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

A CERRE research project by

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Executive summary

- This report presents a 2050 scenario study of the implications of a possible gradual electrification of *road transportation* and *domestic heating and cooking* in five European countries: Austria (AT), Belgium (BE), France (FR), Germany (DE) and the Netherlands (NL).
- The study is intended to derive the consequences that electrification of heating and transport has 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.
- Three scenarios of electrification are considered:
    - *Fossil-Fuel* scenario: a business-as-usual electrification path in which electrification remains quite limited, similar to current practices, even by 2050.
    - *Full Electrification* scenario: a full electrification path as an extreme benchmark in which the residential and road transport sectors (especially passenger cars and motorbikes) are virtually fully electrified by 2050.
    - *Hybrid Electrification* scenario: a path in which electrification reaches intermediate levels by 2050.
- These three electrification scenarios have important consequences for aggregate electricity demand and therefore for the energy mix needed for power generation. Throughout this study, we treat gas as a residual fuel for power generation and Power-to-Gas (PtG) as the first source of flexibility.
- The scenario analyses are not intended to provide policy recommendations; more modestly, we try to shed light on the challenges policymakers and the energy sector might face if electrification is the policy choice for the future. In such a case, which scenario will turn out to be closer to reality will depend on the policy goals of the governments and the market developments. Admittedly, these may vary as time elapses.
- The 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 the 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 to derive the consequences of electrification in each of the scenarios.
    - First, we derive the increase in the power demand originating from electrification of the residential and transport sectors.
    - Then, we compute the power sector energy mix needed to meet demand, taking into account the government commitments and giving gas the role of resource of last resort.
    - We then study the reliability of the electricity sector, using PtG as primary source of flexibility and gas as the secondary source.
    - After this, we compute the CO_2 emissions associated to the three sectors involved in the study, namely the housing, transport and electricity sectors, and compare them to the 1990 levels. While calculating the emissions from burning gas, we take into account that PtG and green gasses have zero emissions.
    - Finally, we compute the social costs of electrification. In computing this, 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 power sector reliability, 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.

- As is the case with all scenario studies, we model some features of the energy markets and purposely leave some aspects outside the analysis. One of the issues that we do not model explicitly is the pricing dynamics of the energy markets. Relatedly, another aspect that is not included in the model is the development of the carbon price within the EU ETS. These two assumptions reflect our objective in this study of placing the focus on the impact of government policy on the supply of electricity 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.

- However, including these aspects would not significantly alter the main qualitative results of our study. For example, a higher price of natural gas might induce gas-fired power plants to buy more biogas as an input for power production and correspondingly more biogas may be produced; this would merely affect our counts of CO_2 emissions but not the other conclusions of our study. Likewise, an increase in the carbon price within the EU ETS might just result in a reduction in the government support for renewables, thus the share of renewables would primarily remain 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.

- Main Results:
    - Increasing electrification in the transport and heating sectors reduces the consumption of fossil fuels in these sectors but because the demand for power increases significantly, the use of gas as resource of last resort gains weight in the generation mix. Specifically, the demand for gas from the residential sector decreases as electrification progresses but, because of the planned phasing-out of coal and nuclear generation and limited increase of renewables, gas demand rises in the power market. The net effect depends on the countries' specific policies and current energy mix, with demand for gas increasing in BE, FR and DE, remaining constant in AT and slightly decreasing in NL.
    - As more renewable sources of generation (specially wind and solar) are progressively deployed in the market, the electricity supply becomes more weather dependent and thus more volatile so that a substantial amount of gas-fired power plant capacity will be necessary for reliability of supply. In BE, FR, DE and NL this capacity should be at least 3 or 4 times the current capacity by 2050, while in AT a small increase would be sufficient.
    - The current plans of the countries' governments regarding the expansion of renewable generation capacity, coupled with a scenario of full electrification, result in very small amounts of renewable electricity being available to use for Power-to-Gas. From now to 2050, only under expectional weather conditions will an oversupply of electricity occur.
    - As both electricity and gas provision rely heavily on the use of transmission and distribution networks, an increase in power generation and/or gas consumption requires a possibly costly resizing of the networks. In 2050, in the scenario of full electrification, the electricity grid capacity would have to increase in BE by 70%, in NL by 50%, in AT by 34%, in FR by 35% and in DE by 37%. Except for NL and possibly BE, the capacity of the gas networks will also have to be extended.
    - Electrification of the residential and road transport sectors will shift CO_2 emissions from these sectors to the power sector. The net effect depends on the technology mix for power generation and is therefore country specific. In 2050, with a scenario of full electrification, CO_2 emissions from the residential, road transport and electricity sectors together in BE would decrease only by 11% relative to the corresponding 1990 levels, in AT by 62%, in DE by 70%, in FR by 48%, and in NL by 40%.
    - The model results show that the social costs of a full electrification path towards 2050 vary significantly, ranging from 0.5% of GDP in FR to close to 7% of GDP in NL, with intermediate rates for AT (2%), DE (4%) and BE (4.5%). The cost per ton of CO_2 reduction would be €250 for NL, €146 for BE, €142 for DE, €78 for FR and €54 for AT.

