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

A case study for Germany

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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 Germany. 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.

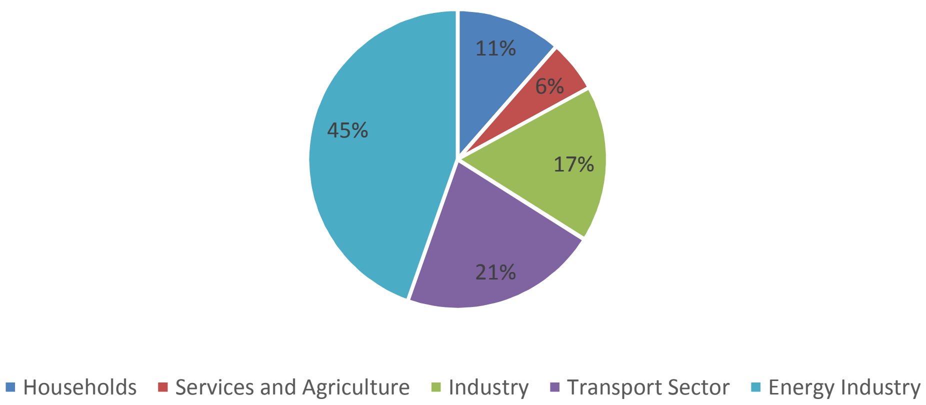
The results of this report should not be seen as a recommendation for a specific policy option. More modestly, we try to shed light on the challenges and choices policymakers and the energy sector will have to manage depending on the extent to which electrification occurs.

1.1 Background

European climate policy has put forward a set of decarbonisation objectives to support the energy transition and to reach climate targets as defined in the Paris Agreement. German decarbonisation goals are in line with this policy, and in parts even more ambitious: German policy mandates a reduction of CO_2 emissions by at least 55% and 80% in 2030 and 2050, respectively, relative to 1990 levels. In addition, policy goals specific to the power sector exist, such as the integration of renewable assets. Yet, next to the power market, the transport and heating sectors are critical for fulfilling the decarbonisation target.

Recently, via electrification of transport and heating, the coupling of all three sectors has developed and been discussed among policymakers. Clearly, the more the transport and housing sector increase their degree of electrification, the more crucial the role of the power sector becomes. To this end, the following case study evaluates the impact of electrification of transport and heating on the power sector and on resulting overall CO_2 emissions in Germany. The time horizon of this projection lasts, in line with policy goals, until the year 2050.

Figure 1: CO_2 Emissions by sector in Germany, 2015.



Source: Umweltbundesamt, 2017.

Figure 1 depicts current CO_2 emissions in Germany. Specifically, it displays the distribution of the total of 752 million tons of energy-related CO_2-equivalent greenhouse gas emissions in Germany in 2015. Emissions in the service sector and especially in agriculture (6%) are often labelled as unavoidable and costly to reduce. In contrast, the energy sector (45%) and in particular the power market are generally found to be the prime candidate to decarbonise due to low abatement costs relative to other sectors.

As such, the prior intuition on sector coupling is that it allows for decarbonisation at lower cost, if emissions of currently about 32% in the transport and housing sectors could be shifted toward the power market. In addition, the coupling of sectors also allows for a more flexible use of generated electricity. However, electrification comes with a range of investment costs in the transport and housing sector. It is this relationship that this case study seeks to shed light on. As can be seen from Figure 1, this study covers (with about 77%; all three sectors combined) the vast majority of all energy-related emissions in Germany.

The below analysis also presents some corollary findings, e.g. on the role of conventional resources. Natural gas, in particular, is a major input factor in both electricity and heat generation. Heating is the major source of emissions in the housing sector. Hence, the more housing is electrified, the more gas consumption will be shifted from the housing to the power sector. As Germany has traditionally been among the top EU gas consumers, this analysis also explores gas demand in Germany as a function of the share of houses and transport being electrified.

1.2 Scope

The data used in this study relate to market fundamentals in the German power, heat, and transport sector. Data is used for two purposes. First, it defines the starting level for our projections, e.g. the current level of emissions or the current amount of cars electrified. Second, data is used to determine the parameters for projection of outcomes in future years, e.g. from the number of houses built in the past years, we draw our parameters for the speed of electrification of housing in the future. Where possible, the study also relies on parameters established by the existing literature or as found by government agencies.

What is the scope of electrification? By electrification of road transportation this study refers to the gradual replacement of conventional gasoline and diesel vehicles (such as passenger cars or trucks) by the corresponding full electric types. Electrification of space and water heating, as well as cooking, refers to the substitution of natural gas boilers and gas stoves in the residential sector by heat pumps and electric stoves.

The outcome variables of the study, here foremost CO_2 emissions, are projected towards 2050 on a yearly base and hence also allow for a discussion of outcomes vis-à-vis 2030 policy goals. It should be noted that a precise forecast of all relevant parameters and outcomes is out of the scope of this study. The outcomes should be understood as a projection given the parameters used, rather than a forecast. As discussed later, some outcomes depend significantly on the chosen parameters. Where this is the case, outcomes are presented using a range of different parameters, or are interpreted highlighting the impact of modelling choices.

2. Method and scenarios

The methodological framework is adapted from Moraga and Mulder (2018). The first block 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.

For the speed of electrification, that is the increase in the share of electrified houses and vehicles per year, the study works with three scenarios: a business-as-usual scenario (FOSSIL FUEL, short FF), a hybrid scenario (HYBRID, short HY), and a full electrification scenario (FULL ELECTRIFICATION, short FE). These three scenarios on the level of electrification will remain the central scenarios throughout all modelling blocks. That is, the level of electrification in each sector constitutes the main exogenous modelling choices.

The second modelling block then takes the power demand modelled in the first block and derives the required electricity supply. 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 phasing-out nuclear plants or increasing renewable generation.

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

Block four and five of the model, respectively, calculate the resulting net CO_2 emissions and infrastructure needs from electrification. Eventually, the last block of the model establishes a net present value approach to electrification.

2.1 Scenario assumptions

The model runs separately for each of the three scenarios FOSSIL FUEL, HYBRID, and FULL ELECTRIFICATION. Table 1 summarises the parameters used in each scenario. The table depicts the assumptions on new houses and cars, as well as the degree to which the existing housing stock will be electrified each year.

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

	Scenarios		
	Fossil Fuel	Hybrid	Full Electrification
Degree of electrification			
Housing			
New	**5%**	**50%**	**100%**
Existing stock (x1000)	**0**	**600**	**900**
Transport			
Passenger cars	**5%**	**40%**	**60%**
Vans	**0%**	**25%**	**35%**
Trucks	**0%**	**5%**	**10%**
Buses	**0%**	**25%**	**50%**
Motorbikes and scooters	**0%**	**50%**	**80%**

For FE, the most aggressive scenario, we assume that each new house built is fully electrified, for instance via the use of heat pumps. In addition, up to 2050, 0.9 million houses, roughly 1/40 of the total stock of 40.8 million houses in Germany, is electrified every year. This scenario reflects a very ambitious policy path, as, using 2011 data, only about 25% of new houses are built with heat pumps (BDEW, 2012), thus far less than needed for this scenario. However, the parameters are chosen to yield fully electrified housing in 2050. Hence, the assumptions also depict the steep increase needed to fully electrify about 40 million (and growing) houses.

The hybrid scenario HY assumes parameters to reach roughly half of all houses being electrified in 2050. In the FF business-as-usual scenario, the share of houses electrified remains insignificant in 2050.

Similar arguments hold for chosen scenario parameters for the electrification of transport. In the fully electrified scenario, electric passenger cars make up almost the entire fleet in 2050. Motivated by previous growth numbers, we assume that the current stock of about 45 million passenger cars increases by 1% each year. This increase reflects the net increase of newly registered and retired cars. We consider 3 million newly registered cars per year, in line with data from the German Federal Motor Transport Authority (Kraftfahrtbundesamt, KBA). To reach a fully electrified passenger transport in 2050, we then need to assume that about 60% of these newly registered cars will be fully electric, as depicted in Table 1.

As for the housing sector, the HY scenario in transport reflects a path that yields roughly half of the transport being electrified in 2050. For comparison, in the business-as-usual case the share of electric passenger cars will grow to only 8% in 2050.

Policy assumptions on the power market are being kept constant in each scenario. In particular, renewable integration paths and nuclear phase-out schemes are identical across the scenarios.

3. Electrification in road transport

3.1 Policy objectives

The German government has so far not implemented clear-cut mandates for the future market penetration of electric vehicles. Plans have been announced to have 1 million electric cars by 2020. Yet, the debate on a more aggressive mandate for e-vehicles or a prohibition of diesel cars is still ongoing. However, previous governments have expressed the ambition to reach a transport system based on renewable energy by 2050 (BMV, 2011). To this end, the German government introduced a subsidy for newly registered electric and hybrid vehicles.[1] It is this ambition that motivates the FE scenario.

3.2 Data and assumptions

As described above, the main input data in this block are the existing stock of cars, its yearly growth rate, and shares of electric vehicles of newly registered cars. Taken together, these data allow the projection of the overall share of electrified vehicles for each year until 2050. All input data and assumptions are derived from statistics published by the German Federal Motor Transport Authority (KBA) and a related publication "VerkehrAktuell" by the German statistical office Destatis (2017).

In detail, the data entail statistics for a range of vehicle types: passenger cars, buses, trucks, and motorbikes and scooters. To evaluate savings in emissions and gasoline, the data also covers the annual average number of kilometres driven for each type of vehicle. Table 2 below summarises the data on the stock of cars for the starting year of our model, the year 2016.

