Groupe PSA

Assessment of green mobility scenarios on European energy systems

Master Project

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Abstract

The paradigm shift in the energy policy of the European Union confronts the member states with the task of developing future renewable and fossil-free energy systems. This change involves the installation of intermittent renewable energy sources such as wind and solar, which induce a demand for storage capacity. The modelling of smart cities with electrified mobility allows the optimisation of mobility and renewable energy combination. However, in order to analyse the system as a whole, system-based cross-sectoral energy models have to be used, including intersectoral exchange.

Within this thesis the system-based and cross-sectoral energy planning tool EnergyScope will be adapted to mobility, in order to analyse the influence of different vehicle technologies on the energy system of two main agents of the European Union. Historical mobility data was analysed to predict the mobility behaviour of France and Germany for the year 2050. These estimates were integrated into two EnergyScope models with different temporal resolution and optimized according to thermoeconomic criteria. The model with the monthly resolution allowed to estimate the impact of vehicles with batteries, fuel cells, synthetic fuels and biofuels on the whole energy system. The model based on typical days allowed to visualize the influence of smart mobility such as vehicle-to-grid technologies in electric vehicle composition. The efficiency of the monthly model also allowed a Morris and Monte Carlo uncertainty analysis of the estimated parameters.

The results show that the vehicle composition strongly depend on the existing renewable energy potential, with electric vehicles being the preferred technology for private passenger transport. Fuel cells are preferably used for road freight transport where electric trains cannot take over. Despite different energy strategies of France and Germany, the optimized energy systems differ mainly in primary energy consumption, with the installed technologies being largely the same. The promotion of synthetic or biofuels leads to an increase in primary energy demand, which pushes up emissions and costs compared to electrically based mobility. Hydrogen benefits from the possibility of energy storage through power-to-gas, although fuel cells for private mobility are not the pareto-optimal solution due to their higher purchase price compared to electric vehicles.

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The Master thesis concludes the study period, whose aim it is to apply the acquired knowledge and to prove that the acquired skills allow to pursue the profession of an engineer. During my studies I have longed for the moment when I would write the acknowledgements to complete the master thesis and thus close the chapter of my studies. And now the time has come, I sit here, look back and realize that the path is and was the goal. Indeed the years at EPFL have left their mark on me. While the bachelor's programme was still very school-based and many a struggle & failure was connected with physics and analysis, but taught me one thing: *"Nid lugg lah gwinnt"* - giving up is not an option...

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Acronyms

ADEME	Agence de la transition écologique
BEV	Battery-Electric Vehicles
CC	Carbon Capture
CHP	Combined Heat and Power
DTU	Technical University of Denmark
EPFL	Ecole Polytechnique Fédérale de Lausanne
EQU	Energy-Equivalent Unit
ES	EnergyScope
EU	European Union
EUD	End Uses Demand
EV	Electric Vehicle
FCV	Fuel Cell Vehicle
FFC	Flexible Fuel Vehicle
GDP	Gross Domestic Product
Groupe PSA	PSA Peugeot Citroën
GWP	Global Warming Potential
HD	Long (High) Distance
HP	Heat Pumps
HR	High Range
ICE	Internal Combustion Engine
INSEE	Institut national de la statistique et des études économiques
IPCC	Intergovernmental Panel on Climate Change
IPESE	Industrial Processes and Energy Systems Engineering
KPI	Key Performance Indicators
LCA	Life Cycle Analysis
LCIA	Life cycle impact assessment
LD	Local Distance
LFO	Light Fuel Oil
LPG	Liquified Petroleum Gas
LR	Low Range

MILP	Mixed Integer Linear Programming
MobES	Mobility EnergyScope
MR	Medium Range
NG	Natural Gas
OECD	Organisation for Economic Co-operation and Development
P2G	Power-to-Gas
PHEV	Plug-In Hybrid Electric Vehicles
rES	R-EnergyScope
Rte	Réseau de Transport d’Électricité
SF	Synthetic Fuels
SNG	Synthetic Natural Gas
TD	Typical Day
V2G	Vehicle-to-Grid

Preface

The present thesis was written at the Section for Mechanical Engineering, School of Engineering Department, Swiss Federal Institute of Technology Lausanne (EPFL). It is submitted as partial fulfillment of the requirements for the completion of the Master's degree.
The thesis was carried out during 18 weeks from February 24, 2020 to July 3, 2020, under the supervision of Professor François Maréchal, Dr. Tuong-Van Nguyen and the co-supervision of Dr. Paul Stadler.
During the project, an energy planning model was refined with the mobility sector, allowing to analyse the impact of green mobility on the European energy system. In addition, a tool in the programming language R was developed, which calculates the input parameters of the energy planning model, executes the model and stores the solutions systematically.

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Jonas Schnidrig

Chapter 1

Introduction

1.1 Background

World energy consumption has more than doubled in the last forty years (factor 2.4) and was mainly (80%) covered by fossil fuels [10]. In Europe the ratio is similar, with 74% coming from fossil fuels, 10% from nuclear energy and 15% from renewable sources in 2018. This growth can largely be attributed to global economic growth, with the largest increase in primary and final energy-demand coming from non-OECD countries. This development will be largely based on fossil-fuel-based energy, the driving force behind the OECD countries' development in the past. [11] At the European level, this dynamic is different, as population and economic growth have grown moderately, which goes hand in hand with energy consumption.

The question of the sustainability in fossil fuels has not been resolved. The green wave is increasing noticeable and action is needed. The 2015 United Nations Climate Change Conference COP21 allowed the gathering of 55 countries responsible for at least 55% of global greenhouse gas emissions. COP21 resulted in the "Paris agreement", which aims to define measures to reduce global warming (maximum 2°C) and the consequences it will have [12]. The European Union has drawn up an "Energy Roadmap 2050", within the "European Green Deal" in 2019, which has the goal of a greenhouse gas emission free economy by 2050. To achieve this necessary transition, all parts of society and economic sectors are involved, as the energy sector, industry, households, services, agriculture or mobility. [13]

In 2016, mobility accounted for 33.2% of final energy consumption and 24.3% of greenhouse gas emissions in the European Union. Private mobility is largely dependent on fossil fuels, with 53.7% of cars powered by petrol and 36.4% by diesel. Trains in Europe are 53.7% electrically powered, with the electricity mix defining the emission of greenhouse gases. [14] The ecological awareness of the population is reflected in the composition of the vehicles sold. Compared to 2018, 22.9% more electric vehicles, 159.8% more hybrids and 33.6% alternative drives were sold in 2019. As in the case of trains, the emissions of the electric vehicles and the alternatively powered vehicles depends on the energy mix of the "socket".

Energy system modelling takes into account different sectors, including mobility. The influence of the different sectors and their interactions can be analysed, by modelling the whole energy system. The effect of the fleet composition influences the primary energy demand and vice-versa. Waste heat from industry can be used as district heating etc. This will be done for the case studies of Germany and France in 2050, using the tool EnergyScope (ES) [1] and putting more focus in mobility by taking into consideration long and short distance mobility, alternative fuel vehicles, infrastructure, battery piloting etc.

1.2 State of the art

1.2.1 Energy Modelling

Energy Modelling is a major interest in science, but also from an economic and political point of view, as the energy transition is related to a lot of unknowns while decisions for the future have to be taken today. In order to guide the decision-takers, several models have been created with the scope on one specific sector, while large-scale models allow to model the cross-sectoral interactions. A review of the existing large-scalemodels have been summarised by Limpens et al. [1]. The summary of the models with the adapted Mobility EnergyScope (MobES) are visible in Table 1.1.