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1. Introduction

This paper presents the results of a 2050 scenario study, which examines the implications of a possible gradual electrification of *road transportation* and *domestic heating and cooking* in five European countries. The countries considered are Austria (AT), Belgium (BE), France (FR), Germany (DE) and the Netherlands (NL).

The objective of the study is to derive the consequences that electrification of heating and transport has on:

- the electricity and gas sectors,
- the CO_2 emissions associated with the residential, transport and electricity sectors,
- and the overall social costs.

In the report, three scenarios of electrification are considered:

- *Fossil-Fuel* scenario: a business-as-usual electrification path in which electrification remains quite limited, similar to current practices, even by 2050.
- *Hybrid Electrification* scenario: a path in which electrification reaches intermediate levels by 2050.
- *Full Electrification* scenario: a full electrification path as an extreme benchmark in which the residential and road transport sectors (especially passenger cars and motorbikes) are virtually fully electrified by 2050.

The three scenarios mentioned above have important consequences for aggregate electricity demand. Therefore, they also have important implications for the energy mix needed for power generation. This study treats gas as a residual fuel for power generation and Power-to-Gas (PtG) as the first source of flexibility.

The scenario analyses are not intended to provide policy recommendations. Rather, the more modest aim is to shed light on the challenges that will be faced by policymakers and the energy sector should electrification be pursued as a policy choice. If it is pursued, how close any scenario will be to reality will depend on the policy goals of the governments and the market developments. Admittedly, these may vary over time.

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

Having established the necessary data and considered the relevant policy commitments, the study takes a number of logical steps to derive the consequences of the electrification of road transport and domestic heating and cooking in each of the scenarios.

- First, we derive the increase in the power demand originating from electrification of the residential and transport sectors.
- Then, we compute the power sector energy mix needed to meet demand, taking into account the government commitments and giving gas the role of resource of last resort.
- We then study the reliability of the electricity sector, using PtG as primary source of flexibility and gas as the secondary source.
- After this, we compute the CO_2 emissions associated to the three sectors involved in the study, namely the housing, transport and electricity sectors, and compare them to the 1990 levels. While calculating the emissions from burning gas, we take into account that PtG and green gasses have zero emissions.
- 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.

The model includes some features of the energy markets and purposely leaves some aspects outside the analysis. This is a typical feature of all scenario studies. One of the issues that we do not model explicitly is the pricing dynamics of the energy markets. Relatedly, another aspect that is not included in the model is the development of the carbon price within the EU ETS. These two assumptions reflect our objective to focus on the impact of government policy on the supply of electricity. By doing this, we intentionally put the emphasis on a case in which the merit order for electricity production is primarily determined by government policy.

Including these aspects, however, 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 demand more biogas as an input for power production; this would increase the production of biogas, which would merely affect our counts of CO_2 emissions but not the other conclusions of our study. Likewise, an increase in the carbon price within the EU ETS might just result in a reduction in the government support for renewables. In such a case, 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.

2. Background

European climate policy aims at reducing CO_2 emissions by 80-95% below 1990 levels by 2050. In reaching this objective, de-carbonising the residential and road transport sectors is essential. Although CO_2 emissions have progressively been reduced in the residential sector, this sector was still responsible for around 10% of the total release of the pollutant in the EU28 by 2014. The situation with regard to the transportation sector is even more worrying because emissions have increased relative to 1990 levels and its share in total emissions in the EU28 by 2014 was close to 25%, with passenger cars being responsible of the bulk of total emissions.[1]