In 2016, 45.8 million passenger cars were registered in Germany, plus 2.5 million vans (incl. light duty vehicles), and about 530,000 trucks and heavy duty vehicles.[2] In addition, our model takes account of 80,000 buses and 4.3 million motorbikes. The total of 200,000 electric vehicles in the starting year include fully electric vehicles (about 35,000) and hybrid cars (about 165,000). 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 kilometres driven and the efficiency of electric vehicles. On average, passenger cars drive around 14,000 km per year, while vans and trucks drive about 19,000 km and 73,000 km per year, respectively.

[1] 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.

[2] Vans comprise duty vehicles up to 6 tons. Trucks comprise duty vehicles above 6 tons. The categorisation was motivated by similar kilometres driven per year among the different types of duty vehicles. The driven kilometres are weighted averages. The data in Table 2 is collected and computed from data on overall kilometres driven in 2016, see KBA (2017), and data on the stock of vehicles, see Destatis (2017).

Table 2: Input data for road transport

Variable	Value
Number of (x million)	
Passenger cars	45.8
Vans	2.5
Trucks	0.53
Buses	0.08
Motorbikes and scooters	4.3
Of which electric (x 1000)	
Passenger cars	200
Vans	0
Trucks	0
Buses	0
Motorbikes and scooters	0
Average distance per year (km)	
Passenger cars	14015
Vans	18900
Trucks	73000
Buses	58615
Motorbikes and scooters	2268

The efficiency of new vehicles, and the amount 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 3 million new cars will be sold every year.[3] As some cars are taken out of circulation mainly because of age, export and accidents, on net we assume that the number of cars increases annually by 1%. This number is in line with previous growth of, on average, 1.1% from 2006 to 2016 (Destatis, 2017). The number of kilometres driven by each type of vehicle is assumed to remain constant.

Data on the efficiency of electric vehicles and on losses when charging are published by the US Department of Energy.[4] 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 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%.

[3] See Destatis (2018).
[4] See www.fueleconomy.gov.

Table 3: Assumptions on new vehicles

Variable	Value
Passenger cars	
Annual number of new cars (x 1000)	3000
Performance - electric (kWh/100km)	20
Vans	
Annual number of new vans (x 1000)	290
Performance - electric (kWh/100km)	35
Trucks	
Annual number of new trucks (x 1000)	36
Performance - electric (kWh/100km)	70
Buses	
Annual number of new buses (x 1000)	6
Performance - electric (kWh/100km)	100
Motorbikes and scooters	
Annual number of new M&S (x 1000)	180
Performance - electric (kWh/100km)	5
All vehicles	
Annual increase in number (%)	1%
Battery charging units	
Annual improvement in charging efficiency	0.5%

3.3 Results

Before we discuss the impact of electrified transport on power demand, we graph the shares of electric vehicles in each scenario in 2050 (see Figure 2). Note again that the share of electrification of passenger cars, the most important driver in transport, is constructed to reach almost full electrification in 2050 by design: the amount of passenger cars grows by 1% net, every year 3 million new cars (thus more than 1% net growth) enter the stock. In the FE scenarios, all these 3 million cars are fully electrified. This process yields almost 100% electrified passenger cars in 2050.

As shown in Figure 3, despite the high shares of all types of electrified vehicles, the power demand generated is highly concentrated on passenger cars. This is in line with the mass of kilometres driven by the high stock of passenger cars. The amount of additional electricity of 193 TWh amounts to about a third of today's total electricity load in Germany of 595 TWh.

Figure 2: Shares of electrified vehicles in 2050

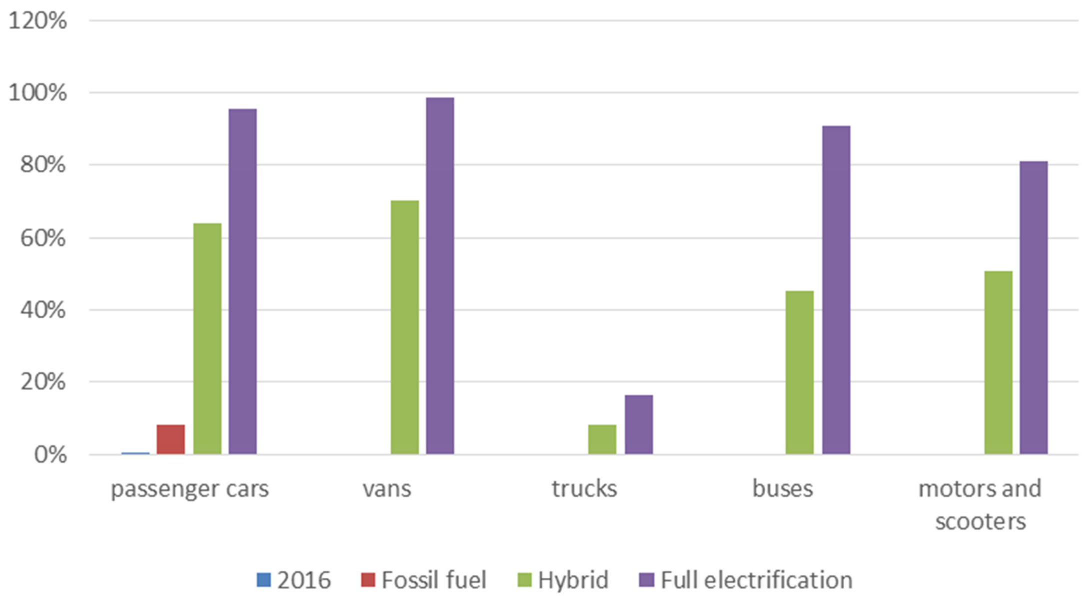
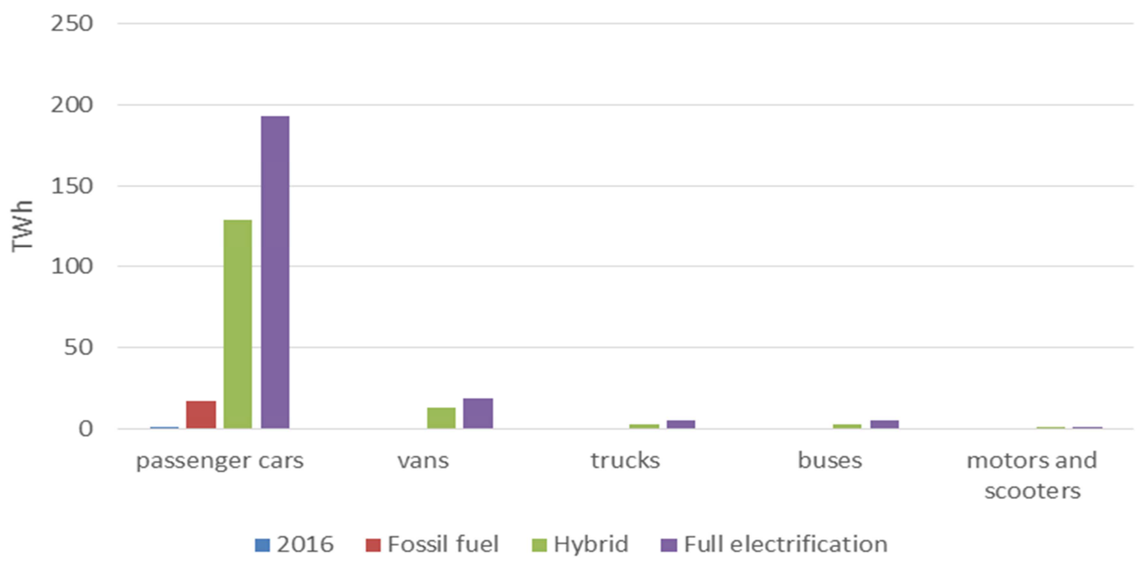


Figure 3: Power demand from electrified transport in 2050



4. Electrification in residential buildings

4.1 Data and assumptions

The second part of this modelling block determines additional power demand from electrification of residential buildings. The model proceeds in a similar way to road transport. To determine the extra demand from the housing sector, we first gather data on the number of residential buildings in Germany, as well as on the annual average consumption of natural gas for cooking, water heating and space heating. Since heating is still oil-fired for a significant share of houses (BDEW, 2015), we also collect data on oil consumption. Similar to the framework for transport, given a net growth rate of the housing stock and assumptions on the share of electrified buildings among new houses, the total housing stock will become more and more electrified up to 2050.

Table 4 presents the input data on the stock of houses and the corresponding energy usage. Destatis (2016) reports that, in 2015, 40.8 million houses exist, with on average 42.7 m^2 per person. The average households consists of 2 persons, so that the average size of a house is 86 m^2. Further, in 2015, the total gas consumption equalled 844 Petajoule or 654 m^3 gas (AGEB, 2016). Only 1% of gas is used for cooking, and 14% 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.

Table 4: Input data on residential buildings

Variable	Value
Number of houses (x million)	40.8
Number of houses electrified (x million)	0
Average size of houses in m2	86
Average gas consumption per house (m3)	654
% of gas used for cooking	1%
% of gas used for hot water	14%
Oil for heating stock of houses (in PJ)	423
CO2 emissions by households in 1990 (Mton)	132

To determine how the stock develops up to 2050, we rely on historical trends and external forecasts. For example, Destatis estimates that in 2035 the stock of houses will grow to 43.2 million. We thus calibrate the annual net increase in houses as 0.3% to match this 2035 forecast. Based on historical data, we assume that each year 220,000 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 (%)	0.3%
Annual number of new houses (x 1000)	220
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

Below we plot the resulting power demand from electrification of the housing sector. The additional demand for electricity is constructed as the sum of power needed for space heating and water – both in newly built fully electrified houses and in existing, but renovated and then electrified, stock. The additional power demand likewise includes the power needed for cooking with electric stoves in new or renovated houses.

Figure 4 depicts the projection results. It should be noted again that the 100% in 2050 in the FE scenario as well as the 50% in 2050 in HY are constructed by design. Likewise, the flat development of the business-as-usual scenario is a direct consequence of our assumption of zero electrification in existing houses and only 5% of electrified heating and water in newly constructed buildings.