1.2.2 Mobility

The driving forces and barriers pushing the evolution towards green mobility has been described by Biresselioglu et al. [15], by comparing the vehicle fleet composition in 2009 to the years 2010-2018, with a special focus on the increase of green mobility vehicles based on energy policies and strategies. Biresselioglu identifies the main barriers of electric mobility being the lack of charging infrastructure & knowledge, fear of costs and limitation in electricity and raw materials. These points are opposed to the motivators being environmental, economic, technical, personal and demographic factors.
A specific glimpse on taxes has been put by Shafiei et al. [16], by observing the correlation between Electric Vehicle (EV) and taxes based on the years 2010-2017. Shafiei concludes that tax-induced technological switch towards electric vehicle will allow to reduce the greenhouse gases emissions deeply on a long term, despite a negligible macroeconomic benefit.

The increase in Battery-Electric Vehicles (BEV) is inducing an increase in electricity-demand to charge the batteries. The energy consumption in mobility for the horizon 2030-2050 has been analyzed by Nematchoua [17] for the city of Liege in Belgium. The outcomes of this survey showed that the local mobility emission can be reduced by 19% by adapting the transportation behaviours towards more public transport and light mobility technologies.

Table 1.1: Comparison of existig large sacel energy planning models [1].

Model	Multisector	Open Source	Optimisation	Comp. time.
Calliope	✓	✓	✓	minutes
COMPOSE	✓	✗	✓	-
DESSTinEE	✓	✓	✗	seconds
DIETER	✗	✓	✓	minutes
EneryPLAN	✓	✗	Operations only	seconds
MARKAL/TIMES	✓	✗	Investment only	5-35 minutes
Oemof	✓	✓	✓	minutes
OSemMOSYS	✓	✓	✓	minutes
PyPSA	✓	✓	✓	minutes
STREAM	✓	✗	✗	-
Switch	✗	✓	✓	10-20 minutes
URBS	✗	✓	✓	60 minutes
EnergyScope Monthly	✓	✓	✓	seconds
EnergyScope TD	✓	✓	✓	1 minute
MobES Monthly	✓	✓	✓	seconds
MobES TD	✓	✓	✓	3-10 minutes

The modelling connection between socio-economic parameters and the mobility of urban regions as London and Chicago has been described by Mohammadi et al. [18], concluding by demonstrating the direct relation between spatial energy consumption variations and mobility.

The variation of electricity and heat consumption based on mobility lead to numerous models, integrating mobility and intermittent renewable energy as modelled by Bracco [19]. Bracco presented a model to integrate V2G technologies in smart cities. Calise et al. [20] applied a case study of combining photovoltaics and batteries to charge the electric vehicles in the cities of Naples and Salerno. The results allowed to identify the major influencing parameter being the solar fields, the storage capacity and the investment cost, leading to the conclusion that renewable energy fluctuations are more affecting the nano-grid than the mobility demand itself.

The analysis of techno-economic optimisation of sustainable mobility, photovoltaic systems and battery storages has been described by Laurischkat and Jandt [21]. This model allowed the consideration of different solutions for fulfilling the demand in mobility based on different resources as fossil fuels, alternative fuels and electricity with different origins (grid and micro-grid consisting of photovoltaics and batteries) Laurischakdt points out that photovoltaic integration for electric vehcile charging induces rather economic the environmental benefits.

The previouslyy described model takes into consideration only specific sectors, while the future energy-system will be strongly depend on mobility. Muratori et al [22] describe the aspects to take into consideration when modelling mobility. In fact, Muratori et al. characterize the new energy system as an integrated system, on which the different sectors as infrastructure, time of use, policies, fuels and connectivity are integrated and dependent on each other. Muratori identifies four areas that are likely to impact future mobility-energy systems: (1) Identification and integration of emerging trends and technologies, (2) locus selection, allowing to take into consideration the possibility of different uses of the same vehicle for different purposes on a household level, (3) the multi-sectoral approach of the energy system and (4) the spatio-temporal resolution.

1.2.3 EnergyScope

Energy planning is (generally) about the future, where assumptions and approximations of parameters such as natural gas price, heating demand etc. have to be done. In order to characterize the impact of the variations in these input parameters on the energy system, the open-source accessible model ES has been created by Moret et al. [23] with a temporal resolution of months. ES allowed to optimize the energy system either on economic or environmental objectives. The purpose of this model was to create a fast and open-source energy model based on energy conservation, in order to determine uncertainty within the parameter estimations by running the model within Monte-Carlo analysis at high iterations.
Limpens et al. [24] restructured ES by adding typical-days with hourly resolution, which allowed to model inter and intraday storage technologies such as batteries. The hourly resolution furthermore allowed to model the intermittent character of renewable resources as wind, solar etc. The increase in temporal resolution entails an increase in computational time being estimated to 1-2 minutes.
The integration of mass balance allows to model the carbon flows. Li et al. are currently working on the carbon flows within ES, by creating different layers of CO_2 flows, being biogenic, atmospheric, captured segregated etc. This separation allows to take into consideration carbon capture technologies and increasing the resolution on the environmental aspect.

1.3 Problem Statement

The aim of this project is to investigate various technological options for moving towards green mobility and their impact on the energy system. These alternatives, together with

their efficiencies, costs and impacts will be implemented within the Mixed Integer Linear Programming (MILP) model ES.
Different scenarii for future mobility will be derived, simulated and optimised, considering their benefits in terms of renewable energy share and greenhouse gas reduction.
The impact of uncertainties associated with future energy planning will be discussed, based on the reference scenario.

1.3.1 Research questions

With the aim to answer the question of the mobility impact on the energy system, the problem can be resolved by responding to the different research questions:

- How can we model and implement the actual mobility demand?
- How can the different mobility technologies be modelled and what are their specific parameters?
- How can we estimate and model the mobility demand and behaviour of the population in 2050?
- What are the economic, environmental and energetic impacts on the energy system due to renewable mobility integration?
- How can we estimate the future demands in mobility and the other sectors?
- What are the characteristics of representative European countries?
- How can extreme scenarios in mobility demand be taken into consideration?
- What are the scenarios allowing to take into consideration different mobility fleet technologies?
- What is the reference solution for the studied countries?
- What are the economic, environmental and energetic impacts on the energy system due to renewable mobility integration?
- Which parameters are subject to highest impact on the energy system?
- How does uncertainty impact green mobility technology penetration in thermo-economic optimisation?

1.3.2 Objectives

The objective of this thesis is to investigate the roadmap for different mobility options on the European energy system. The strategy to answer these research questions is:

1. analyse historical mobility demand measurements to model mobility behaviour;
2. split the mobility demand in short and long distance to take into consideration specific vehicle technologies;
3. determine typical days for long and short distance mobility by applying clustering methods to take into consideration inter and intradaily phenomena;
4. estimate future mobility demand by basing on socio-economic historical data and projections;
5. create a database of existing vehicle types and apply statistical methods to determine their efficiency, global warming potential etc.;
6. estimate characteristic parameters of evolving mobility technologies based on historical behaviour of similar technologies to estimate the price evolution;
7. adapt the existing MILP framework ES while integrating mobility-induced infrastructure and behaviour to determine the inter-sectoral impacts of green mobility technologies;
8. determine Key Performance Indicators (KPI) to define the behaviour of the system under multi-objective optimisation;
9. identify critical parameters in sensitivity analysis by applying Morris screening methods;
10. analyse the impact of uncertainties based on Monte-Carlo simulations.