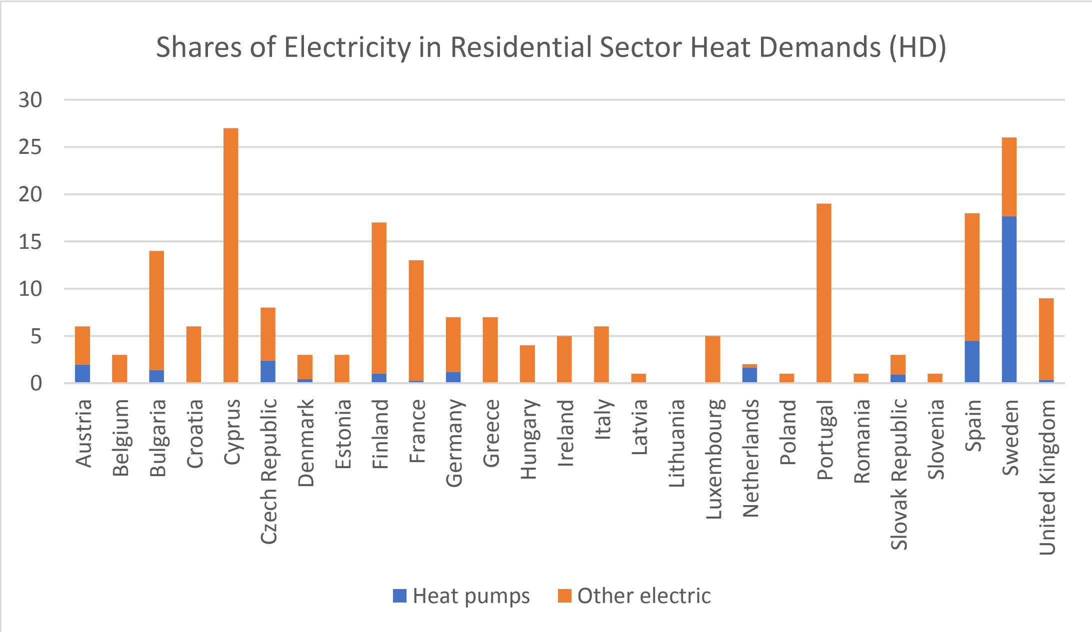
Across countries, there is a significant amount of heterogeneity. In Belgium, the residential sector released 15.4% of the total CO_2 emissions in 2014, while the transport sector was responsible for 24.8%. In France, these shares are 13.3% and 36.7%, respectively, while in the Netherlands they are 9.06% and 17.8%. In Germany, the residential sector emitted 10.3% of the total CO_2 released while the transport sector accounted for 19.5%. In Austria, these shares are 8% and 33%, respectively.

Electrification of the residential and road transport sectors is one of the options contemplated in various European countries to reduce CO_2 emissions. By electrification of road transportation, we mean the gradual replacement of conventional gasoline and diesel passenger 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. Provided that electricity is generated by renewable sources, electrification can potentially be a way to cut emissions because the technology for heating houses and powering cars is quite efficient.

The existing degree of electrification in these two sectors varies greatly across European countries. Figure 1 shows the different degree of house electrification across countries. Electric heating is quite prevalent in Bulgaria, Cyprus, Finland, France, Portugal, Spain and Sweden; its presence is rather limited in countries such as Austria, Belgium, Latvia, Poland, Romania and the Netherlands. Moreover, the graph shows that the use of heat pumps, except in Sweden, is not widespread. Most of the existing electric heating is, instead, conventional, i.e. via electric radiators.

[1] See "*EU Energy in Figures: Statistical Pocketbook 2016*," European Union 2016, pages 164-169.

Figure 1: Shares of Electricity in Residential Sector Heat Demands (HD) among EU states

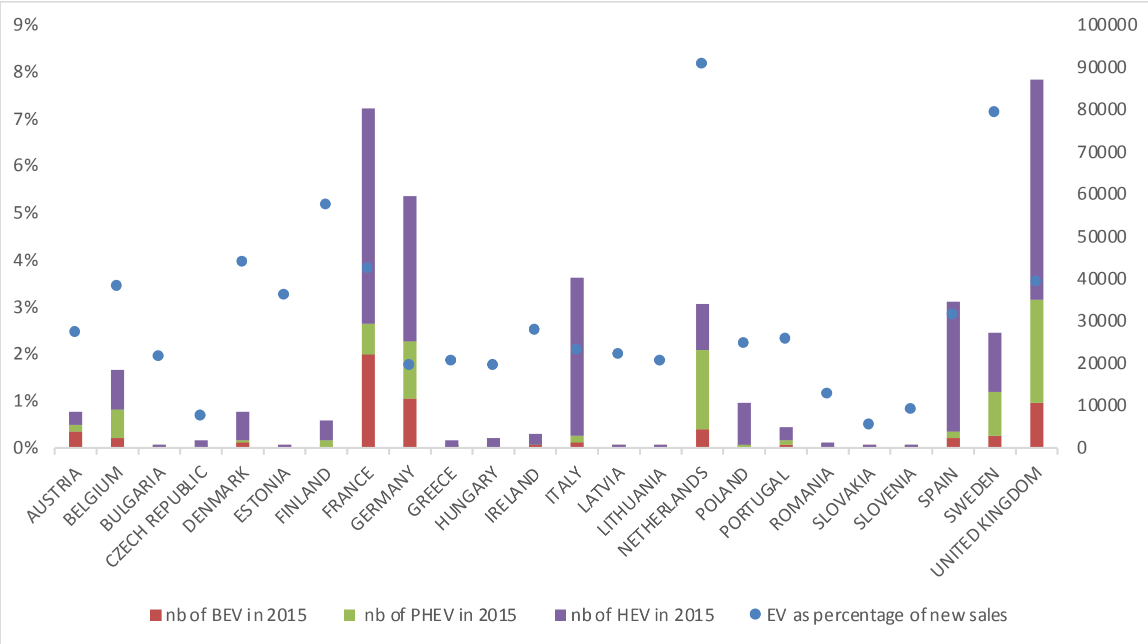


Source: Urban and Werner (2016)[2]