Figure 5 shows the resulting 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 by about 80 TWh, all applications combined. This projected increase from electrification represents an increase of about 60% relative to today's total electricity demand of German households of about 132 TWh.[5] The increase is almost halved in the HYBRID scenario, and insignificant in the business as usual FF scenario.

[5] Corresponding to 2015 data, see Destatis.

Figure 4: Share of electrified houses by scenario, 2016 to 2050

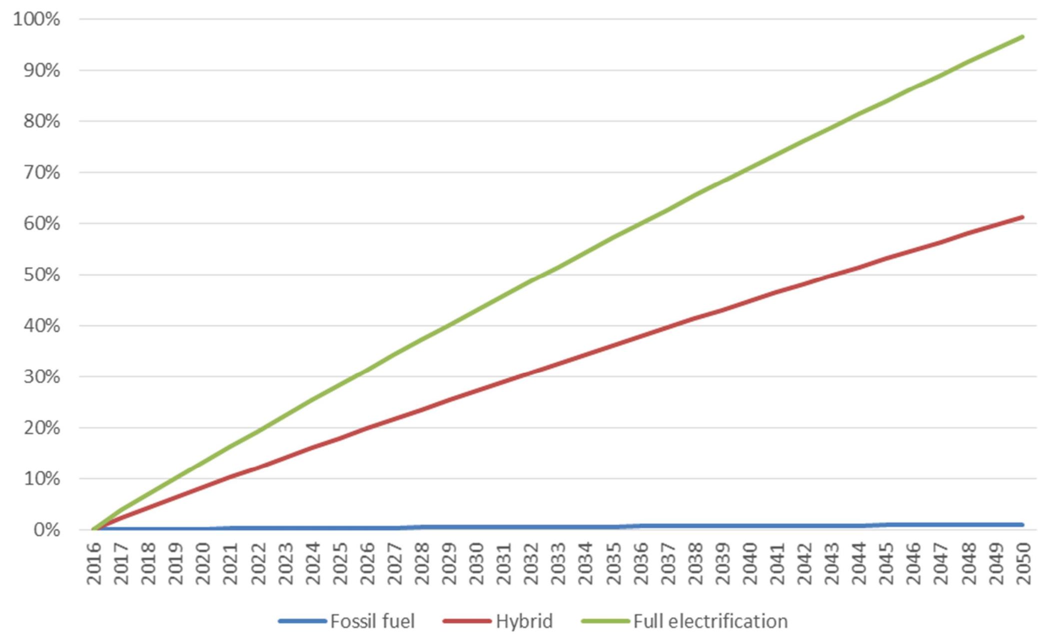
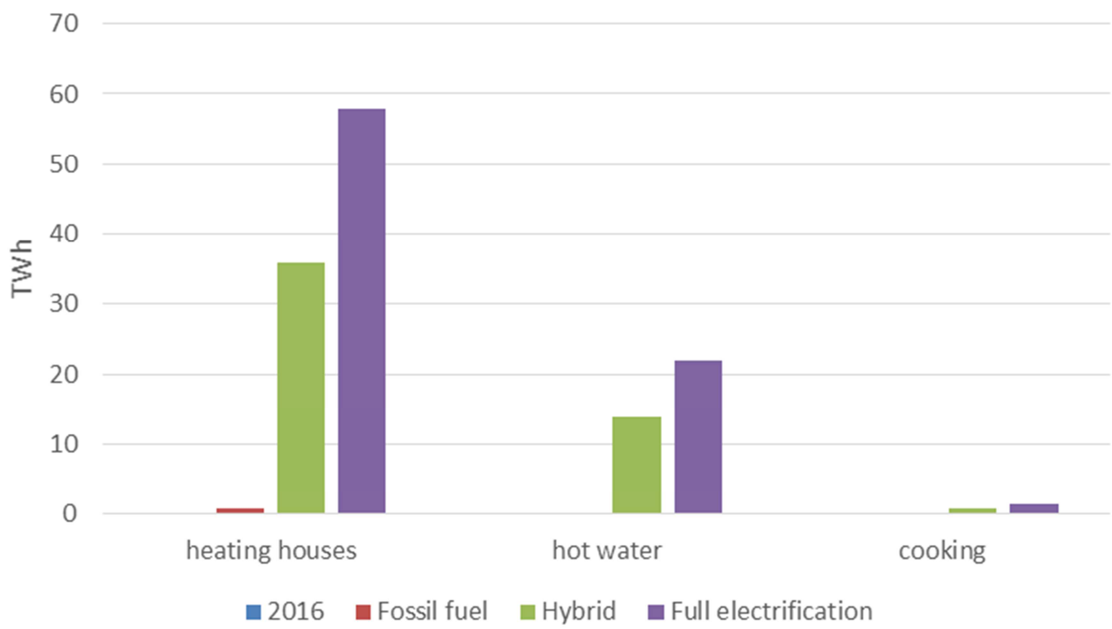


Figure 5: Household electricity demand by scenario and type, 2016 to 2050

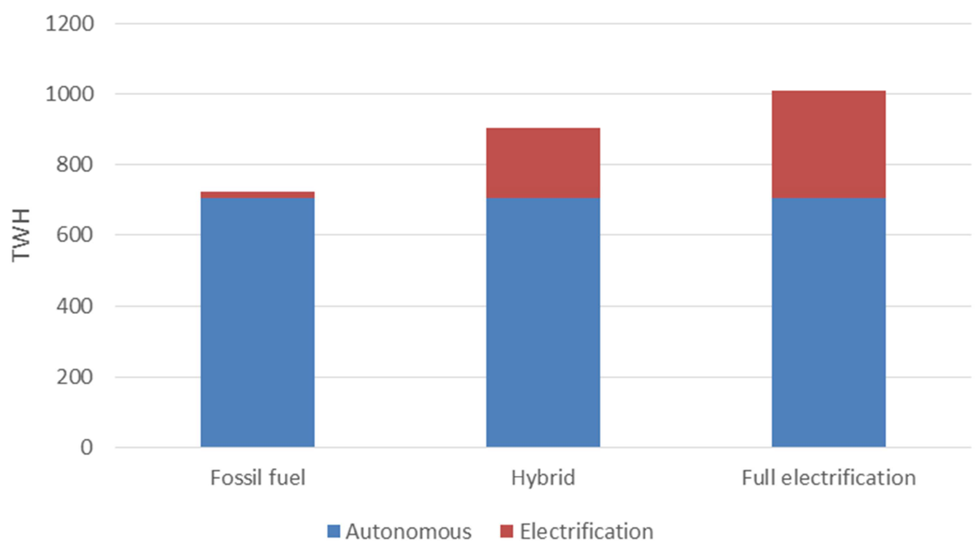


5. Total electricity consumption

Total electricity consumption is not altered by electrification only, but also by other factors such as GDP, general trends in energy efficiency, or patterns in the amount and type of electrical appliances. The net effect of energy efficiency enhancing measures on the one side and the increase via GDP or new electrical appliances on the other is difficult to project. We assume a low, positive growth rate in autonomous electricity usage of 0.5% per year. As such, the impact of electrification will be only one factor that leads to an overall rise in consumption. Figure 6 displays the absolute demand levels in 2050 broken down to autonomous growth and the growth due to electrification of housing and transport.

First, it becomes apparent that even in the FF scenario the autonomous growth leads to a significant increase in consumption as compared to the 595 TWh in Germany in 2016. The impact of electrification is negligible in this scenario. In contrast, in the full electrification scenario the absolute consumption reaches more than 1000 TWh, of which electrification accounts for about 300 TWh. The latter splits up into roughly 200 TWh demand from fully electrified passenger cars and about 80 TWh from electrified buildings, plus some additional demand from the transport sector (vans, trucks, buses). 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 6: Electricity consumption in 2050, broken down to autonomous growth and electrification



Having projected the additional demand from electrifying housing and transportation, the next modelling block turns to the power market and investigates the evolving supply mix needed to satisfy this demand.

6. Generation of electricity

6.1 Policy objectives

The generation technology mix used to supply future demand depends significantly on national policy, and the way it steers investment in different technologies. While in the short run, demand will be covered according to marginal cost, i.e. the merit order, in the long run investment decisions follow not only price but also additional incentive mechanisms such as those for renewable support. Accordingly, the analysis uses a merit order approach to determine the supply mix year by year. Market entry and exit across years is instead determined exogenously according to policy decisions. In Germany, these decisions predominantly relate to i) the phase-out of nuclear generation, ii) the phase-out of coal-fired plants, and iii) the further integration of renewable generation. Ultimately, all policy decisions share the overarching policy goal of reducing CO_2 emissions by at least 80% by 2050.[6]

6.2 Data and assumptions

The phase-out of nuclear generation is clearly determined by the German government, with the last nuclear plant leaving the market in 2023.[7] In contrast, there is no clear-cut strategy for coal-fired generation. Small steps are being made already, for instance, via a newly formed reserve ("Sicherheitsbereitschaft") made up of coal power plants. Yet, how a large scale phase-out can be implemented is still to be discussed. However, the emission reduction targets require a significant reduction of coal-fired generation at least by 2030.[8] For the below analysis we thus assume that coal-fired generation will slowly reduce and ultimately be phased-out by 2030. Lastly, for renewable generation we assume that the speed of market integration will continue as implemented by the renewable energy law in 2017.

Table 5: Modelling choices for market exit and entry of different generation technologies

Variable	Modelling Choice		
Coal-fired generation	Phasing-out in	Year	2030
Nuclear generation	Phasing-out in	Year	2023
Wind in 2030	Including Off-shore	GW	110
Wind, investment p.a. after 2030	As in EEG 2017	GW	2.9
Solar PV in 2030	As in EEG 2017	GW	75
Solar PV, investment p.a. after 2030	As in EEG 2017	GW	2.5

[6] Further modelling details are discussed in the Netherlands case study.
[7] See DIW (2014) for a more detailed analysis on the nuclear phase-out.
[8] See DIW (2017) for a discussion on the role of lignite in the German power market.