1.3.3 Approach

The present work is based exclusively on numerical simulations. The data which the models are based on are derived from actual measurements and statistical evaluations of existing technologies and systems. Due to the different strategies for energy system transformation, the energy systems of Germany and France were selected as examples of application. Other specific data were provided by project partners. In a first step, this study considers the validation of the model for the year 2017 and the projection into the year 2050 without considering the transition. It is also assumed that all decisions concerning the installation and implementation of technologies will be made in 2050. The costs are annualised to one year as a function of their life cycle. The energy systems France and Germany are modelled completely independently and spatial average is taken. The models differ in temporal resolution (hourly resolution of typical days and monthly resolution).

1.4 Project Background

This project has been realised as Master Thesis within the Mechanical Engineering program at Ecole Polytechnique Fédérale de Lausanne (EPFL). This thesis has been created within the laboratory Industrial Processes and Energy Systems Engineering (IPESE) under the supervision of Prof. François Maréchal and Dr. Tuong-Van Nguyen.

The main project is a sub-project of the EuroTechPostDoc Programme "AdvancedGreen - Towards advanced fuels and vehicles for green transport", conducted by Dr. Tuong-Van Nguyen under the supervision of Prof. François Maréchal (EPFL) and Prof. Lasse Røngaard Clausen (Technical University of Denmark (DTU)). The aim of this project is to optimize the energy efficiency and cost-effectiveness of the production of synthetic fuels for mobility by modeling the different processes in a first step and integrating these processes into an energy model in a second step. The integration into mobility will be investigated taking into account uncertainties such as driving behaviour, fuel prices, etc. The novelty of this project lies in the combination of techno-economic modelling and statistical tools to analyse the influence of transport technologies on a complete, cross-sectoral energy system.

Within IPESE, the collaboration with PSA Peugeot Citroën (Groupe PSA) aims to model the impact of mobility technologies on the energetic system. Being faced with a major evolution within the automotive sector, Groupe PSA needs to determine in which directions their market is evolving and the consequences of different fleet compositions on the energetic and electric system. Groupe PSA commissioned IPESE to conduct a study to determine latter impact under different fleet composition scenarios, as the penetration of synthetic fuel, electric vehicles etc. on the energetic systems of Germany and France of 2050, based on the projections of Agence de la transition écologique (ADEME). Latter simulations will allow to determine the energetic-equivalent person-kilometer or t-kilometer by type of transport, being validated using the data of ADEME and Institut national de la statistique et des études économiques (INSEE)

Chapter 2

Mobility

According to the Oxford Dictionary, mobility can be defined as

> "The ability to move or be moved freely and easily."

Indeed, mobility of people, infrastructures and technologies is the central pillar for the development of societies and regions over time. Mobility can be seen not only as a consequence of historical events such as the migrations of peoples, but also as a driving force behind the development of prosperity such as the flourishing port cities. Mobility is dependent on society, economy, culture and ecology, but also drives the latter. The present chapter describes the scientific basis and work conducted in the project to answer to the following research questions, as mentioned in Section 1.3.1:

- How can we model and implement the actual mobility demand? (Section 2.1)
- How can the different mobility technologies be modelled and what are their specific parameters? (Section 2.2)

2.1 Demands and Profiles

The energy planning model used and improved during this project focuses on a given year (e.g. 2017, 2035 or 2050), for a temporal resolution of one hour (hourly) or one month (monthly). Human mobility can be split according to the transportation mode: light (bicycles and pedestrians), medium (cars, motorcycles etc.) and heavy mobility (trucks, trains, buses, etc.). Medium and heavy mobility technologies are powered by various energy sources such as diesel, electricity and hydrogen, and the production and use of these fuels have a large impact on the energy system. By contrast, the energy demands and environmental impacts of light mobility are not directly accounted for energy assessments and are usually neglected. The modelling of mobility will be achieved by applying the following four steps:

1. analyse historical mobility demand measurements;

2. split the mobility demand in Local Distance (LD) and Long (High) Distance (HD);
3. determine typical days for long and short distance mobility by applying clustering methods;
4. estimate future mobility demand based on socio-economic historical data and projections.

2.1.1 Passenger Mobility

According to Réseau de Transport d'Électricité (Rte) [3], passenger mobility can be separated in two categories, corresponding to long and short distance travels, where the limit is set to 80-100 kilometers. The demands and hourly profiles vary from one country to another, as observed with the car traffic measurements for several cities of Germany and Frances.

Measurements

In order to determine daily traffic profiles for each day of the week, the hourly traffic measurements of the city of Paris collecting data of 367 measurement points [25] have been imported, being the measurements on the central axes.
For Germany, hourly data of 1513 measurement points are available from the *Bundesanstalt für Strassenwesen* [26], for the big axes of highways (Autobahn) and highroads (Bundestrassen) of Germany. These datasets allow to have the hourly data of a city (Paris) corresponding to urban traffic, highroad being suburban traffic and finally interurban traffic, with the highways (Germyn).

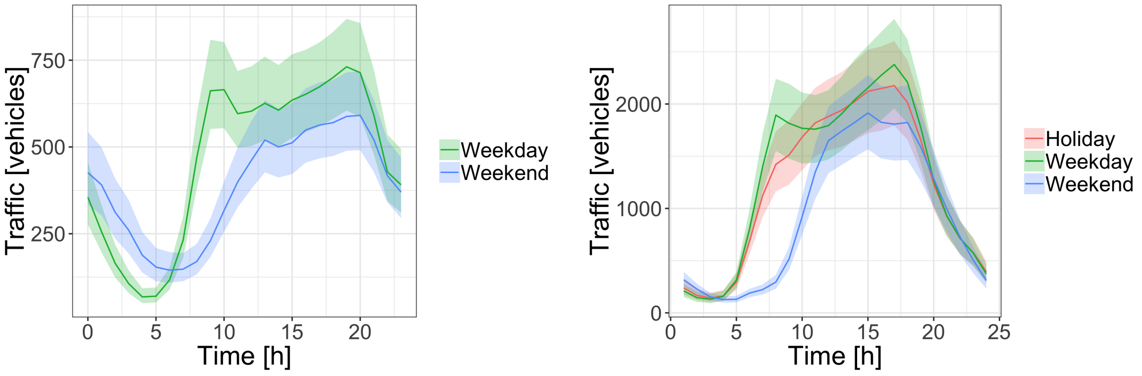
Type of Traffic days

Mobility demands are generally expressed in person-kilometers and their annual values can be found in official statistics ([27]).
Monthly mobility demands are *not* available but are usually derived from the annual demands and the duration of each month. Differences because of a punctual demand variations such as the increase in long-distance mobility demand for example are neglected.
These approximations may not be suitable when simulating the use of cars on an hourly to daily resolution. For example:

- the demand for local mobility decreases during bank holidays with the lower number of people commuting to work;
- the transportation needs are lower in nighttime than in daytime.

Averaging the mobility demand over a day without accounting for these variations would underestimate the peak demands of electricity caused by the connection of electric cars to charging stations.