Figure 2 shows the number of different types of hybrid and fully electric vehicles (EVs) sold in 2015 as well as the market share across EU member states. Clearly, the sales of hybrid and fully electric cars were in 2015 relatively small across Europe. The Netherlands had the largest percentage of electric vehicles (around 8%) sold in 2015, while France and Belgium had about half of this share. Austria and even more Germany had a relatively low market share of electric vehicles in 2015, with 2.4% and 1.72% respectively.

[2] Persson Urban and Sven Werner (2016), Quantifying the Heating and Cooling Demand in Europe, STRATEGO project.

Figure 2: EVs as percentage of total sales and Total EV car sales in EU member states in 2015



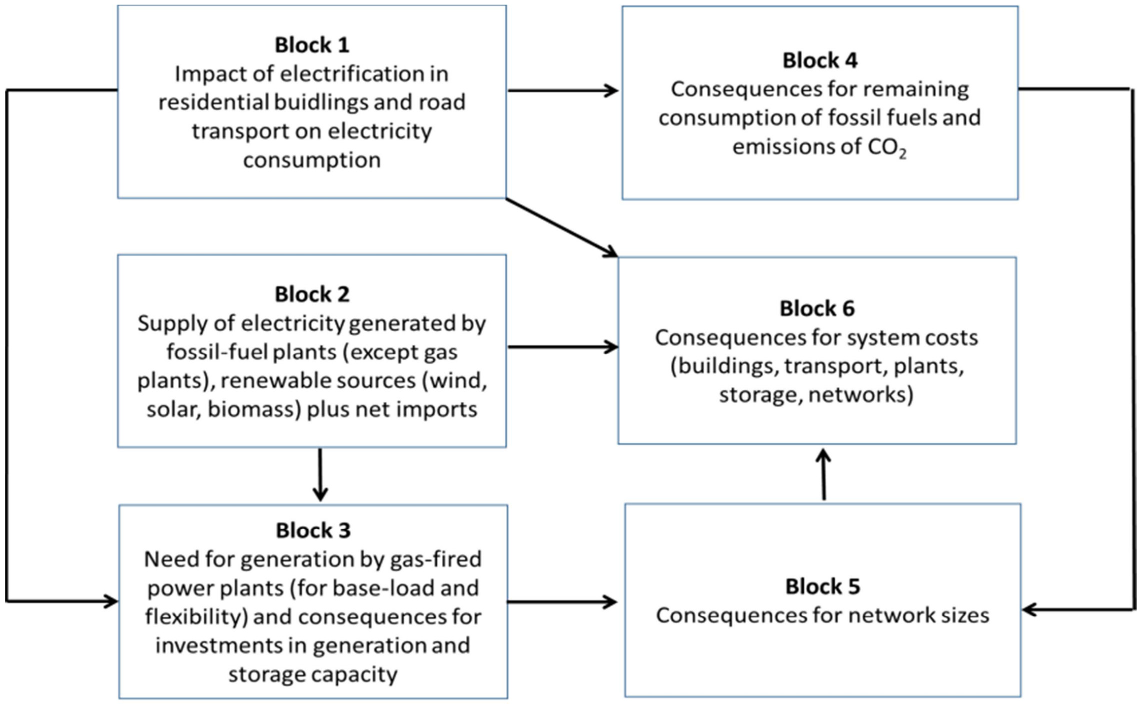
Source: Data from the *European Automobile Manufacturers Association* (*http://www.acea.be*)
Battery Electric Vehicles (BEVs), Plug-in Hybrids (PHEVs), Range-extender electric vehicles (REEVs), Hydrogen fuel cell electric vehicle (FCEV)

The European climate policy sets general emission targets, but each Member State develops its own path towards the policy targets. Our set of selected country cases (Austria, Belgium, France, Germany and the Netherlands) is, to some extent, representative of different European realities regarding the housing, transportation and electricity sectors. For example, while France has an important share of houses with conventional electric heating, and electricity production is predominantly nuclear and therefore CO_2 free, the Netherlands is mainly a gas country with almost all houses being connected to the gas distribution networks and power production being primarily based on fossil fuels. In Belgium, nuclear power production is predominant and a large share of houses are heated using heating oil. In Germany, power production uses a lot of coal and renewable generation is significant. In Austria, electricity production is based, largely, on hydropower.