Table 5 gives an overview on the modelling assumptions. Next to nuclear and coal-phase out, the assumptions on the further expansion of wind and solar PV are crucial and obtained as follows. Capacities in 2016 are about 50 GW wind (about 45 GW on-shore and 5 GW off-shore) and 41 GW solar PV. In the coming years, the government, via the EEG law, procures annually 2.9 GW for wind, and 2.5 GW for PV. In addition, off-shore capacity is planned to reach 25 GW in 2030. These additions yield a projected 110 GW wind and about 75 GW solar PV capacity in 2030. After 2030, the same speed of integration is assumed, as there is no known policy mandate for a further yearly expansion. To establish yearly projected generation mixes, the phase-out plans and renewable expansion path are applied to the generation mix of 2016 and projected towards 2050. The generation mix of the starting year 2016 is presented in Table 6.

Table 6: Generation mix in Germany in 2016

Variable	Value (TWh)
Gas-fired generation	81
Coal-fired generation	262
Nuclear generation	85
Hydro	21
Wind	77
Solar	38
Biomass	46
Other	40
Net import	-54
total load	595

6.3 Results

Results for the supply mix are, of course, strongly driven by the assumptions as discussed above. However, using these simplistic assumptions, an overall picture emerges when comparing the shares of renewable generation across the three electrification scenarios. First, in the fossil fuel scenario, we reach the policy goal in 2050 of a largely renewable-based power system (see Figure 7a). This outcome is driven by the assumptions that closely follow policy goals for the expansion path of renewables. It should be noted that most uncertainty will lie in how the share of conventional generation will turn out around 2025 to 2030, in particular how the coal-phase out will evolve. In addition, our model lacks demand flexibility and is blind vis-à-vis imports that would reduce the role of gas as coal is being phased-out.

Figure 7b depicts the results for the full electrification path. As can be seen, dominating shares of renewable assets will not be reached under full electrification, unless the renewable expansion path will be further increased after 2030.

Figure 7a: Generation mix business-as-usual, 2016 to 2050

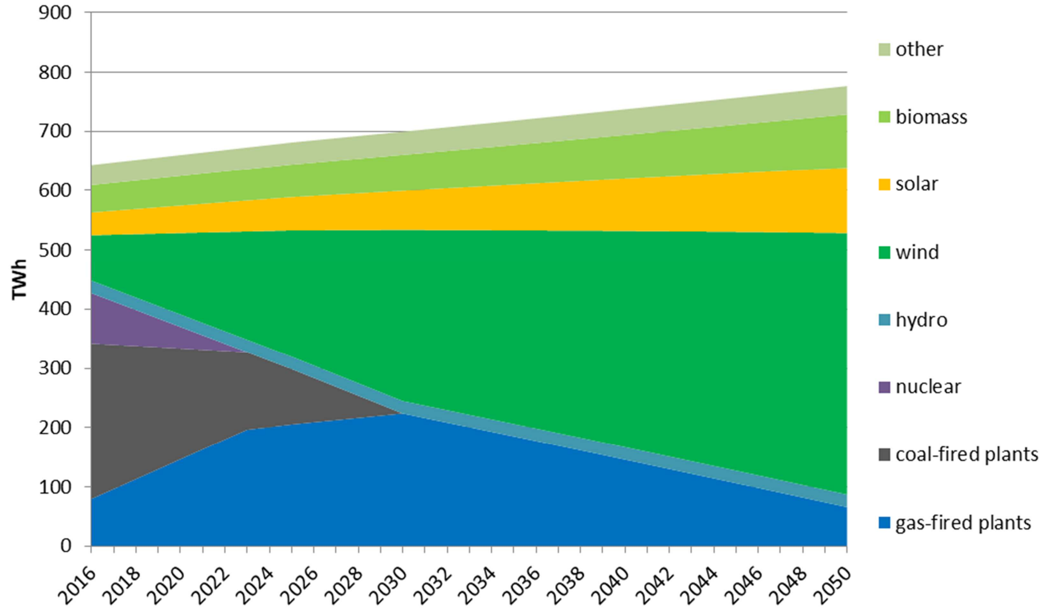
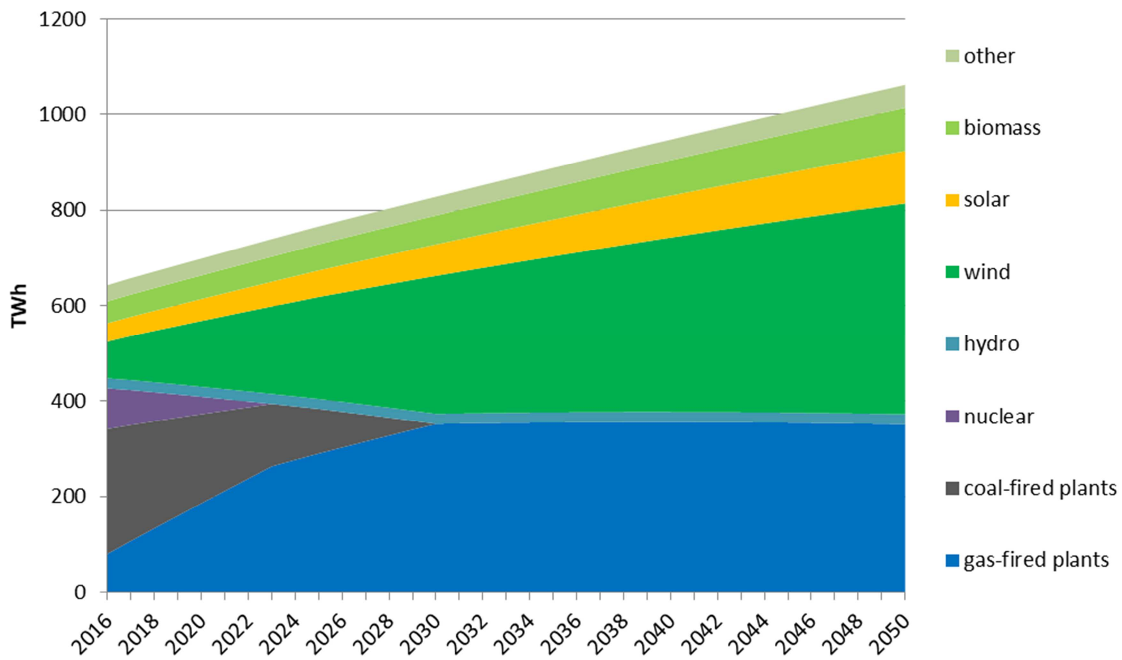


Figure 7b: Generation mix full electrification, 2016 to 2050



7. Demand and supply of flexibility

7.1 Data and assumptions

The generation mixes shown above illustrate supply under regular conditions, i.e. using average capacity factors for wind and solar. While for a full year, this is an appropriate approach, at a more granular level, for instance within-day, the supply mix may look different. To analyse extreme conditions, the model investigates a representative "best" and "worst" day. 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 Moraga and Mulder (2018), 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 20% of what is generated on an average day, wind output of less than 36%, demand above 115% of the average day, and a low temperature, measured in heating degrees, of higher than 216% of the average day.[9] A day among the best days is characterised by PV output of more than 177% of the daily average, wind output of more than 135% of the daily average, load below 85%, and a heating degree of 15% of the daily average. Note that these flexibility considerations are hypothetical and exclude a range of flexibility sources not treated in the model. Specifically, pooling effects of cross-border trade and demand response are not considered.

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 renewables, even in the full electrified scenario. The main sources of supply then are wind (on-shore and off-shore), solar PV, and biomass, as illustrated in Figure 8a.

The picture changes significantly when illustrating the outcome for 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, as apparent in Figure 8b, that illustrates a hypothetical worst day in the full electrification scenario. Note that generation on the y-axis is scaled as TWh by day.

[9] The measure of heating degree days is defined as MAX(Daily Avg. Temperature – Base Temperature, 0), where 18 degrees is used as Base Temperature.