The link between the annual mobility demands (person-kilometer) and the hourly measurements (vehicles counted) is obtained by applying clustering methods to the traffic measurements, in order to determine types of days as holidays, weekends and weekdays allowing to assess day-to-day mobility rather than short-distance and long distance mobility.
Figure 2.1 displays the hourly average traffic of each type of day for the short and long distance mobility with the 25% and 75% quartiles interval. In terms of traffic, one can observe that local distance mobility has a lower vehicle-flow than long-distance mobility roads.
Another difference between LD and HD mobility is the time of the day when traffic peaks and sinks occur (Figure 2.1(a)). The demands for short-distance mobility reach a peak right after the beginning and end of the working hours (07:00 and 18:00). On the contrary, the long distance mobility demands reach a peak earlier in the morning (people taking highways towards cities) and in the evening.
Differences between weekends and weekdays are visible in both mobility types. The morning rush is shifted by 2 hours which can be explained by people sleeping longer in the morning on free days. The maximum peak is also attenuated as less people are on the roads.



(a) Short Distance (b) Long Distance

Figure 2.1: Mean traffic for day types (Weekdays, Weekends and Holidays).

Hourly mobility demand

Knowing the traffic situation (vehicles per hour) and the annual mobility demand (person-kilometer per year), the hourly mobility demand (person-kilometer per hour) is estimated assuming a constant number of passengers per vehicle type.
The normalization of the mobility time series is calculated as:

$$x_t = \frac{X_t}{\sum_{t=1}^{8760} X_t}$$

where X_t is the traffic measurement at the hour t and x_t its corresponding normalized value. These normalized time series can be multiplied by the respective passenger mobility demand, allowing to estimate the hourly mobility demand.

2.1.2 Freight Mobility

In contrary to the passenger mobility, the freight mobility is assumed being assumed constant over time. Freight mobility can occur on different ways as water (ship), air (plane), road (trucks), rail (train) and pipeline. Within this project, only road and rail mobility are considered, as the other transporting media take a negligible share of freight transport in the studied countries.

2.2 Vehicle technologies

Conventional automotive technologies are based on Internal Combustion Engine (ICE) running on gasoline and diesel.
Compared to gaseous fuels, such as natural gas, or renewable feedstocks, such as hydrogen, these fuels are characterized by a high calorific value (above 40 MJ/kg) and high density at near-atmospheric conditions (above 800 kg/m^3). Fuel tanks are therefore small for these liquid fuels and can be refilled within minutes.
However, gasoline & diesel are limited resources, have a high carbon content (more than 75% weight) and high emission factors, as visible in Table 2.1.

Table 2.1: Estimated emission factors from combustion of selected fuels. [2]

	CO_2 $[t_{CO_2}/t_{fuel}]$	SO_2 $[kg_{SO_2}/t_{fuel}]$	Pb $[g_{Pb}/t_{fuel}]$
Auto Diesel	3.17	0.015	0.1
Aviation Gasoline	3.13	0.4	675.7
Coal	2.52	16	0.2
Light Fuel Oil (LFO)	3.17	0.928	0.1
Natural Gas (NG)	2.34	0	0.00025

In the course of decarbonization and the awareness of global warming, new sustainable technologies such as hydrogen, hybrid, BEV or CNG propulsion are being developed as will be explained later on in section 2.4. Within this project, different mobility technologies are implemented, divided according to three categories

- Private mobility, consisting of vehicles owned privately by the population and mainly used on personal purpose
- Public mobility, which are vehicles being in possession of companies or by the state, allowing group transport, rather than individual people.
- Freight transport, which allows to transport freight, separated according to the transportation path (railway and road)

2.2.1 Parameters

Different vehicles were modelled and integrated into the energy planning model named ES.

Reference factor $f_{ref}^{vehicle}$

Within this project, we assume that the use of cars will not change until 2050, meaning that

- d_{annual} the annual distance travelled by vehicle will be constant;
- n_{lpv} the load per vehicle will remain constant;
- c_p the capacity factor (fraction of time the vehicle is used for driving), remains constant

With these assumptions, the reference factor f_{ref} can be determined as:

$$f_{ref}^{vehicle} = \frac{n_{\text{load per vehicle}} \cdot d_{\text{annual}}^{vehicle}}{8760 \cdot c_p^{vehicle}} \; [\text{lkm/h}]$$

with the load l, corresponding to people for passenger mobility and tons of freight for freight transport.

Efficiency

Each car can be modelled as black box, converting resources to mobility, in the case of cars, it "generates" person-kilometers. Using the database, the consumption of all cars had been determined selecting the WLTP cycle [1].

In order to be able to compare the different vehicles, their efficiency is normalized such that the efficiency is expressed as energy consumption per unit of transport per distance, using the reference factor $f_{ref}^{vehicle}$.

$$e^{vehicle} \; [\frac{\text{GWh}}{\text{Mpkm}}] = \frac{E^{vehicle}}{f_{ref}^{vehicle}}$$

Costs

The total cost of a vehicle over its lifetime, considering the fuel costs apart, can be determined by summing the annualized investment c_{inv} and maintenance c_{maint} costs as

$$c_{tot}^{vehicle} = c_{inv}^{vehicle} + c_{maint}^{vehicle} \cdot t_{op}^{vehicle}$$

As for the efficiency, the vehicle costs for the present situation can be determined using the generated car database (Appendix H.1.1 & H.1.2). They are expected to decrease over time, being the case of conventional and hybrid electric vehicles.

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[1] WLTP (Worldwide Harmonised Light Vehicle Test Procedure) is a harmonised test cycle divided into four parts with different average speeds, in which each part contains a number of driving phases, stops, acceleration and braking phases. For a given vehicle type, each powertrain configuration is tested with WLTP for the lightest (most fuel efficient) and heaviest (least fuel efficient) version of the vehicle.

Projecting the vehicle costs by a 2050-horizon is inherently difficult, but those can be estimated at first with the use of *learning curves*. This concept depicts the relationship between a greater production volume and a given investment/maintenance cost, based on historical data. For vehicle technologies, the learning curves are usually modelled following a power function relation:

$$P(x_t) = P(x_0) \cdot (\frac{x_t}{x_0})^b$$

where $P(x)$, x_0 is the cumulative production at the reference year and x_t is the estimated production at the year t. The learning rate LR is defined as, allowing to determine the slope parameter b:

$$LR = (1 - 2^b)$$

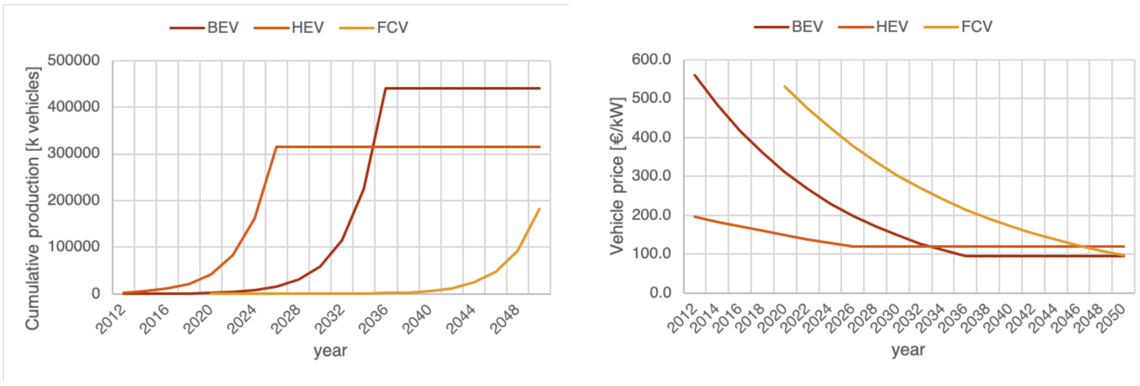
The following assumptions were taken:

- the costs of vehicles with internal combustion engines are assumed to remain constant, as no significant evolution, in terms of production volume or technological improvement, is expected. Filters and other treatment technologies are expected to compensate the improvement of efficiency by minor modifications on the engine;
- for electric vehicles (BEV and Plug-In Hybrid Electric Vehicles (PHEV)), the projected costs for 2050 can be calculated based on the learning curve data of Weiss et al. [28];
- for fuel cell vehicles (Fuel Cell Vehicle (FCV)), the same approach was used, using the learning curve data given in Ruffini et al.;
- historical data for the period 2000-2018 was used for BEV and PHEV and for the period 2010-2018 for FCV;
- an annual growth rate of 40% was taken for estimating the cumulative production, with a maximum set to the current cumulative production of conventional vehicles;
- a threshold was set for the minimum vehicle cost - for BEV and [29], and for FCV it was fixed to the value given in Ruffini et al. [30].