3. Framework

To study electrification in the selected countries, each study relies on the modelling framework developed in Chapter 1 for the case study for the Netherlands. The model can be divided in six blocks, as illustrated in Figure 3.

Figure 3: Main building blocks of the analytical framework



Source: see case study for the Netherlands

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 the projected 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 the additional power demand arising from electrification of both sectors, also taking into account energy efficiency gains over time.

Block 2 derives 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 based on the assumption that gas-fired power plants act as the residual supplier. Investment and market exit of all other technologies are exogenous and follow policy objectives, e.g. for the discontinuation of nuclear electricity production or the deployment of renewable generation.

Block 3 determines the required generation by gas-fired power plants. The model also derives the gas-fired generation capacity required under extreme weather circumstances, that is, when the renewable sources are not able to produce while the demand for electricity is high. This is a crucial ingredient for the computation of the total system costs of electrification. In addition, this block also determines the possibility to store excess supply of electricity, through power-to-gas, in case of extremely favourable circumstances for renewable production while the demand for electricity is very low.

Block 4 calculates the resulting consumption of fossil fuels (gas and gasoline) and net CO_2 emissions. The higher the degree of electrification, the higher the share of gas demand stemming from the power market, and the lower that from the residential sector. This modelling block thus presents outcomes on the net impact of electrification on gas demand over the years. Cuts in CO_2 emissions represent social benefits and we take them into account in our calculation of the costs of electrification.

Block 5 builds on Block 3 and derives the costs of infrastructure needs for electrification.

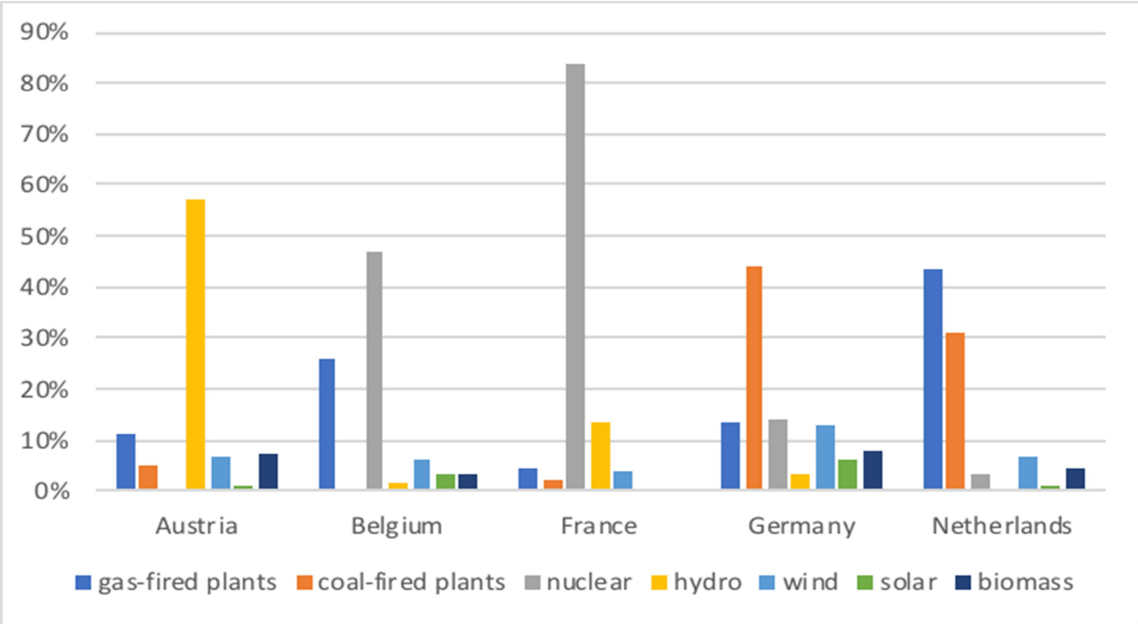
Block 6, the last block of the model, aggregates all the benefits and costs of electrification, also providing a net present value approach to electrification.

Naturally, the speed of electrification, as the share of electrified houses and vehicles per year, is a crucial element of the analysis. Therefore, we have defined three scenarios that only differ in the speed of electrification. Importantly, policy assumptions on the power market are being kept constant across scenarios. In particular, renewable integration paths and the phasing-out of nuclear and fossil fuel technologies are identical across the projections.

Different context

As mentioned above, the set of countries considered in this study represents a range of different underlying market characteristics at play in different EU countries. First, the power market fundamentals differ as each country relies on a different energy mix. The current power generation technologies for the studied countries are depicted in Figure 4. Austria, Belgium and France have a relatively low-emission electricity sector, the first mainly based on hydro and the second and third mainly based on nuclear. Germany and the Netherlands, by contrast, burn a lot of coal and gas for electricity generation.