Figure 8a: Power supply on a hypothetical best day under full electrification

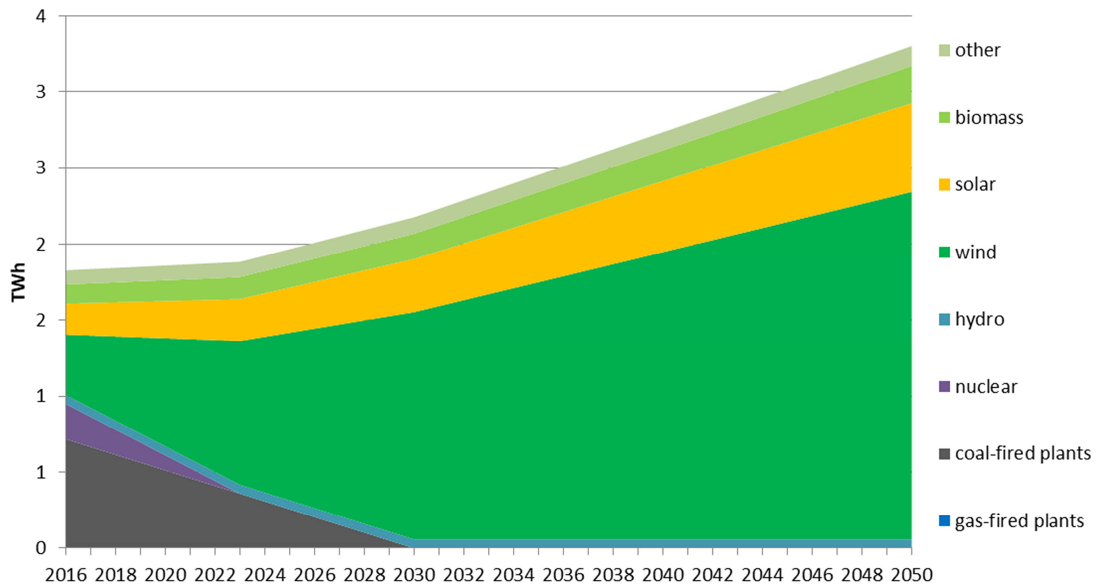
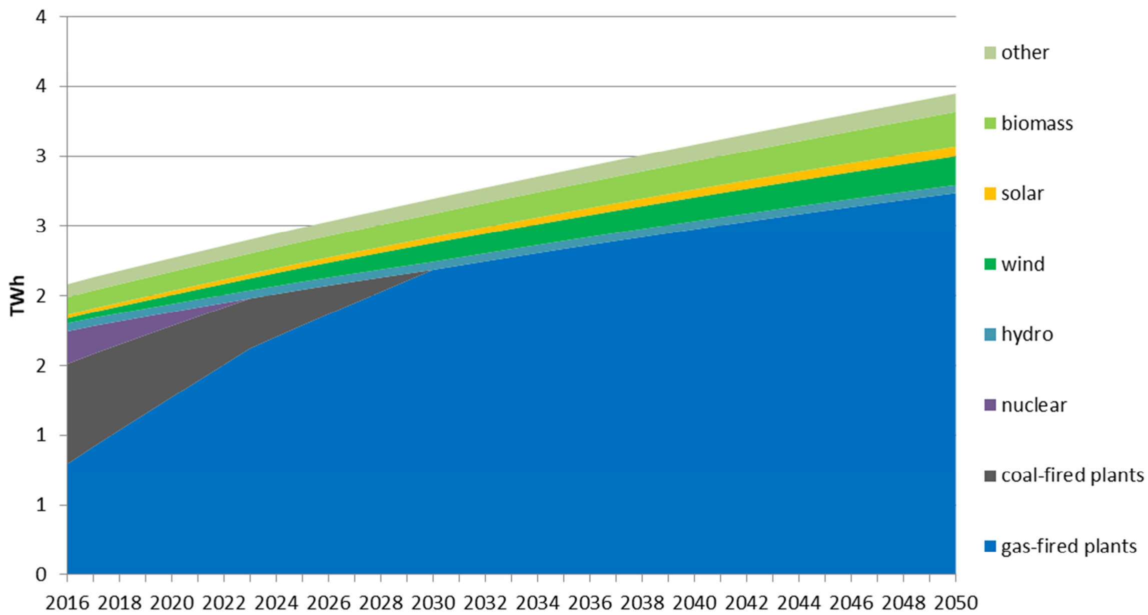


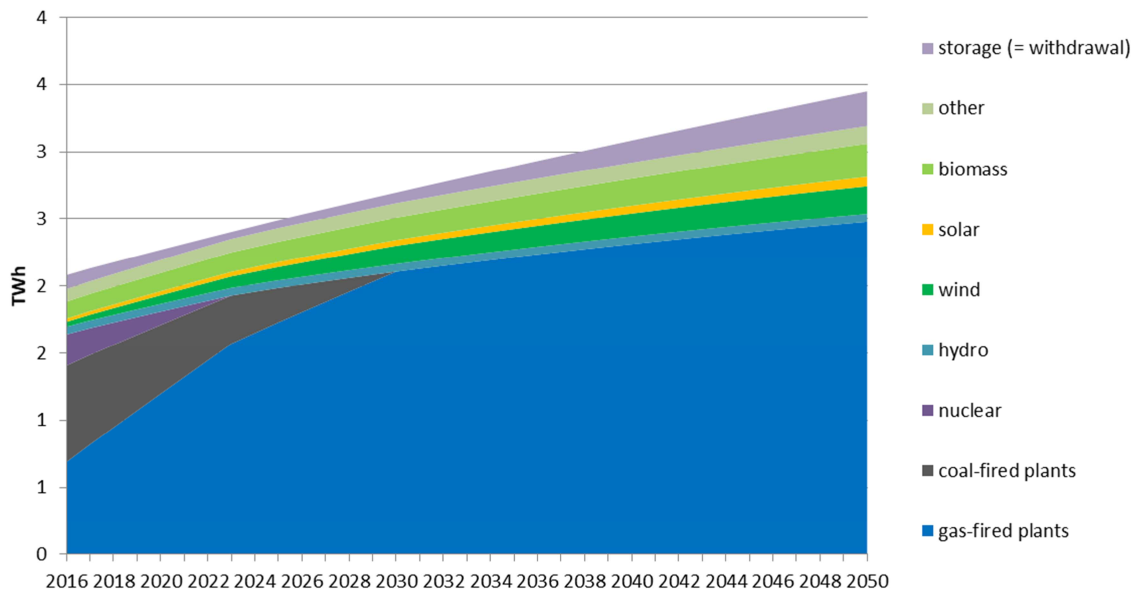
Figure 8b: Power supply on a hypothetical worst day under full electrification



Further, note that because the results above exclude flexibility sources, the shares of gas-fired generation can only be interpreted as upper bound, and would be lower if trade, storage, and demand response were included in the model.

To shed light on the role of gas (and gas storage) in the above, the model also can be used to integrate power-to-gas plants to deal with seasonal storage. Specifically, if oversupply occurs during the hypothetical best day modelled, the model considers seasonal storage provided by power-to-gas infrastructure (assuming it is in place). Oversupply is then stored during best days by converting electricity into hydrogen. Next, the model simulates demand and supply of electricity on a worst day. If all conventional sources, excluding gas plants, are insufficient to meet demand, hydrogen from storage is used to generate electricity. If this additional supply is still insufficient to satisfy demand, gas-fired power plants are dispatched as the supplier of last resort. As Figure 8c shows, oversupply indeed occurs during best days and can be used during worst days. The modelling approach specifically addresses seasonal storage. It should be noted that other flexibility options that offer flexibility at a more granular time frame, e.g. hourly, are excluded and thus the more detailed breakdown of storage technologies requires additional research. Yet, allowing for seasonal storage in the model shows that the latter will play a role for the full electrification scenario.

Figure 8c: Power supply on a hypothetical worst day under full electrification, with storage withdrawal



8. Consumption of natural gas

The next block of the model calculates the net impact on the consumption of natural gas in each scenario. 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 5), and, on the other hand, the increase of gas consumption in the power sector (see Figure 7b above). The following derives this net impact.

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 changes over time. As Figure 9 shows, gas demand first increases until 2030. This increase results from the power market and is a result of phasing-out coal in the electricity sector, and a simultaneous increase in power demand from electrification. The latter cannot be covered by renewables only, as the speed of market integration cannot make up for the diminishing market shares of coal. The initial increase in gas demand until 2030 is strongest for the FE scenario, where power demand increases most rapidly.

The trend reverses after 2030, when coal has been phased-out. The decrease after 2030 is due to the further increase in renewable generation whilst demand from electrification grows at a slower pace from 2030 onwards. In the business as usual FF scenario, the demand for gas even drops below current levels in 2050. With full electrification, gas demand is higher than today.

Figure 9: Gas demand from residential buildings and power, 2016-2050, by scenario

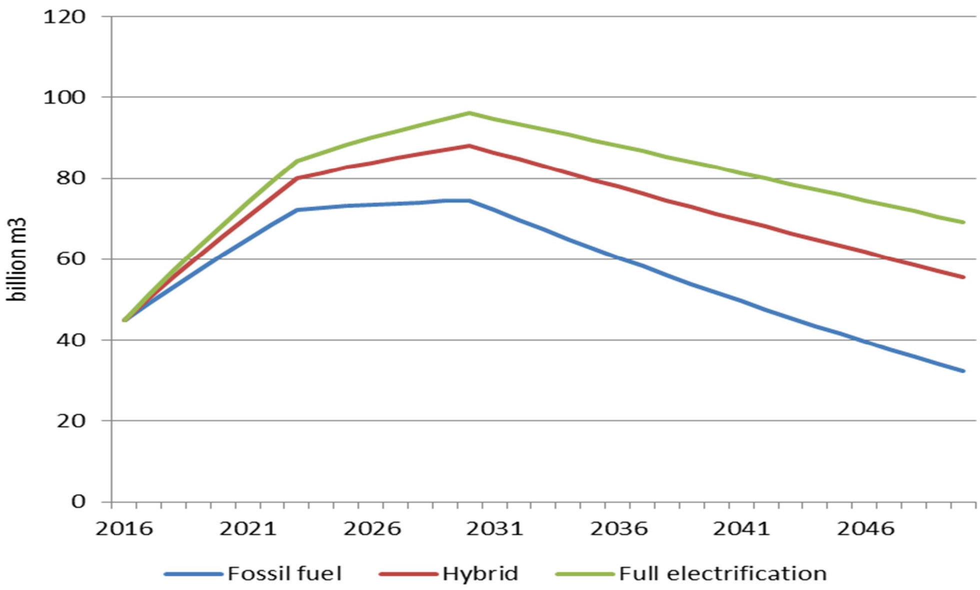
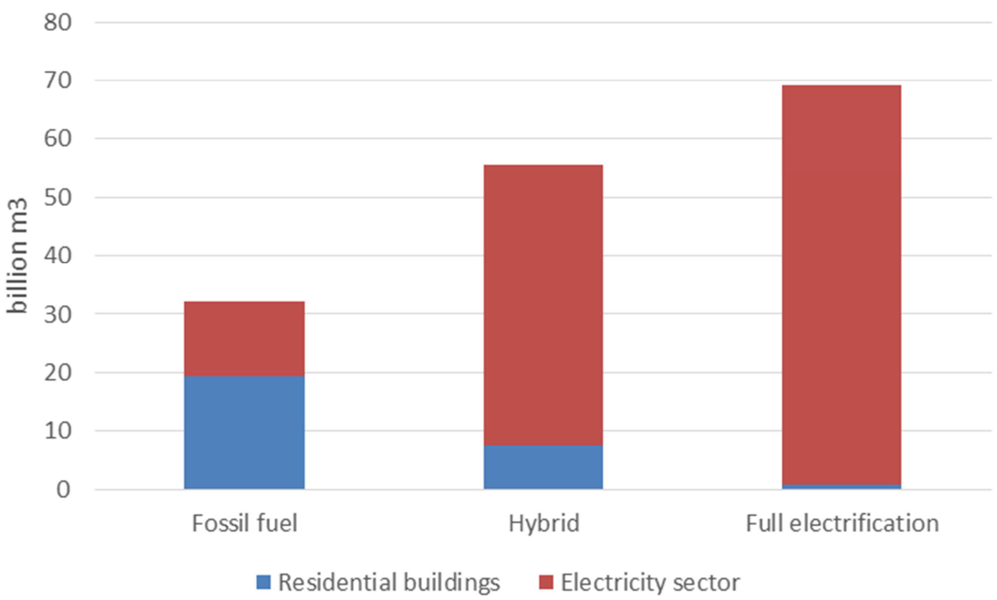


