectors, we take into account that part of the gas consumed by households and gas-fored power plants is biogas. In particular, the volume of biogas in the gas system is 0.08 bcm in 2016 and we assume that this volume increases yearly by 2%.

9. Electricity and gas distribution networks

Both electricity and gas provision rely on the use of distribution and transmission networks. Thus, network capacity has be to large enough to accommodate an increase in power generation or gas consumption. Below, we highlight the changes in load that the power grid, and the changes in gas demand that the gas network, have to accommodate.

9.1 Data and assumptions

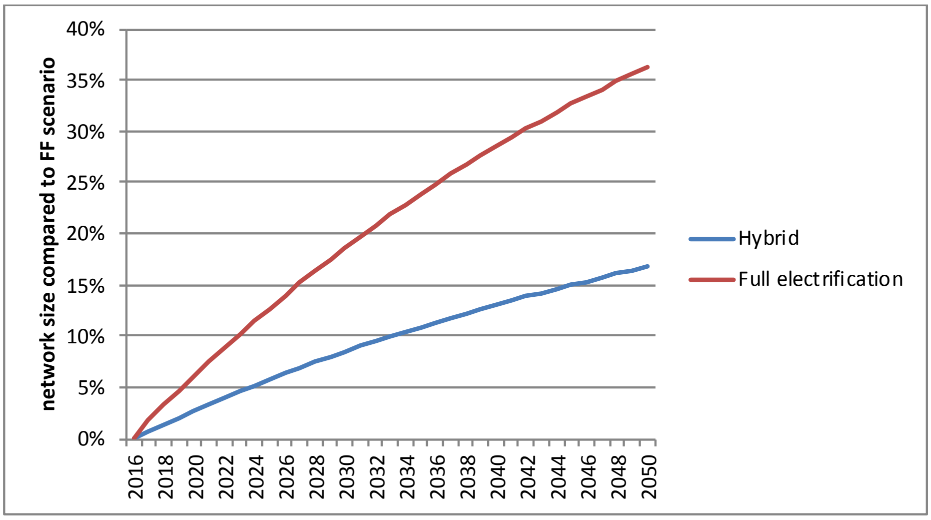
The gas demand increase is calculated using the 5% worst days defined above, because network capacity is usually constructed according to maximum demand instances. Thus, these conditions represent a high demand case (i.e. demand for electricity is above the 95th percentile). The implicit assumption is that distributions networks' capacities are sufficient for "average" volumes of load and gas.

9.2 Results

Figures 16a and 16b illustrate how the peak demand that the power and gas network have to transport changes in percent as compared to today.

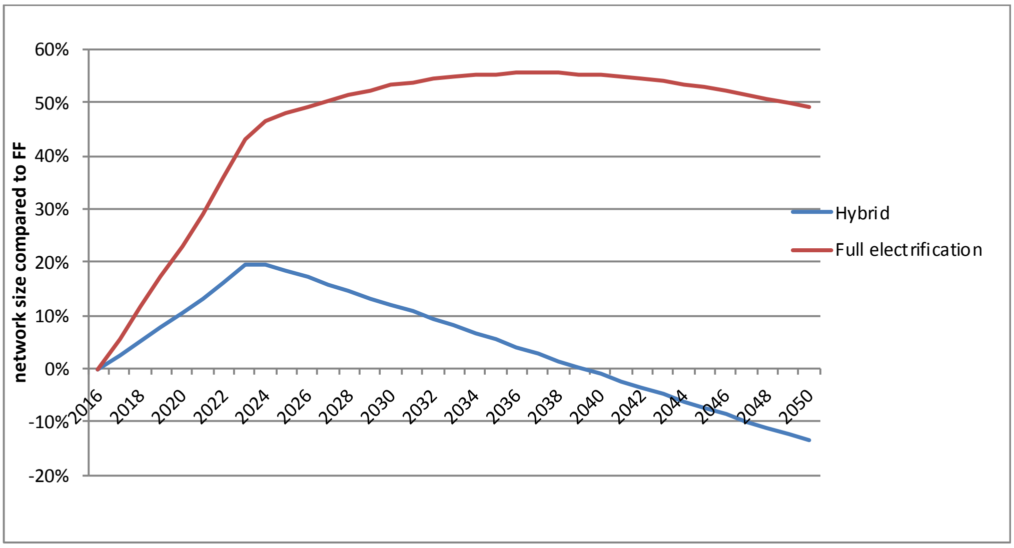
The electricity grid capacity has to greatly increase to ensure full electrification of the transport and residential sectors, even compared to what happended in the HY scenario (see Figure 16a). The gas network capacity also needs to be extended in the case of full electrification, by more than 40% (see Figure 16b).[15]