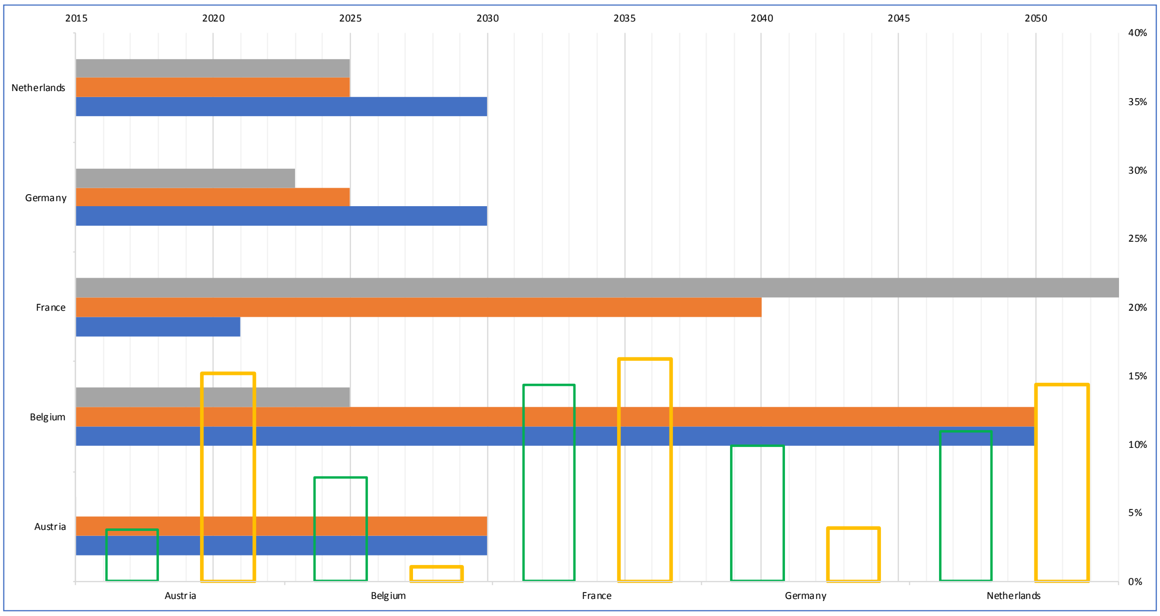
Figure 4: Energy mix by country in 2016 (% of annual generation)



Source: see relevant case studies.

Another relevant difference across the countries in this study pertains to the government policy objectives known at the time of writing this report (see Figure 5). Power generation based on nuclear energy will be phased out in Germany by 2023 and in Belgium and the Netherlands by 2025, while there is no such commitment by the French government. The phase-out of coal and other fossil fuels is also planned at distinct points in time in the different countries. Note that where phase-outs of conventional generation are currently discussed but governments have not announced a clear-cut time horizon for doing so, our projections assume a gradual decline until a chosen target year.

Figure 5: Energy mix policy objectives, by country



Source: The phasing-out patterns (horizontal bars) for nuclear (grey), other fossil fuels except gas (orange) and coal (blue) are directly taken from the policy objectives defined at the national level, or otherwise assumed by the authors based on current policy discussions. The expected annual growth rate of solar (vertical yellow bars) and wind (vertical green bars) are also calculated using the current policy targets. The standard cumulative annual growth rate (g) has been calculated using the following equation: Policy Target = Current generation * (1 + g)^(14). The policy targets are all for 2030 and the generation is using figures from 2016.

Finally, reducing the CO_2 emissions stemming from the transport and housing sectors has not always been a priority for the various governments. Germany has long focussed on reducing emissions from the energy sector, especially in the power sector and only recently has the policy focus turned to the transport and housing sector. An example of this policy focus is the introduction of a subsidy for newly registered electric and hybrid vehicles.[3] The same holds for the Netherlands, and a similar policy was recently put in place. In contrast, because the Austrian and the French power sectors are relatively low-carbon, the transport and (to a lesser extent) heating sectors contribute heavily to the respective country's CO_2 emissions and have been the specific target of early climate protection regulations. Belgium, on the other hand, does not have a clear policy towards electrification of the road transport and housing sectors yet (even though there are voices within the current government pushing forward an agenda of electrification of the road transport sector).

[3] Buyers receive a subsidy ("Umweltbonus") of €2,000 (€1,500) for an electric (hybrid) car, conditional on the manufacturer subtracting the same amount from the officially listed price.

4. Results

In this section, we summarise the different results of our quantitative scenario analysis performed on Austria, Belgium, France, Germany and the Netherlands. Here we focus on the case of full electrification in the heating and transport sector (FE scenario). For the results under the business-as-usual FF scenario and intermediate HY scenario, we refer the reader to the chapters 1-4 below.