Figure 10 illustrates how gas demand is shifted from the residential sector to the power market. In particular, while in the FF scenario in 2050 more than half of gas demand still stems from the housing sector, in the FE scenario nearly all gas demand shifts to the power market. In addition, it becomes apparent by how much gas demand overall increases as the residential demand declines (blue bar in FF) and demand is shifted to the power sector.

Figure 10: 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-fired power plants is biogas. In particular, the volume of biogas in the gas system is 0.86 bcm in 2016 and we assume that this volume increases yearly by 2%.

9. Electricity and gas distribution networks

9.1 Data and assumptions

So far, the case study has derived additional power demand from electrification, how this demand will be met on the supply side, and what the net impact on gas demand will be. What remains are the effect on power and gas networks as well as on CO_2 emissions. Both electricity and gas provision rely on the use of distribution and transmission networks. Thus, an increase in power generation or gas consumption has to be accompanied by sufficient network capacity. Below, we highlight the changes in load that the power grid, and the changes in gas demand that the gas network, have to accommodate. Note that these demand increases represent the same 5% worst days as used above, because network capacity usually is constructed according to maximum demand instances. Thus, these conditions represent situations in which demand for electricity is above the 95th percentile and gas demand is high accordingly.[10] In what follows, we take the assumption that current distribution network capacities suffice to deal with current volumes of load and gas, respectively. In this vein, Figures 11a and 11b illustrate how the peak demand that the power and gas network have to transport change in percent as compared to the FF scenario.

9.2 Results

In the FE scenario, the electricity grid has to increase most significantly over the years in order to deal with the increase in peak demand, as shown in Figure 11a. In 2050, the electricity network capacity should be able to transport about a third more peak load than today. Similar results hold for the gas network. Both, the HY and FE scenario also require more gas to be transported, see Figure 11b. Note that, as gas demand has been declining in Germany and the networks are not constrained today, this does not mean that additional investments will be needed with certainty. Further note that the model does not take network topology into account. That is, as gas demand shifts to gas-fired plants and away from meshed networks in residential areas, network requirements may change locally, with more capacity needed to deliver spots of gas-fired generation, and less capacity for vast residential areas.

[10] To the degree that other sources of flexibility reduce maximum load and gas levels, also the network needs will appear lower. As discussed for the flexibility analysis, these illustration hence consider upper bounds.

Figure 11a: Increase in electricity network usage, as compared to FF

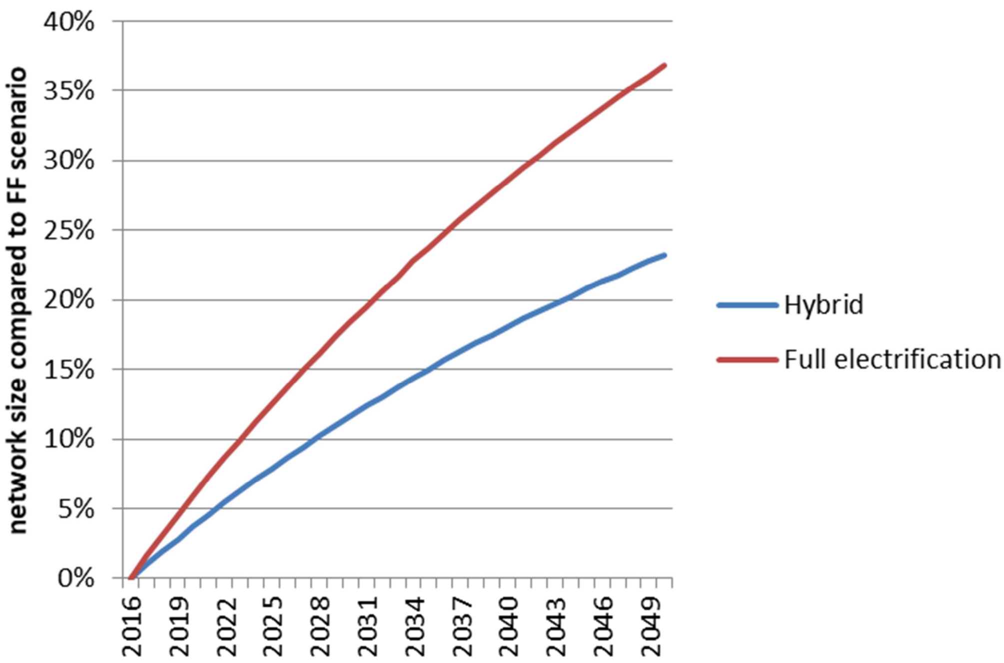
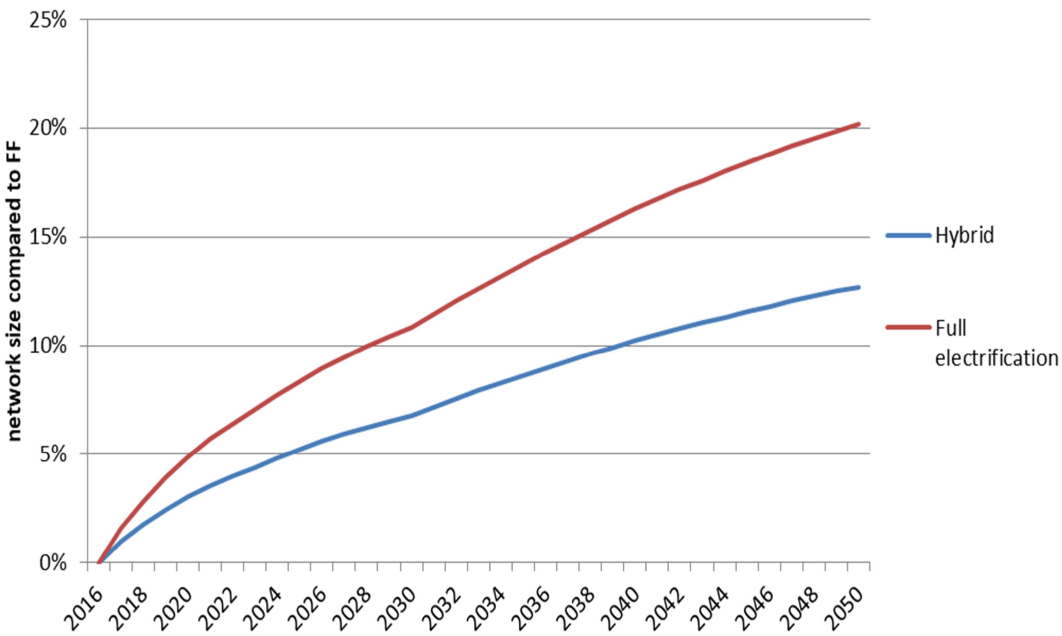


Figure 11b: Increase in gas network usage as compared to business-as-usual



10. Carbon Emissions

Ultimately, policies in favour of electrification should be measured vis-à-vis the overall policy goal of reducing CO_2 emissions. The policy objective is to reduce emissions by 80 - 95% as compared to 1990 levels. What is the effect of electrification on emissions? Note that emissions have already been decreasing from 1990 in Germany. As of 2015, the last year before the start of the analysis, the overall CO_2 balance already decreased by 26%, dropping from 1250 million tons of CO_2-equivalent in 1990 to about 925 million tons (Agora, 2016). Much of these reductions have taken place in industry and the energy sector. In the power market, emissions decreased from 366 million tonnes in 1990 to 306 million tonnes in 2015 (UBA, 2017).

In line with policy, the analysis below measures reductions against 1990 levels. To do so, we need to gather data on emissions from transport and buildings in 1990, in addition to the power market. Table 9 summarises the emissions data for 1990 by sector. The transport sector emitted 163 million tons in 1990, of which 61% was from passenger cars and 35% from duty vehicles, which due to the lack of more granular data are assumed to equally split into vans and trucks. Importantly, the main driver of emissions turns out to be passenger cars, so that this approximation between vans and trucks is secondary. Table 10 then illustrates assumptions that are used to translate the switch from fossil fuelled to electrified cars and the corresponding impact on emissions.

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

Variable	Value
CO2 emissions in 1990	
Residential buildings	132
Road transport	
Passenger cars	99.4
Vans	28.5
Trucks	28.5
Electricity sector	366

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.[11]

To obtain emissions from gas and oil 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 CO2 emissions per m^3 of natural gas are taken to be 2.2 kg. The same is done for oil-fired heating, with a factor of 2.6 tons of CO_2 per ton of oil.

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.

10.1 Results

In the FF scenario, the emissions originating from all three sectors together decrease by about 50% by 2050 (see Figure 12a). This reduction stems foremost from the power market, where apart from limited emissions from gas-fired units, the decarbonisation goal will be reached under business-as-usual assumptions. However, due to growth in road transport and no large-scale electrification efforts in this sector, the bulk of emissions from transport remain. Also, carbon emissions from residential buildings are more or less stable in this scenario.