Figure 16a: Increase in electricity network usage, as compared to FF



[15] Note that the model does not take network topology into account. That is, as gas demand shifts to gas-fired plants, network requirements may change locally, with more capacity needed to deliver spots of gas-fired generation, and less capacity for vast residential areas.

Figure 16b: Size of gas grid compared to the FF scenario (in %), 2016-2050



10. Carbon Emissions

This section discusses the effect of electrification (and in particular, of the increased power demand) on carbon emissions.

10.1 Assumptions

Table 9 summarises the French data on emissions from transport and buildings in 1990. The transport sector emitted around 120 million tons in 1990, of which 51% was from passenger cars, 15% from vans and 28% from trucks.

Table 9: Emissions by sector in 1990, in million tons of CO2 equivalent

Variable	Value
CO_2 emissions in 1990 (x Mton)	
residential buildings	57
road transport	
- passenger cars	66.1
- vans	18.5
- trucks	33.9
- buses	0.0
- motors	0.6
electricity sector	45

Table 10 then illustrates assumptions that are used to translate the switch from fossil fuels to electrified cars and the corresponding impact on emissions.

Table 10: Assumptions on fuel efficiency and carbon intensity of vehicles

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
Motorbikes	5	0.0024

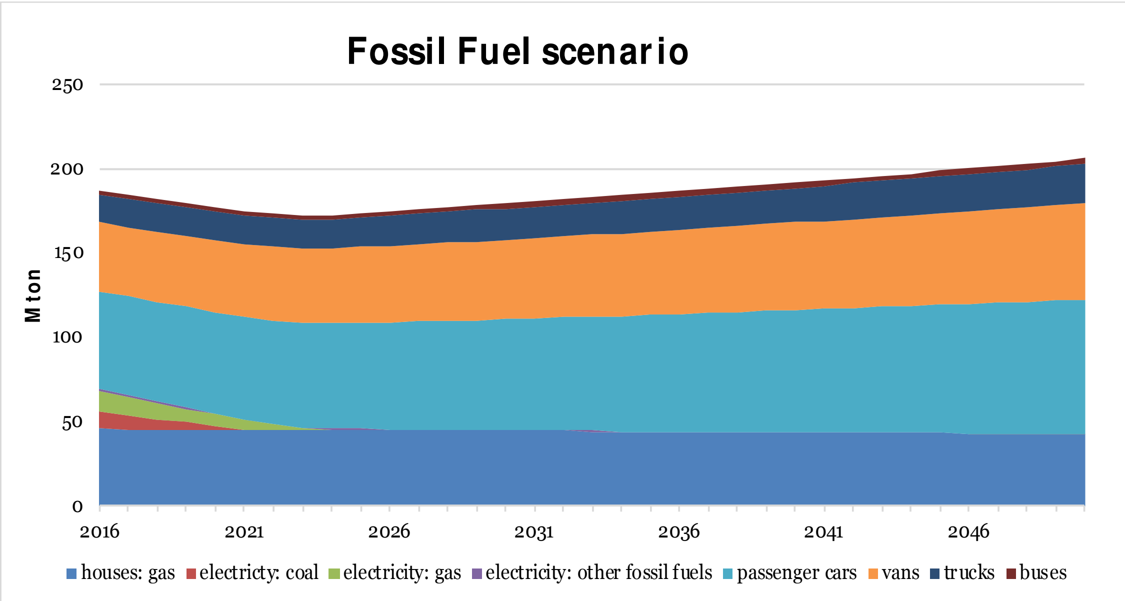
The calculation for carbon emissions for each scenario proceeds as follows. We determine the consumption of fossil energy per sector and multiply this consumption with the carbon intensity per unit of fossil energy, i.e. natural gas in electricity and heating, and oil in heating and transport. For the 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 10 above gives the assumptions made regarding these factors.[16]