Table 2.2: Learning curves parameters

	ICE	PHEV	BEV	FCV
Base price [€/kW]	220	300	650	532
Base year	2000	2000	2010	2020
Base production [k vehicles]	50’000	50	70	7.5
Learning rate	0.42	0.07	0.14	0.11

The vehicle specific parameters are summarised in Table 2.2. Figure 2.2(a) depicts the evolution of cumulative produced vehicles. Weiss et al. [28] estimate a plateau for the produced vehicles, being located at 44 Million BEV and 31.5 Million PHEV. These plateaus stop the decrease in specific cost (Figure 2.2(b)).



(a) Cumulative production

(b) Specific cost

Figure 2.2: Learning curve parameter estimations outscope by vehicle technology.

Global Warming Potential

According to the United States Environmental Protection Agency (EPA) [31], Global Warming Potential (GWP) can be defined as:

> "The Global Warming Potential (GWP) was developed to allow comparisons of the global warming impacts of different gases. Specifically, it is a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide (CO2). The larger the GWP, the more that a given gas warms the Earth compared to CO_2 over that time period."

The construction and recycling of vehicles causes emissions of greenhouse gases, which impact is measured in GWP. The emissions associated with the usage of the vehicle are due to the fuel consumption and are calculated separately.

The GWP of a given vehicle was calculated by estimating the GWP of its main parts, using the Ecoinvent database and the life cycle impact assessment (LCIA) methodology of the Intergovernmental Panel on Climate Change (IPCC) 2017:

- propulsion system
- battery
- other units (Fuel Cell etc.)

2.2.2 Private Mobility

These parameters are varying according to the country and are summarized for France and Germany in Table 2.3

Table 2.3: Reference factor parameters for private mobility

	f_{ref} [pkm/h]	c_p [$-$]	n_{ppc} [p/car]	d_{annual} [km/year]
France	48.18	0.05	1.21	17423
Germany	45.77	0.05	1.46	13727

Vehicle Types

Private mobility technologies were split based on their propulsion technology and fuel, as visible in Figure 2.3:

- conventional vehicles running on standard fuels with an internal combustion engine;
- electric vehicles, characterised by an electric motor powered by a battery and charged on the electric grid;
- vehicles running on pure or blended synthetic fuels (hydrogen, ammonia, methanol, ethanol, etc.), with either an internal combustion engine or a fuel cell;
- The impact of motorcycles and private buses on the energy system was neglected.

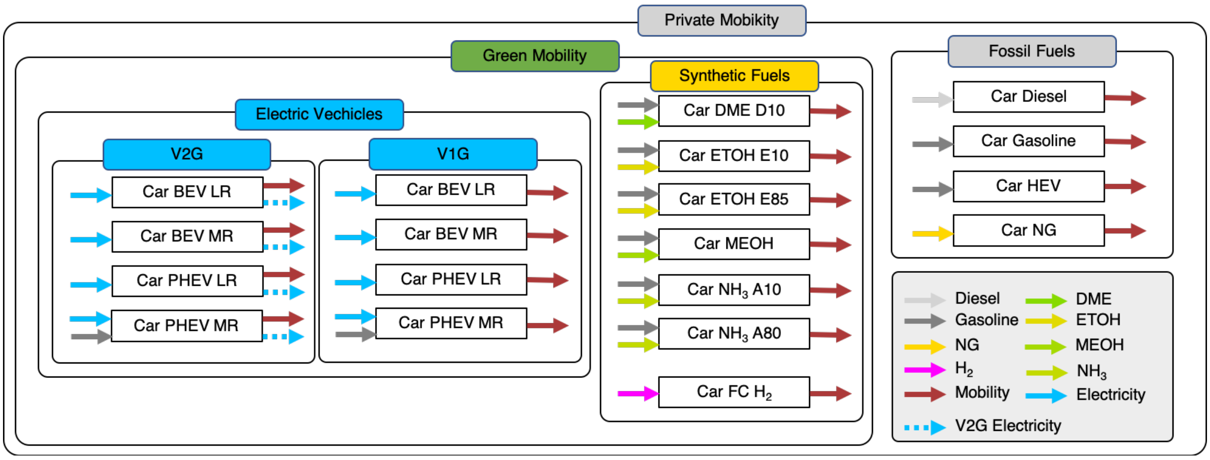


Figure 2.3: Technologies of private mobility with classification.

All vehicles are able to be used for long and short distance mobility, except for the low range electric vehicle which only can be used for short distance travels.

Electric Vehicles EV are vehicles driven by electric motors and charged by the power grid[2]. EV can be divided into two categories BEV, which use only electrical energy (batteries) for propulsion, while PHEV have an additional thermal engine that generates electricity being stored in intermediate batteries before the vehicle is powered by the electricity.
Another differentiation is if the vehicle is Vehicle-to-Grid (V2G)-compatible, where the battery of the car can be used as electricity storage when connected to the grid.
Due to the long charging time, we assume that EV are connected to the grid when not used for mobility purposes. This allows "smart-steering", meaning charging the battery when electricity is cheap.
The BEV currently on market and the confirmed cars launched in the years 2020-2022 have been integrated in a database. By grouping according to the segment, the cars have been separated in two categories, corresponding to the modelling separation

- Low Range (LR) corresponding to vehicles of the car segment *A*
- High Range (HR) corresponding to vehicles of all other car segments

The summarising allowed to determine the values integrated in ES (Table 2.4).

Table 2.4: Specific EV parameters with (min/max) values in brackets.

	Battery Capacity [kWh]	Power [kW]	Cost [kCHF]	Consumption^{WLTP} [Wh/km]
BEV LR	28.74 (16/40)	73.11 (44/135)	28.19 (20.65/43.43)	169.8 (156/200)
BEV MR	76.1 (35/200)	247.72 (80/1000)	64.21 (25.5/215)	189.8 (104/267)
PHEV	12.56 (7.6/24)	247.68 (90/500)	67.66 (34.15/160.6)	190.9^{elec} (135.5/450.5) 193.6^{fuel} (105.4/318.5)

Thermal Vehicles Thermal Vehicles correspond to the vehicles powered by fossil fuels, being a major part of the private mobility in 2017 (96% of private mobility in France and 97% in Germany). Mainly diesel and gasoline powered cars were in circulation, while NG-powered vehicles were in rise starting in 2010.