The main findings are summarised in Table 1.

Table 1: The main outcomes of the "Full Electrification" scenario in 2050

FE scenario-2050	Austria	Belgium	France	Germany	Netherlands
Additional load required in 2050 FE *(% current load)*	63%	91%	62%	64%	83%
Share of GAS *(% 2050 load)*	15%	70%	18%	33%	50%
Share of RES *(% 2050 load)*	78%	19%	47%	62%	44%
Additional grid/ gas network capacity *(% 2016 capacity)*	+34% grid +63% network	+70% grid +50% network	+35% grid +33% network	+ 37% grid +20% network	+50% grid 0% network
Net costs of electrification in billion euros *(% GDP)*	7 (2% GDP)	19 (4.5% GDP)	15 (0.5% GDP)	144 (4.6% GDP)	50 (7% GDP)
CO_2 target achieved with FE scenario ***(Relative to policy goals)***	**62% (instead of 80%)**	**11% (instead of 80%)**	**48% (instead of 75%)**	**70% (instead of 80%)**	**40% (instead of 80%)**

Significant rise of power demand. Increasing electrification in the transport and heating sectors, by design, reduces the consumption of fossil fuels; primarily gasoline and diesel in the transport sector and coal, heating oil and gas in the residential sector. Indeed, the rationale behind this political decision is often to reduce the consumption of such non-renewable energy sources and, in turn, reduce one of the largest sources of greenhouse gas emissions. Simultaneously, the electrification of the two sectors has a direct impact on power demand.

Model projections show that the increase in demand for power including that stemming from fully electrified transport and heating sectors by 2050 is quite significant in all country cases, though different from country to country. For Austria, the increase amounts to an additional 63% compared to the current load, and for Germany about 64%. For France, the increase corresponds to 62% of the current load. In the Netherlands and Belgium, the increase is much more significant, with the extra power demand projected to be 83% and 91% higher than the respective 2016 electricity load.

Differences across countries stem from various reasons. Amongst others, countries differ in their status quo, which serve as starting points for our projections. In France, for instance, heating is already electric to a significant extent. The growth rates for the stock of residential buildings and the demands for new passenger cars are also country-specific. The energy needs in the north where the weather is less benign is much higher than elsewhere. Finally, electricity demand from other sectors, mainly industry, can differ quite a bit between countries.

Insufficient increase of renewable energy to meet additional demand. The generation technology mix used to supply future power demand depends largely on national policy, and the way it steers investment in different technologies. There is a common view among policy makers that electrification of the economy will be ensured by the increasing share of energy renewable generation. However, we do not observe this to be the case in our scenarios of full electrification. Conventional generation will still be needed after 2030, when electrification of transport and housing has reached a significant level. Projections show that with full electrification, on a day with average wind and solar output, significant shares of gas-fired generation will remain in each country's power generation mix. These shares amount to around 79% for Austria, 20% for Belgium, 47% for France, 67% for Germany, and 40% for the Netherlands.

Effect of full electrification on gas demand varies by country. While gas demand declines in the housing sector (especially due to reduced gas needs for space heating), gas demand rises in the power market in order for it to meet the additional power demand stemming from electrified transport and houses. In all countries, the increase in power demand from electrification requires further reliance on conventional thermal generation, unless renewable capacity is expanded. Note, however, that the increase in renewable generation across the three scenarios is, by assumption, constant. It is the share of gas-fired generation that is the adjustment variable across the scenarios: higher levels of electrification automatically translate into higher gas consumption in the power market. Yet, the net effect on gas demand differs by country: Belgium, France and Germany experience increased gas demand in 2050. In contrast, gas demand remains somewhat constant in Austria. In Austria, the power market is largely hydro-based and falling gas demand in the housing sector is thus not over-compensated by drastically increasing gas-fired generation. Overall gas demand in the Netherlands in 2050 falls below today's levels.

Model results show that CO_2 reduction targets would not be met. As first-order effect, the shift towards full electrification will lower the CO_2 emissions via reduced fossil fuel consumption in the transport and housing sector. In all countries, because of full electrification of the transport and residential building sectors, carbon emissions in both sectors are significantly reduced in 2050 compared to 1990 levels. Notably, for all studied countries, this reduction is well close to 80% relative to 1990 for both sectors combined.

However, because of the increase in power demand, the net effect on the balance of CO_2 emissions depends on the technology mix for power generation and is therefore country specific.

For Germany, to start with, full electrification of the heating and transport sectors would reduce emissions by 70% in 2050 compared to 1990's level. However, it would shift about a third of current total emissions to the power market (with the electricity sector becoming relatively more polluting).