To obtain emissions from gas consumption by (non-electrified) residential households, the model multiplies the total gas consumption in residential buildings in m^3 by the CO_2 content per m^3. The CO_2 emissions per m^3 of natural gas are taken to be 2.2 kg. Last, for the electricity sector, the analysis considers the sum of CO_2 emissions stemming from the fossil fuelled power plants. For coal-fired plants, CO_2 emissions per ton of coal equal to 3.66 tons are assumed. For gas-fired plants, the model applies 0.4 tons of CO_2/MWh.

10.2 Results

In the FF scenario, there is no large-scale electrification of the two sectors. So the increased emissions come only from the old and new vehicles fleet, while the emissions from the residential sector stay constant (see Figure 17a).

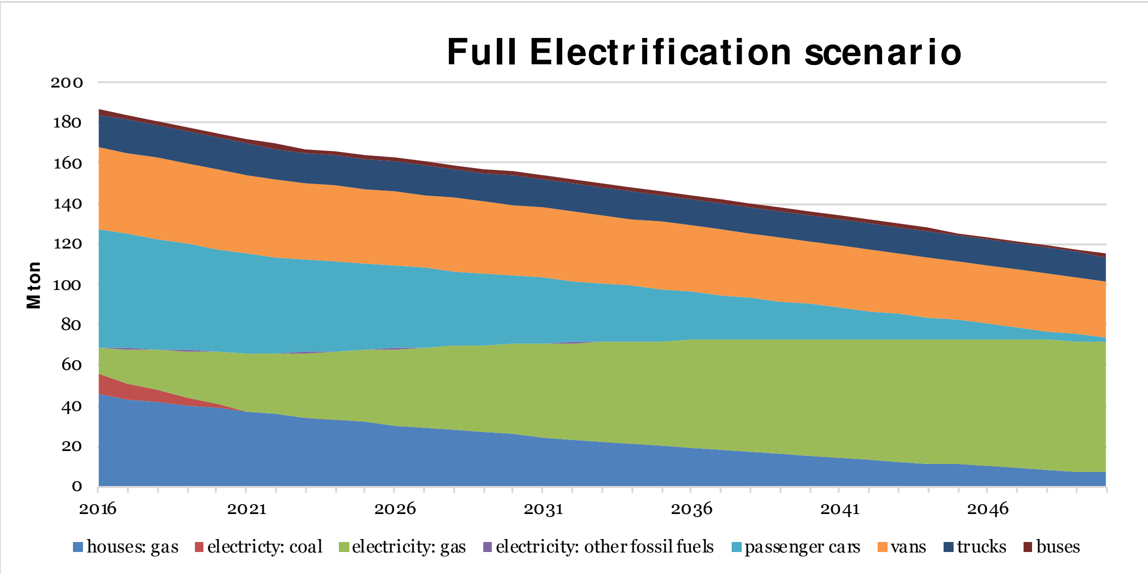
Figure 17a: CO_2 emissions over time, fossil fuel scenario



The picture is very different in the FE scenario, with the carbon emissions constantly decreasing between 2016 and 2050 (see Figure 17b). The reduced emission levels are due to the switch from energy usage from fossil fuel intensive traditional heating and transport, to the 'renewable' power market. Indeed, in 2050, the carbon emissions left come only from gas-fired generation. As illustrated in the Appendix, the electrification of residential buildings and transport leads to zero carbon emissions at the end of the period.