Synthetic Fuels Synthetic Fuels are fuels that are synthesized using renewable or non-renewable resources, in contrary to fossil fuels as diesel and gasoline that are directly processed and refined from crude oil. The different processes to synthesize fuels are explained in section 2.4.2. These fuels can be used in several types of vehicles

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[2] Hybrid vehicles do mot count as EV within this project, as they cannot be charged by the power grid in contrary to PHEV

- FCV use hydrogen as fuel, from water electrolysis or from fossil fuels (natural gas reforming). Today, only few vehicles are in circulation and only Toyota is producing FCV in series and selling it commercially.
  In contrary to the other synthetic fuel powered vehicles, FCV uses a fuel cell, generating electricity which is stored in an intermediate battery powering the electric engine.

- ICE can be run with Synthetic Natural Gas (SNG), synthetic diesel or synthetic gasoline, to which a certain amount of ethanol can be mixed.

- Flexible Fuel Vehicle (FFC), being ICE-driven vehicles with the ability to run on blends of several fuels, as for example methanol, ethanol, ammonia etc.
  France started creating blended Fuels, while mixing up to 10% of ethanol and ammonia to gasoline (E10, A10). Fuels with higher concentrations of ethanol, methanol and ammonia (up to 85% of the final fuel) can be synthesized and used as fuels in cars (A80 & E85).

Efficiency

The efficiencies for private mobility vehicles are visible in Figure 2.4. The least efficient vehicle is the NG car with 0.48 [Wh/pkm], while the most efficient one is the Low-Range Battery Electric vehicle, consuming more than 6 times less than the NG vehicle. A general trend is visible regarding the categories of vehicles: the EV are consuming less than the thermal powered engines, which can be explained by the efficiency of the engines. While thermal combustion engines have a maximum fuel-to-wheel efficiency of 33%, electric engines are way more efficient, going up to 95% of battery-to-wheel efficiency. In between, the Fuel-Cell driven vehicles can be found, being more effective than thermal combustion engines and hybrid vehicles, combining electric and thermal engines.

Costs

The investment cost per private mobility technology by year for Germany and France can be found in Table 2.5 and are represented for the year 2050 in Figure 2.5. Maintenance cost for vehicle types are estimated according the propulsion technology. The vehicles are separated in three categories based on their type of engines. An electric motor needs less maintenance than a thermal combustion engine, whereas hybrid vehicles have both engines and therefore need most maintenance.

Global Warming Potential

The GWP for private mobility vehicles is summarized in Table 2.6. One can observe the Fuel Cell vehicles have the highest GWP in 2017, due to the Life Cycle Analysis (LCA)-emissions created by the Fuel Cell itself, corresponding to 56% of the total car GWP, compared to 26%

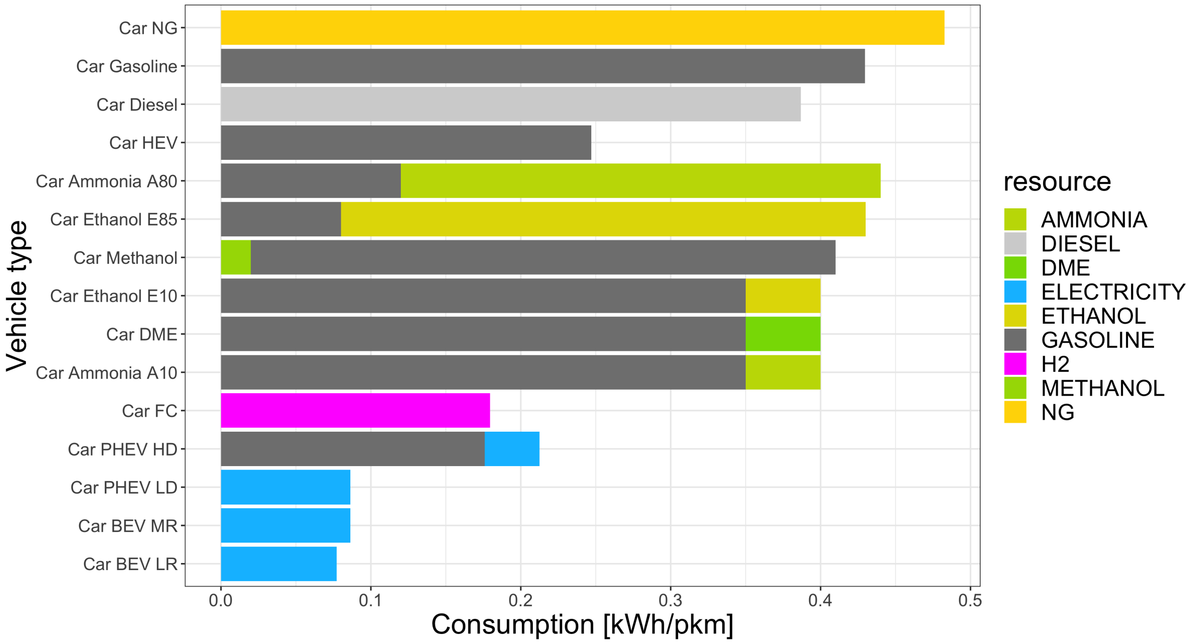


Figure 2.4: Efficiency of Private Mobility Technologies, represented in Energy consumption of resources by by transported unit (people-km).

Table 2.5: Normalized costs private mobility vehicles by country

	c_{inv}^{2020} [CHF/car]	c_{inv}^{2020} [CHF/pkm/h]		c_{inv}^{2050} [CHF/pkm/h]		c_{maint} [CHF/pkm/h/y]	
		Germany	France	Germany	France	Germany	France
BEV LR	28’190	616.1	585.7	188.51	179.2	10.6	10.1
BEV MR	64’210	1403.3	1334.0	429.2	408.0	10.6	10.1
(P)HEV	67’660	1478.7	1405.7	1196.1	1137.0	36.2	34.4
NG	25’420	555.5	528.1	-	-	25.6	24.4
Gasoline	32’000	699.4	664.8	-	-	25.6	24.4
Diesel	29’500	644.7	612.9	-	-	25.6	24.4
Fuel Cell	70’000	1529.8	1545.3	612.3	582.0	25.6	24.4
VFF	32’500	710.3	675.2	-	-	10.6	10.1
Other	30’000	655.6	623.3	-	-	10.6	10.1

for BEV LR. Due to the learning curve, the Fuel Cell Vehicles will have a similar GWP as PHEV and will be situated in between long and short-range BEVs.

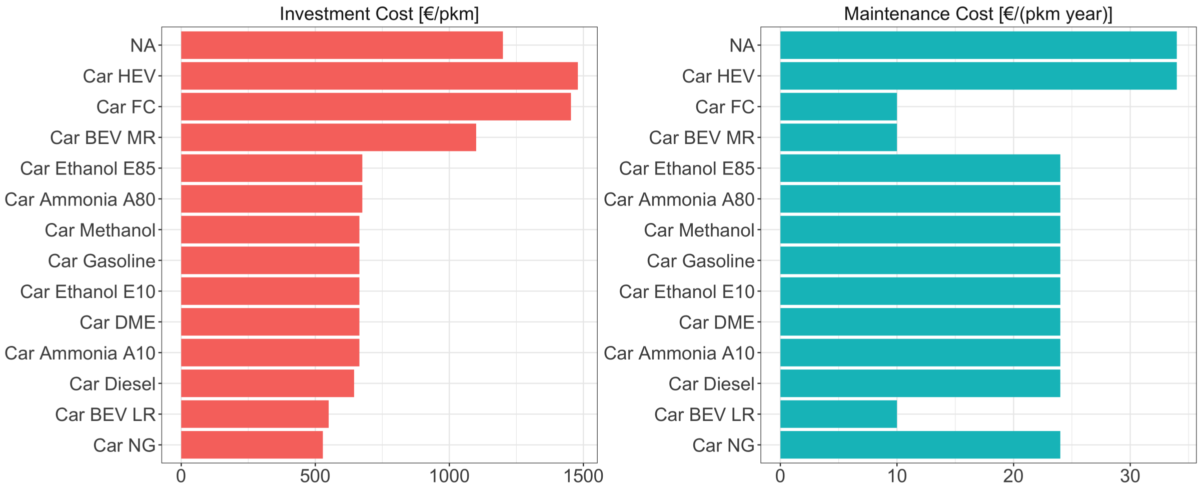


Figure 2.5: 2050 Germany Cost of Private Mobility Technologies, represented in cost by transported unit (people-km).