For Austria and France, the overall effect on emission reductions from electrification is also positive. This is mostly due to the low-carbon electricity sector. In Austria, projections show that full electrification results in a more than 60% reduction of carbon emissions as compared to business-as-usual in 2050.

In France, as expected, because of full electrification of the transport and residential building sectors, the carbon emissions are significantly reduced, by 37% in 2030 and by 71% in 2050. When taking into account the emissions from the electricity sector, the effect is however much smaller; the emissions are reduced by 29% in 2030 and by 48% in 2050.

Similarly, in the Netherlands, there is a strong reduction in carbon emissions in the case of full electrification (40% less in 2050 compared to 1990). Despite the modest reduction in emissions from the electricity sector (by around 20%).

In Belgium, the reduction of CO_2 emissions is much more modest, with only 11% less emissions in 2050 compare to the 1990's level. The reason is that the electricity sector becomes much more fossil fuel based because of the closure of nuclear plants.

As such, applying the same model to our set of countries shows that the emission reductions linked to electrification are strongly country-specific, with the main driver being the different choices for power generation in each country.

Expansion of the electricity or/and gas network required. As electricity and gas provision relies heavily on the use of transmission and distribution networks, an increase in power generation and/or in gas consumption requires a possibly costly resizing of the networks. The need for expansion is not the same across countries. The electricity grid capacity has to increase significantly in 2050: in Belgium by 70%, in the Netherlands by 50%, in Austria by 34%, in France by 35% and in Germany by 37%. Similarly, except for the Netherlands, the gas network capacity also has to be extended, by around 50% in 2050 for Austria and Belgium and to a less extent in France (33%) or in Germany (20%). Yet, these figures do not automatically imply grid expansion of a corresponding amount. Findings relate to the additional quantities to be transported relative to the business-as-usual case. Thus, where grid and/or gas network capacity is underused today (or can be re-optimised after changing the type of gas transported), the figures represent upper bounds.

Reliability of electricity supply requires more investment in conventional generation capacity. As already mentioned, the production of extra electricity to satisfy the 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 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. However, the amount of capacity required depends on the technology mix for power generation. In most countries, securing supply on high-demand days with little wind or solar power supply, would require significant investments.

For example, in the Netherlands where full electrification would imply close to a doubling of the current power generation, there is a need for an installed capacity of about 25 GW of gas-fired plants, almost a 3-fold increase compared to current installed capacity. In France, current gas-fired capacity would need to increase by 7 times. In Belgium and Germany, the increase in gas-fired generation capacity would also be of the order of 3 or 4 times the current installed capacity. In Austria the effect on needed capacity would be less pronounced, yet still constituting an increase of factor larger than one.

Limited renewable electricity available to use for Power-to-Gas. 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 from the growing need for provision of flexibility.[4] Seasonal storage of electricity in the form of Power-to-Gas can partly solve this problem, but this help will be limited as only under very exceptional weather conditions there will be an oversupply of electricity.

Main cost drivers are heat pumps and electric vehicles. While savings from reduced emissions occur, i.e. social costs decline, electrification comes, among others, at the cost of retrofitting existing houses, replacing household heating systems and cooking stoves, switching to electric vehicles, building charging stations, and possibly expanding network infrastructure for electricity and generation capacity of the resource of last resort, which in this study has been considered to be gas. Projections show that, under today's cost parameters, the main cost drivers in this list are heat pumps and electric vehicles.

The modelling exercise results in high costs for electrification. The net costs of electrification of the housing and transport sectors are positive and sizable but vary significantly across countries. That net-present costs are positive implies that the benefits (in terms of CO_2 emissions reductions and savings in the use of fossil fuels) fall too short relative to the costs. In the Netherlands, the net present value of the costs for the period up to 2050 are about €50 billion, which is about 7% of 2016 GDP. In Belgium, these costs are €19 billion in total, around 4.5% of 2016 GDP. For the case of France, we find total costs equal €15 billion, which represent 0.5% of 2016 GDP. For Austria and Germany, the total costs sum up to €7 and €144 billion, representing 2% and 4.6% of 2016 GDP, respectively.

Another metric of interest is the total cost a country incurs per ton of CO_2 emissions reductions under the full electrification path. For the case of The Netherlands, this cost amounts

[4] Include something from disclaimer on NL case study

approximately to €250 per ton of CO_2; for Belgium, it is around €146. For France, we compute €78 per ton of CO_2 cut, while for Austria and Germany we obtain €54 and €142 per ton of CO_2 reduction.

It is interesting to note that most of the countries will not meet the decarbonisation goals. The full electrification of the heating and transport sectors would imply reaching a decarbonisation well below the 80% relative to 1990 in 2050, unless renewable capacities are further expanded up to 2050; note, however, that the costs associated with a further expansion of the capacity of renewable power generation should be added to the computation we have made.