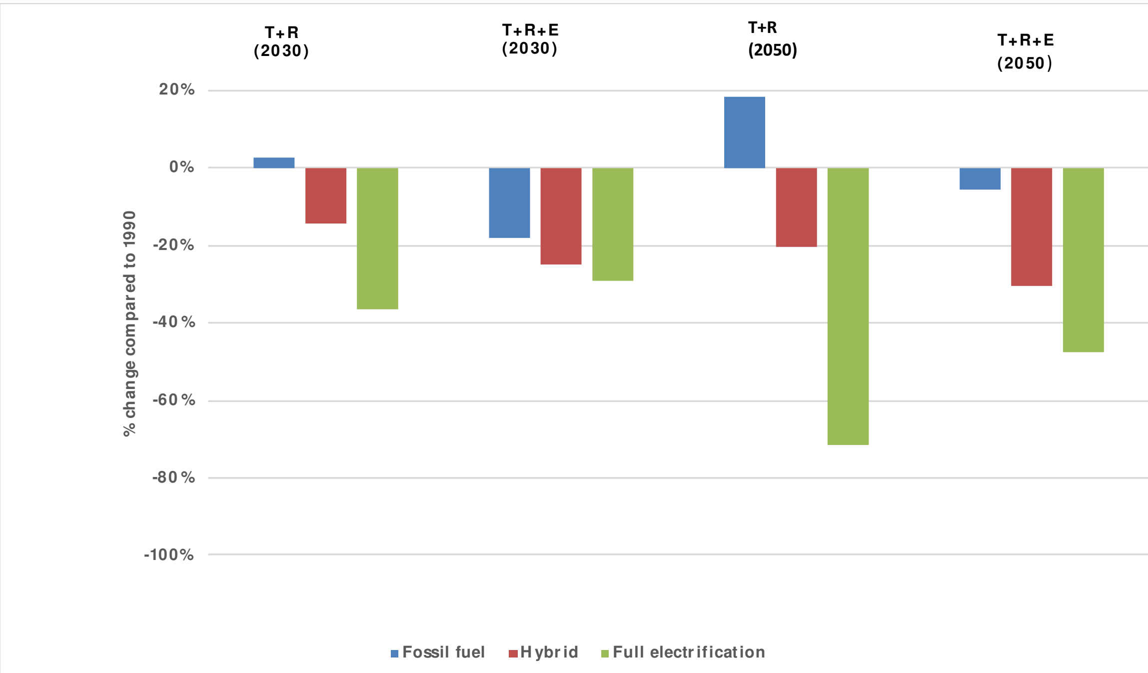
[16] Further, it is assumed that (non-electrified) cars and two-wheelers use gasoline, while vans, trucks and buses use diesel.

Figure 17b: CO_2 emissions over time, full electrification scenario



Finally, Figure 18 illustrates the projected reduction as compared to 1990 levels. The first two sets of entries relate to projected reductions in 2030, first transport and buildings only (labelled T+R (2030)), and second, for all sectors (labelled T+R+E (2030)). The second set of entries relates to 2050, again first for transport and buildings only and then for the three sectors.

Figure 18: Carbon emission reduction per group of sectors, per scenario, in 2030 and 2050 (in % of 1990)



In the FF scenario, the carbon emissions in 2030 or 2050 are only reduced if emissions from the power sector are taken into account.

The results are different when looking at the FE scenario. As expected, because of full electrification of the transport and residential building sector, the carbon emissions are significantly reduced, by 47% in 2030 and by 97% in 2050. When taking into account the emissions from the electricity sector, the effect is however much smaller; the emissions are reduced by 32% in 2030 and by 58% in 2050.

Note that the overall policy goal of reducing CO_2 emissions to 75% as compared to 1990 levels is reached in none of the scenarios.

11. System costs

This last section considers a net-present value approach. We compare the benefits from reducing carbon emissions with the costs from switching to electrified houses and transport.