Table 2.6: Global warming potential private mobility vehicles construction (D/F).

	GWP 2017		GWP 2017	
[kt CO_2^{equ}/Mpkm/h]	Germany	France	Germany	France
BEV LR	405	385	332	316
BEV MR	779	741	585	556
PHEV	546	519	539	512
NG & Gasoline	360	342	360	342
Diesel	364	346	364	346
Fuel Cell	827	786	538	512
Other	366	348	366	348

2.2.3 Public Mobility

Vehicle Types

Public mobility is separated in long and short distance as visible in Figure 2.6. While with private mobility only cars have been modelled, different vehicles for public mobility are available, distinguishing by the rolling ground:

- Rail, such as trains and tramways
- Road, such as cars, commuters and coaches

Each vehicle type has different parameters for defining the reference factor $f_{ref}^{vehicle}$. The respective values of the parameters and the resulting reference factor are visible in Table 2.7.

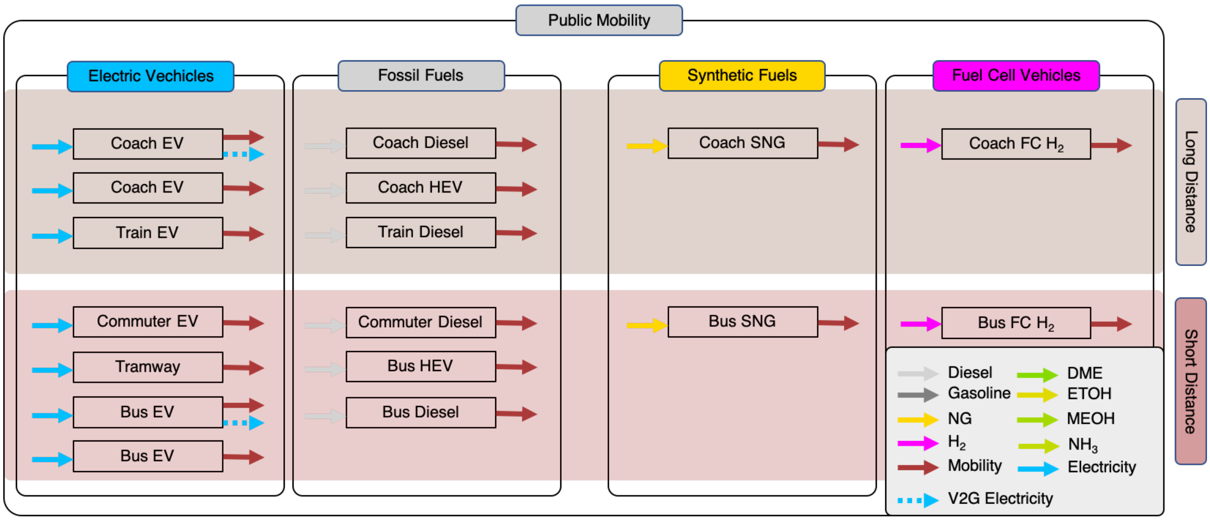


Figure 2.6: Technologies of public mobility with classification.

Table 2.7: Reference factor parameters for public mobility (F/D)

	f_{ref} [pkm/h]	c_p [−]	n_{lpv} [p/vehicle]	d_{annual} [km/year]
Bus	360	0.3	24	39’000
Coach	1’485	0.07	27	32’000
Commuter	6’640	0.28	80	200’000
Train	53’170	0.26	343	350’000
Tramway	4’000	0.34	200	60’000

The major distinction between vehicles is as for private mobility, the type of fuel-powering resource.

Electric vehicles Bus, coach, train and tramways are powered by electricity, by the difference that Buses and Coaches are charging batteries while being immobile and trains and tramways don’t have this intermediate step and need constant electricity powering by electric power lines.

Electric coaches have the same principle as electric vehicles, being charged before the trip and then emptying the battery until the end with optional refueling stops. They imply therefore high capacity batteries (600 [kWh]) in contrary to the small batteries of buses (75 [kWh]), travelling from bus stop to another equipped with fast-charging stations.

The option of V2G is available for EV-coaches only, as buses are constantly in use and their battery is designed for short charging and discharging cycles.

Others Fossil fuel powered vehicles for public transport represent 93% of french public transport in 2017 [32] (excluding trains). The remaining share is mainly electric while synthetic fuel powered vehicles were slightly nonexistent, but tripling within the last two years [33] in Germany.

Synthetic fuels based on methanol, ethanol and ammonia are not available, as they can be used as blend of gasoline, not being present in the fossil fuels category of public mobility. Nevertheless, synthetic diesel can be generated using Fischer-Tropsch process (more detail in section 2.4.2).

Efficiency

The efficiency of the different public transport vehicles has been estimated using their consumption and normalizing with the vehicle-specific factor $f_{ref}^{vehicle}$. In Figure 2.7, the consumption of the modelled public transport vehicles are visible.

On first sight, the difference in efficiency regarding the fuel is visible. As in private mobility, electric vehicles are more efficient than hydrogen, followed by fossil fuel powered vehicles. For the road-driven vehicles, the most efficient way to commute is the EV coach with 0.059 [Wh/pkm], while the NG coach is the least efficient way with a consumption of 0.306 [Wh/pkm].

The rail-driven vehicles are less efficient than the road vehicles, due to the c_p and n_{pp} as visible in table 2.7. A difference of 3% in consumption between Buses and Cars can be explained by the driving cycles of latters: while Coaches mainly travel long-distance travels with nearly constant velocity, the buses are used in cities with traffic and short trips between bus-stops, inducing a lot of acceleration and braking which is more fuel-consuming than the ideal steady-state mapping of the engine.

Cost

The total cost is determined in the same way as for the private mobility, with the exception that the reference factor $f_{ref}^{vehicle}$ is dependent on the vehicle type. A general trend is visible while analysing Figure 2.8. Commuters are the most expensive public mobility technology, being nearly three times more expensive than buses and trains, and ten times as much as coaches. Despite the expected trend of railway technologies being more expensive than road technologies, train is showing the contrary, being at the average cost of public mobility technologies (570 € per people-kilometer). Buses are slightly more expensive than the average.

No major difference is visible between different propulsion systems. In fact, the values represented in Figure 2.8 are the estimates for 2050, where Battery and Fuel-Cell driven vehicles are submitted to the learning curve, leading to a decrease in investment cost. Fuel Cells are expected to decrease by 62.3% and EVs by 69.5% of the 2017 cost.