As can be seen, in the full electrification scenario (Figure 12b), emissions reductions are larger than the business as usual scenario. This implies significant cost savings from reduced damage from CO_2 emissions. Reduced emission levels are due to the switch from energy usage from fossil fuel intensive traditional heating and transport to the “greening” power market. In line with this, Figure 12b also shows that power market emissions, mainly from gas-fired generation, are higher under the FE scenarios than for FF in 2050. However, overall we confirm a reduction of CO_2 emissions due to the electrification of residential buildings and transport. A more detailed breakdown of emissions in road transport and residential buildings can be found in Figure A1 and A2 in the Appendix.

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

Figure 12a: CO_2 emissions over time, fossil fuel scenario

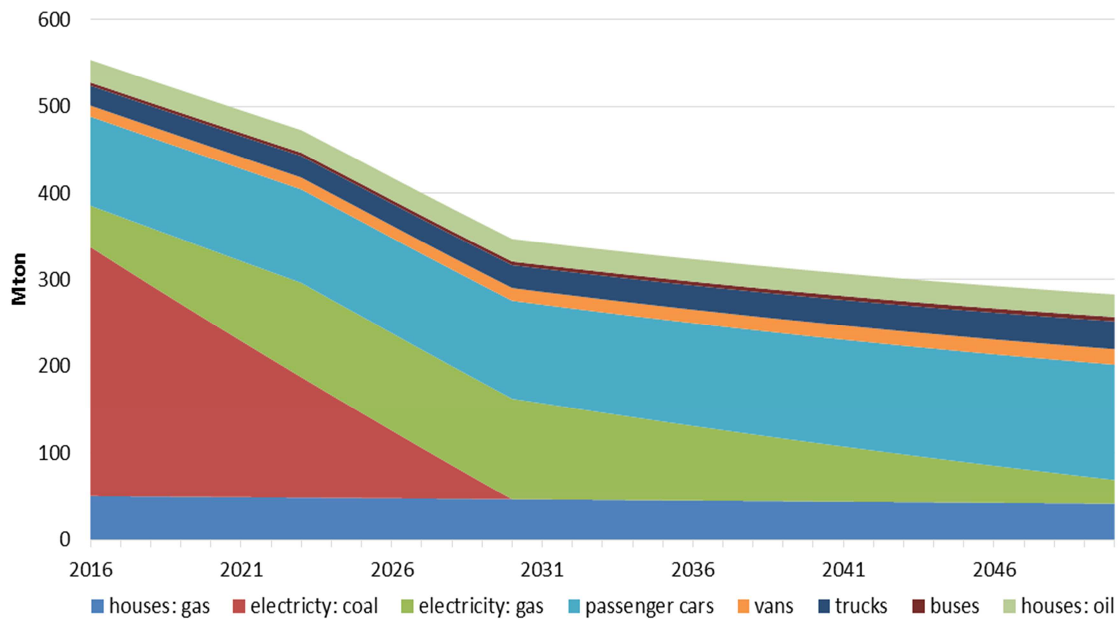


Figure 12b: CO_2 emissions over time, full electrification scenario

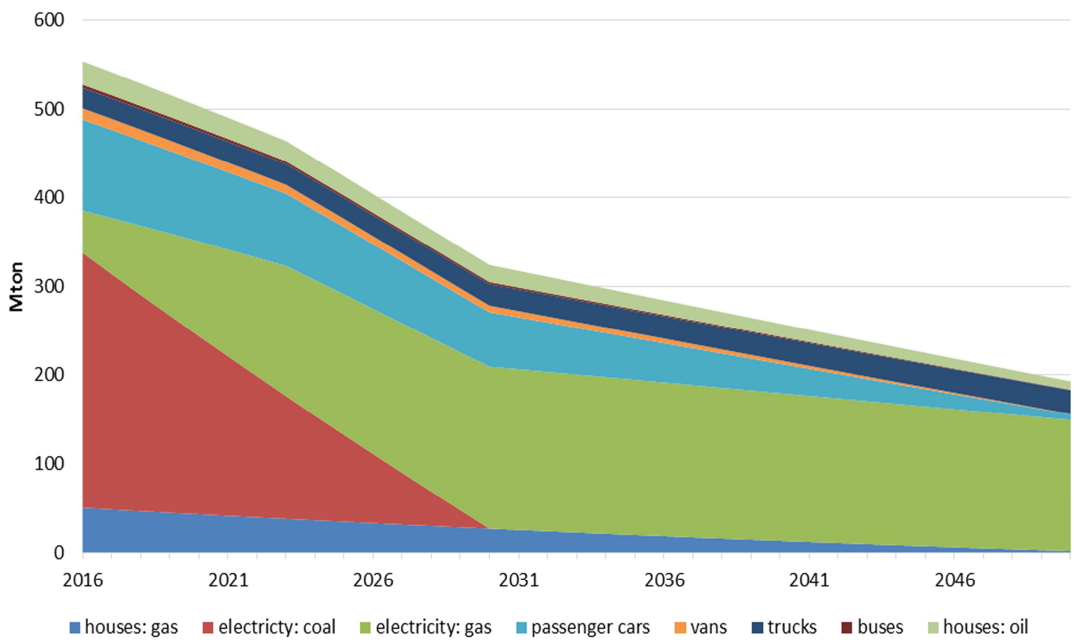
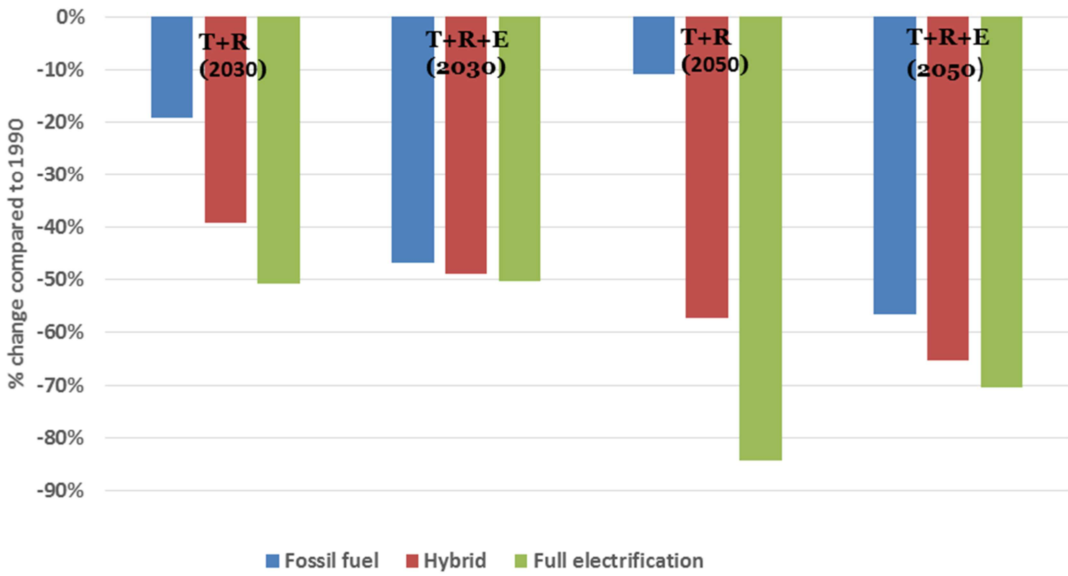


Figure 13: Projected CO_2 emission reductions by sector and scenario in 2050



Note: The first two sets of entries relate to projected reductions in 2030, first for transport and residential buildings only, and second for all sectors. The second set of entries relates to 2050, again first for transport and buildings only, and second for all three sectors.

Finally, Figure 13 illustrates the projected reduction as compared to 1990 levels. In the FF scenario, emissions (all three sectors combined) will be reduced and reach 50% in 2030, when coal-fired generation is phased-out. After 2030, emission reduction in the power sectors alone do not suffice for reaching the overall 2050 goal. Emissions reduce by only about 55% in 2050. This is largely due to constant emissions in road transport and from residential buildings. Also in the FE scenario in 2050, emission reductions of slightly above 70% do not suffice to meet the policy goal of at least 80%. Here, in contrast, the main driver for emissions is the share of fossil fuel power generation to cover increased demand from electrification.

Thus, if one remains in the business as usual case, policy goals will not be reached due to emissions from the transport and building sector. If, however, policy aims for the FE scenario, policy goals will only be reached when renewable generation is increased in conjunction.

11. System costs

Last, the model evaluates the scenarios within a net-present value approach. In essence, this implies comparing benefits from reduced emissions against costs from switching to electrified houses and transport. As for housing, the model accounts for costs of insulating old houses, and the excess costs of installing heat pumps relative to gas boilers. 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 case study on the Netherlands by Moraga and Mulder (2018).