11.1 Assumptions

The model accounts for costs of insulating old houses, and the excess costs of installing heat pumps relative to gas boilers. As for road transport, the model accounts for the excess price of electric cars relative to conventional ones, and the costs of deploying the necessary battery charging infrastructure. The model also includes savings of conventional fuels due to electrification. Parameters for this net-present value approach are depicted in Table 11. For additional details see the Netherlands case study. The computation of the system costs below assumes a social cost of carbon of €50 per ton.

Table 11: Assumptions on fuel efficiency and carbon intensity of vehicles

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)	49
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 CO_2 (euro/ton)	50

CO_2 price in ETS (euro/ton)	10

11.2 Results

Costs of electrification are reported by comparing total system costs across each scenario.

Note that the degree of electrification is the only difference across scenarios, so any difference in costs can be fully attributed to differences in the degree of electrification.

Because of the largest fixed costs, electrification of houses and of vehicles are the main cost drivers (see Figure 14). Moreover, the relative large cost reductions due to less spending on gasoline and lower carbon emissions, reduced the total damages given the assumed social cost of carbon of €50 per ton.

Figure 19: Contribution of different cost drivers (negative costs represent benefits)

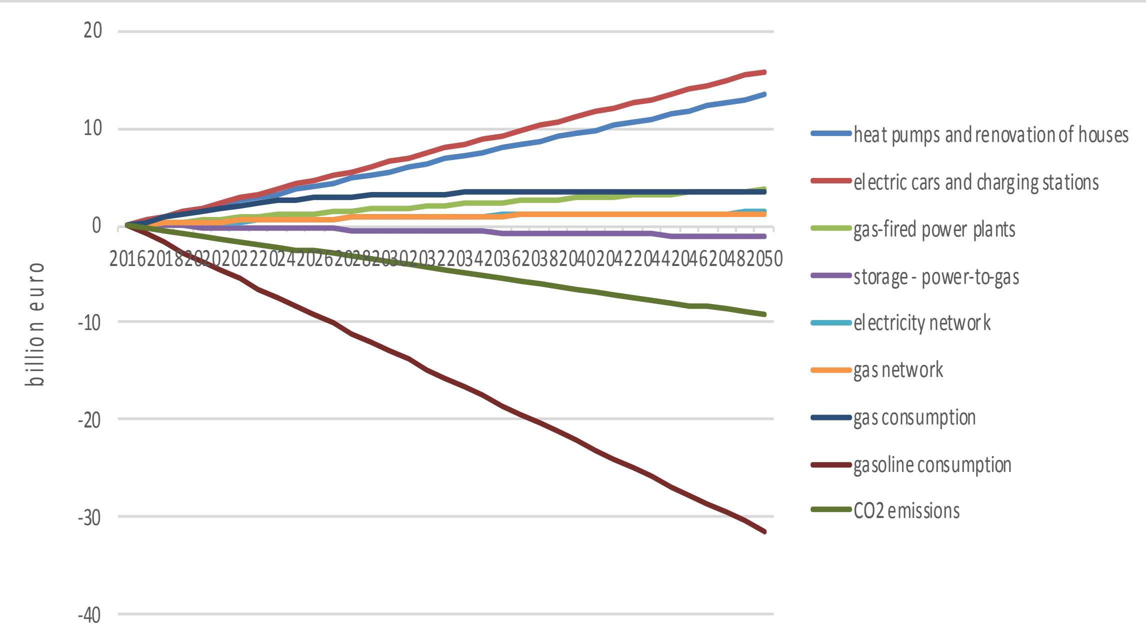
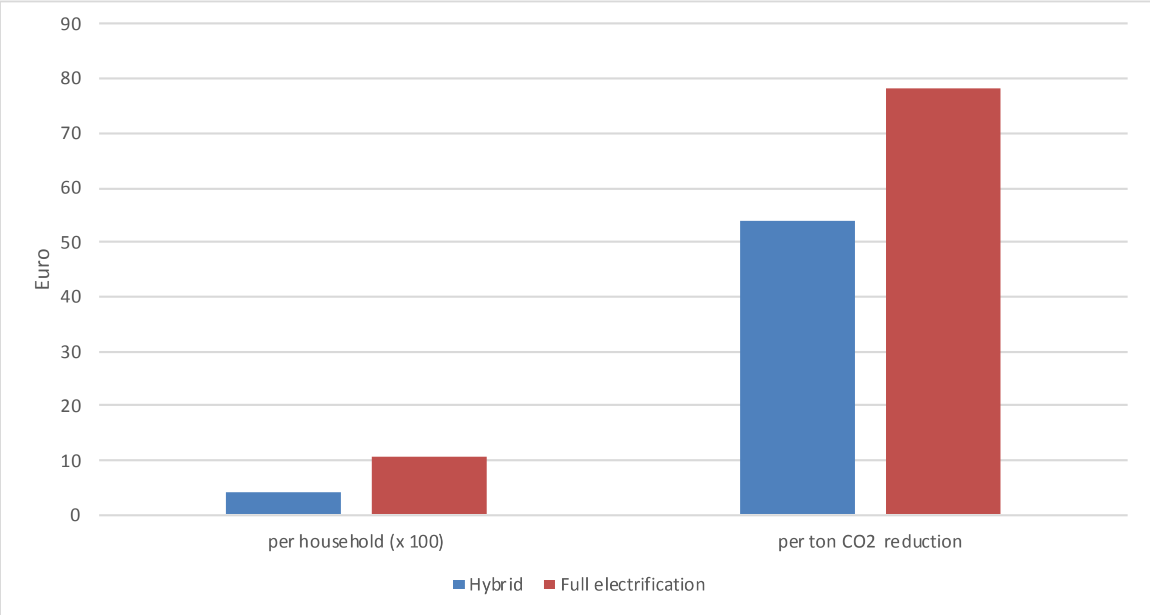


Figure 20 shows the positive net-present value estimates for both HY and FE scenarios.

Figure 20: Net-present system cost for Hybrid and Full Electrification scenario, today's investment cost



12. Conclusion

The objective of this report is to understand how electrification of the residential building and transport sectors may impact electricity and gas supply, the tension on the network and the impact on CO_2 emissions in France.

The analysis, based on the model developed for the Netherlands case study, studies the impact on CO_2 emissions of three different electrification path scenarios towards 2050 – business as usual, hybrid, and full electrification. The model's result depends on a number of parameters – such as the share of new electrified houses and cars, the phase-out targets, and the energy mix. The parameters used in this report are all derived using historical data or estimates from the existing literature.

The estimated additional electricity demand due to electrification is met, on the supply side, by renewable energies and gas-fired plants. Because investments in renewables are capped by assumption, higher levels of electrification automatically translates into higher natural gas shares. In the case of full electrification, this share is estimated to be 22.5% in 2050 and is significantly lower than the share of renewables (44%). Under extreme weather conditions, however, for example a winter day with low levels of renewable generation but high demand levels due to low temperatures, the major back-up technology will be gas-fired.

Moreover, even with full electrification, the share of renewable energies remains constant and the target of 40% of electricity production is achieved in 2050. In the full electrification scenario, carbon emissions are decreasing constantly until 2050 due to lower energy usage from fossil fuel intensive traditional heating and transport. And yet, the increase in power demand from electrification cannot be achieved through renewables only. This exercise shows that the target of reducing GHG emissions by 75% compared to the 1990 levels is unlikely to be reached even with full electrification. It is necessary to increase renewable generation when targeting full electrification of the economy.

Finally, it is important to mention some limitations of the current framework. First, the modelling does not include demand flexibility which would reduce the role of gas. The French governement has expressed an ambition to deploy smart gas meters (*Gazpar*) and electricity meters (*Linky*) on a large scale. The hope is to increase demand response by providing users with more detailed information regarding their energy usage. More generally, online and mobile applications may significantly change the consequences of full electrification of the economy. Second, the report does not explicitely take into account targets related to energy consumption reductions. The Law on Energy Transition for Green Growth states for instance that total energy consumption should be reduced by 50% in 2050 compared with 2012. Third, electricity supply is likely to be more decentralised in the future as it relies more heavily on renewable energy. This in turn will likely require a new network architecture. Because these features are excluded from our analysis, the shares of gas-fired generation may be interpreted as an upper bound. The consequences of allowing trade and demand responses could in fact be an interesting avenue for future research.