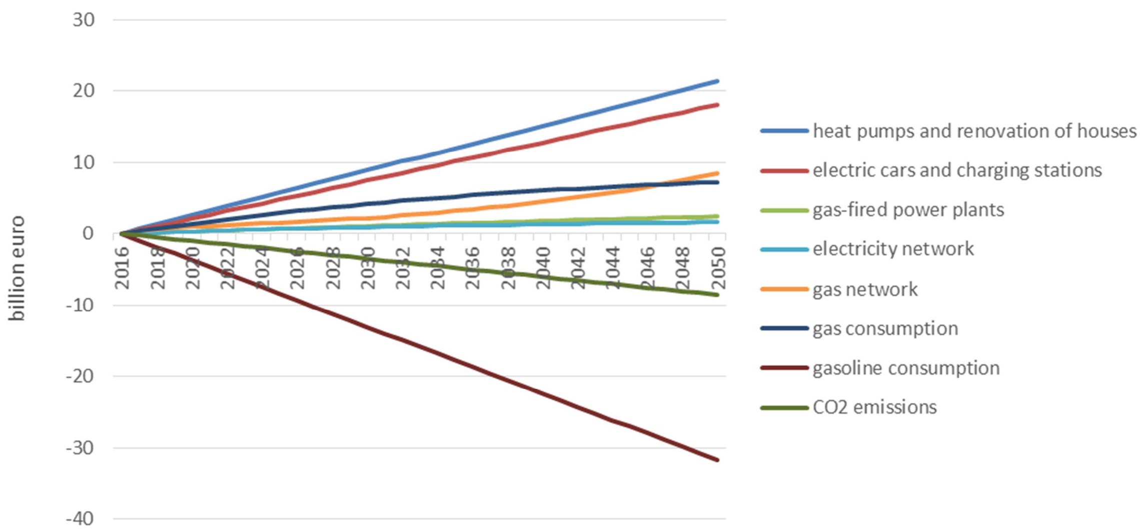
Table 11: Assumptions on system costs

Variable	Value
Weighted Average Costs of Capital (WACC)	5%
Discount rate (for NPV calculations)	3%
Depreciation periods (years)	
- grid	20
- power plants	20
- houses	40
- cars	10
Investment 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)	62
Investment costs residential buildings	
- heat pump (euro / house)	6000
- renovating house (euro/m2/house)	105
Investment costs road transport	
- quick charging stations (per unit)	35000
- ratio charging stations / cars	0.08
- extra costs of electric cars (euro/car)	7500
Gas price (Euro/MWh)	20
annual change in gas price	0%
Price motor fuels (Euro/lt, excl taxes)	0.5
annual change in price motor fuels	0%
shadow price of CO2 (euro/ton)	50
CO2 price in ETS (euro/ton)	10

11.1 Results

Costs of electrification are reported by comparing total system costs in the HY and the FE scenario with the FF scenario. The degree of electrification is the only factor that is different across scenarios; any difference in costs can thus be fully attributed to differences in the degree of electrification. Before we present the net-present value across each scenario, Figure 14 illustrates the main cost drivers. As can be seen, the electrification of old and new houses via heat pumps constitutes the main cost driver, followed by the extra costs of electric vehicles. This is intuitive, as these represent the largest fixed costs. On the benefit side are, first, cost reductions due to less spending on gasoline, and second, reductions in CO_2 emissions.

Figure 14: Contribution of different cost drivers (negative costs represent benefits)



Eventually, we present two outcomes for the net-present value for different parameters of fixed costs. As shown above, fixed costs for heat pumps and electric vehicles are major cost drivers. The model thus calculates the value for today’s investment costs for heat pumps, electric cars, and charging equipment (Figure 15a) and a net present value using 75% of total costs (Figure 15b). This is to represent learning curves, which, as well-known, have occurred for many technologies after market take-off, such as for solar PV. As can be seen, with today’s investment costs, the net present costs of both electrification scenarios are positive. For an assumed cost reduction of 75%, positive net present costs remain, albeit significant cost reductions occur, which illustrate the strong sensitivity to cost parameters.

Figure 15a: Net-present system cost for Hybrid and Full Electrification scenario, today's investment cost

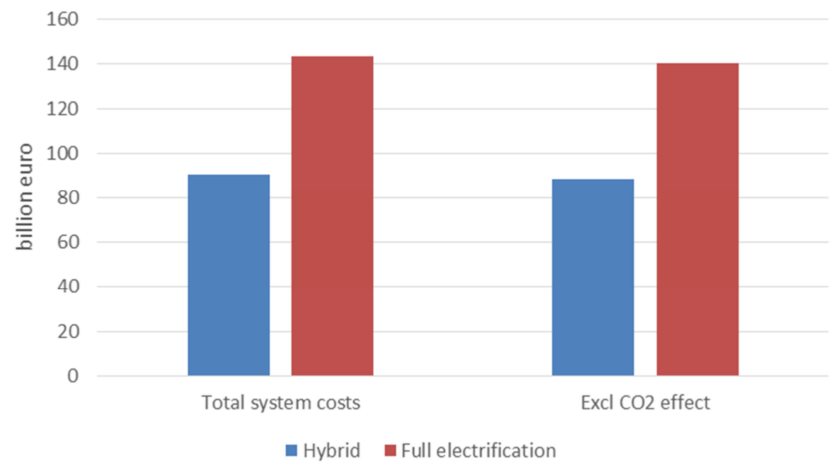
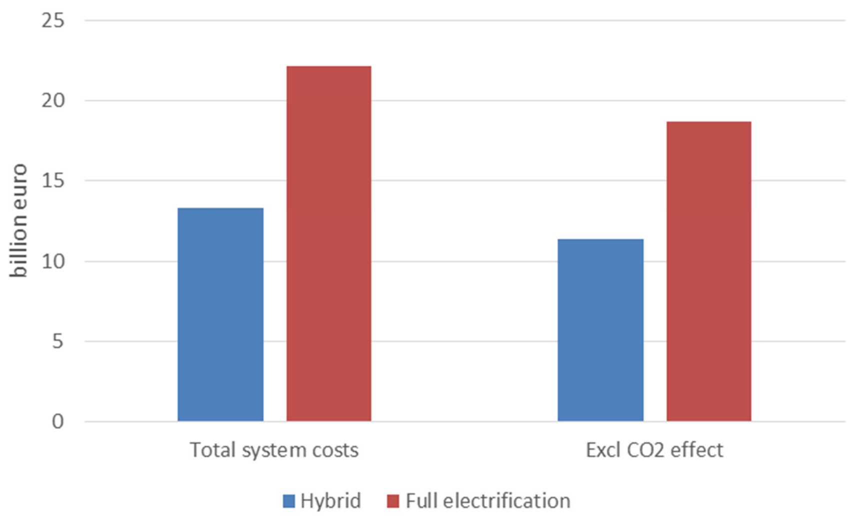


Figure 15b: Net-present system cost for Hybrid and Full Electrification scenario, 75% investment cost



12. Conclusion

This case study presents a scenario approach to analyse consequences of electrifying road transport and residential buildings in Germany. The analysis projects assumed electrification paths in three scenarios (business as usual, hybrid, and full electrification) towards 2050. In doing so, the analysis can be understood as a projection given chosen parameters rather than a forecast. All parameters are derived using historical data or estimates from the existing literature. The overarching motivation for this study is to investigate the benefits of electrification of transportation and housing in CO_2 emissions, taking into account costs for electrification. The study also investigates corollary findings, such as on the remaining use of fossil fuels, and in particular natural gas. That is, it analyses the net impact on gas demand of reduced gas consumption in the heating sectors but increased demand for power generation.

As for CO_2 emissions, the case study evaluates achieved reductions vis-à-vis the policy goal of reducing emissions by at least 80% in 2050, relative to 1990 levels. In the business as usual case, while the power market is nearly decarbonised in 2050, the overarching policy goals of reducing emissions across all sectors is not reached. This is due to a relatively constant emission path for transport and housing in the business as usual fossil fuel scenario.

However, in the full electrification scenario, emission targets will also not be reached, unless renewable generation is deployed more significantly than currently envisaged. Still, emissions decrease in the full electrification scenario as compared to business as usual, indicating a positive net effect of electrification on emissions.

Total system costs are ambiguous. Given today' investment costs for heat pumps and market prices of electric cars, electrification has negative net-present benefit. This finding however, depends significantly on the evolution of relevant cost factors (such as for electric vehicles), as sensitivity analyses show. Another relevant cost factor is the increase in distribution grids to cover increasing peak demand. It should be noted, however, that improving distribution grids will not be required due to electrification (that is an increase in demand) only. Also growing decentralised power supply will make it mandatory to invest in distribution grids.

In sum, four findings emerge. First, full electrification, that is, shifting emissions from the transport and housing sectors to the power market can reduce overall emissions. Second, if decarbonisation goals ought to be fulfilled, however, renewable integration has to increase alongside to cover the additional power demand from the transport and housing sectors. Third, the infrastructure needs, especially at the distribution level, will inevitably rise. However, because decentralised generation is also increasing, enhancing distribution grids -to the necessary degree- appears as a no-regret option. Fourth, today's investment costs for heat pumps and electric vehicles still represent a barrier to coupling the power, heat, and transport sector.

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Appendix

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

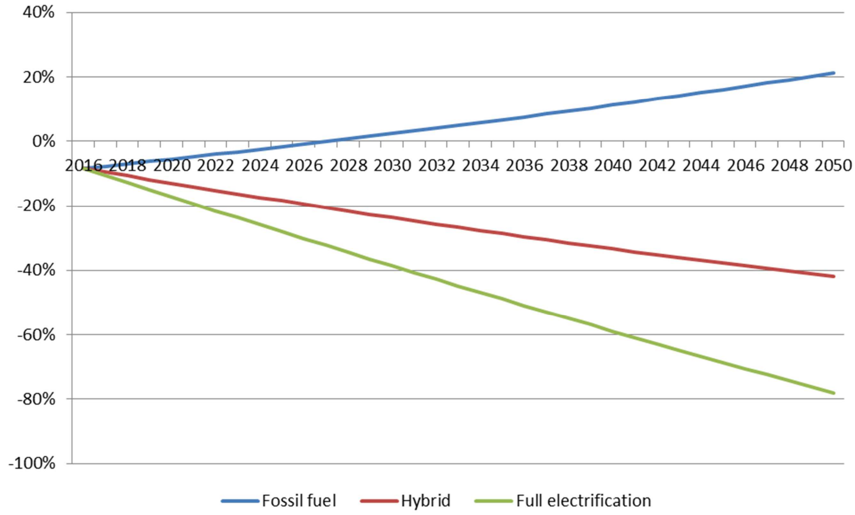

Figure A2: Projected CO_2 emission from residential buildings, by scenario