References

ADEME (2017) *2035-2050 : Actualisation du scénario énergie-climat*, ISBN : 979-10-297-0921-0.

INSEE *(2017) Les conditions de logement en France*.

LOI n° 2015-992 du 17 août 2015 relative à la transition énergétique pour la croissance verte

Moraga, J.L. and M. Mulder (2018): Electrification of Transport and Heating - A scenario analysis for The Netherlands up to 2050. Working Paper

Persson Urban and Sven Werner (2014), *Quantifying the Heating and Cooling Demand in Europe*, STRATEGO project

Plan de programmation pluriannuelle de l'Energie (PPE) published in 2016

RTE (2016), Electricity Outlook 2017-2035 (link)

SDES (2017) Key Figures on climate – France, Europe and Worldwide, ISSN: 2555-7580

Data accesss:

Temperature, wind

https://donneespubliques.meteofrance.fr/?fond=contenu&id_contenu=37

HDD: 2006-2014

Per month: http://ec.europa.eu/eurostat/web/energy/data

Average load

http://clients.rte-france.com/lang/an/visiteurs/vie/courbes.jsp

Appendix

Figure A1: Projected CO_2 emission in road transport, by scenario

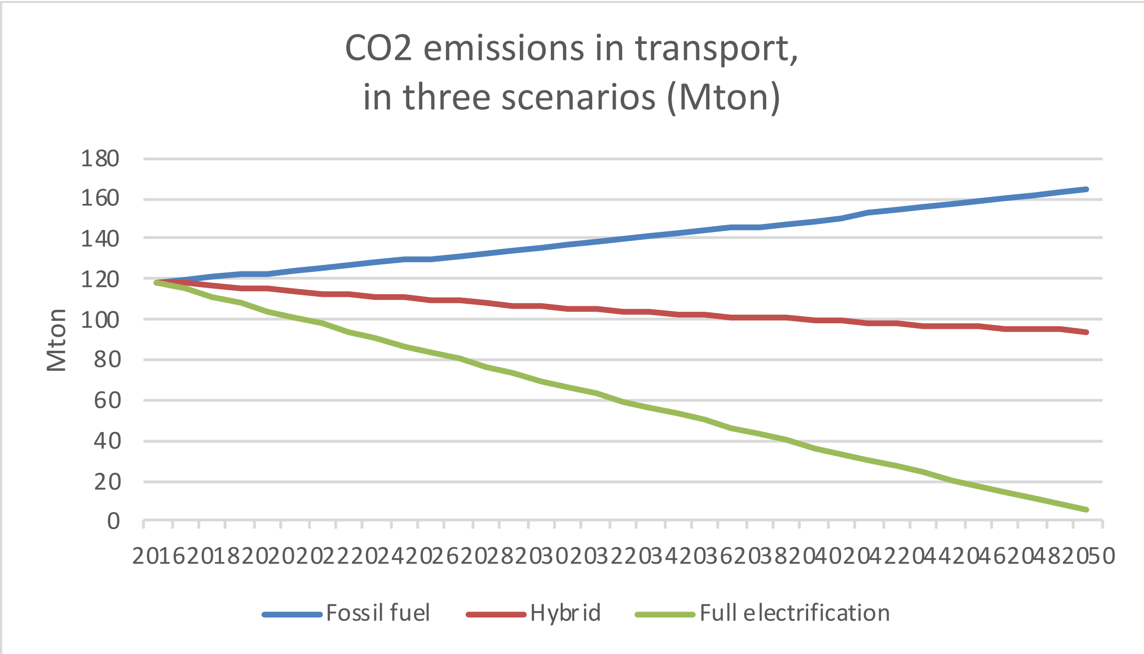


Figure A2: Projected CO_2 emission from residential buildings, by scenario