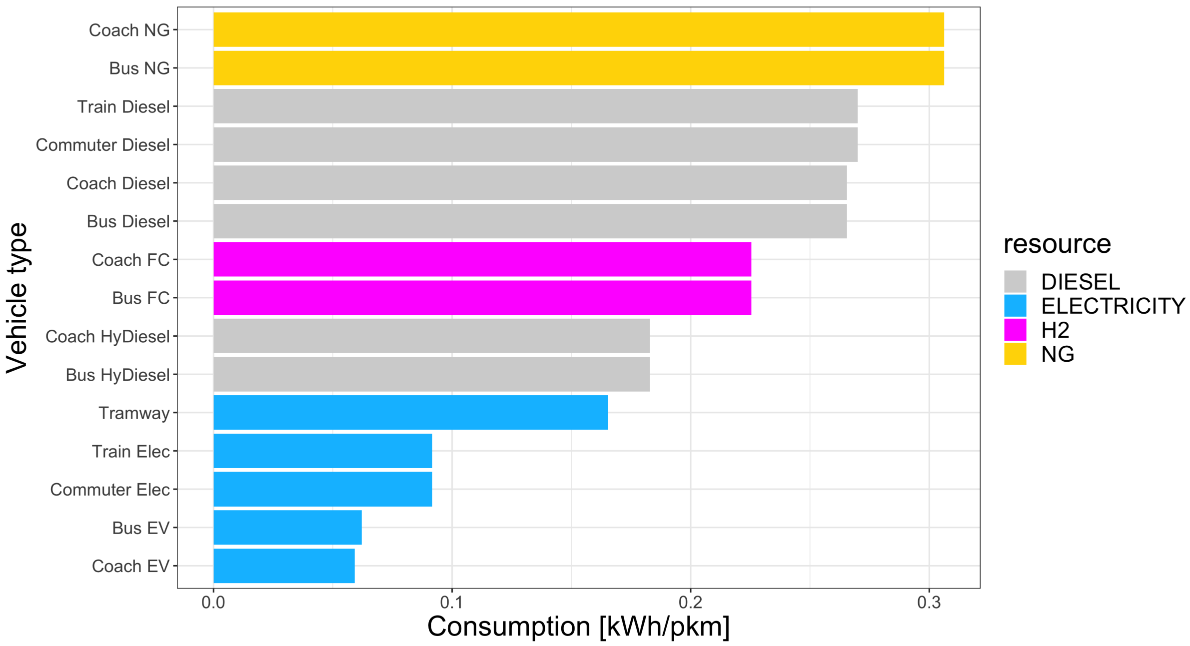


Figure 2.7: Efficiency of Public Mobility Technologies, represented in Energy consumption of resources by transported unit (people-km).

Global Warming Potential

The GWP of the public mobility vehicles has been determined by decomposing the potential according to the vehicle basis, the batteries and other additional elements with non-negligible potential as fuel cells. Figure 2.8 lists the GWP of all modelled public mobility vehicles. A clear distinction between railway and road vehicles is visible as trains, tramways on commuters are emitting 12% in 2017, resp. 14% in 2050 of the road-driven vehicles in average. The least emitting technology are the thermal motor propulsed vehicles, while the battery-driven vehicles are emitting in average 23% more in 2017. This difference shrinks to 8% in 2050 thanks to the progress in technology and the accumulated production volume, summarized by the learning curve.

2.2.4 Freight Transport

Freight transport is considered being either on the road or the rail. Maritime and air transport are not taken into consideration within this project, due to the low impact (air 5.6% & maritime 7.9% in Germany 2017 [34]) on the total freight mobility demand . In contrary to the passenger transport, the normalization is expressed according to the annual freight demand in tons-kilometers.

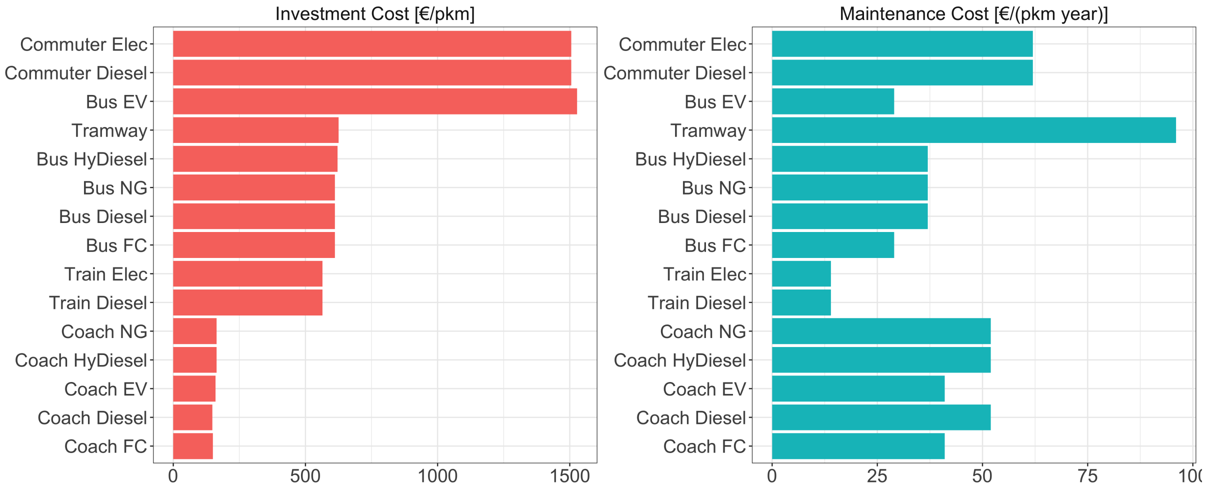


Figure 2.8: Cost of Public Mobility Technologies, represented in cost by transported unit (people-km).

Vehicle Types

Two different types of vehicles are modelled, the truck transporting goods on the roads and trains, moving on rails. The different vehicles with the separation according to the fuel type is visible in Figure 2.9.

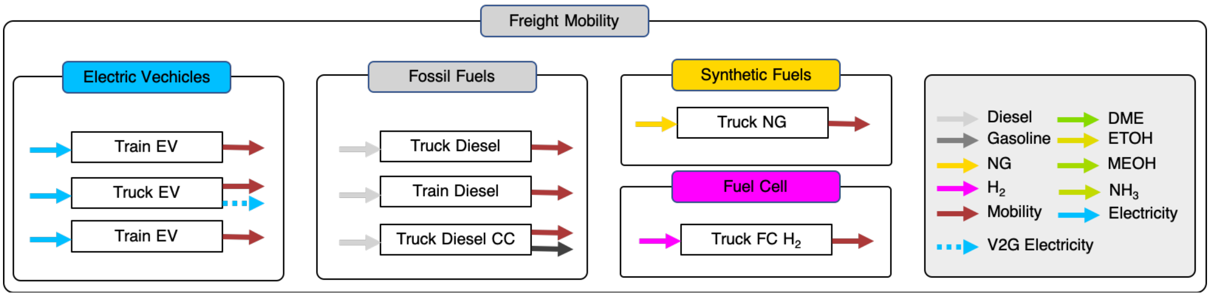


Figure 2.9: Technologies of freight mobility with classification.

Each vehicle type has different characteristic parameters as visible in Table 2.9. Trains have a 85 times higher theoretical capacity f_{ref}^{train} than trucks, due to the higher load per vehicle (55 times more), the higher capacity factor (4 times) and a higher annual distance (5.75 times more).

Trains Two different types of trains are modelled, differentiated by the fuel. The diesel train is operating with a thermal engine using diesel. The advantage of this type of vehicle, is the independence of the continuous connection to the power lines. This allows to deliver freight

Table 2.8: Global Warming Potential Public Transport

	GWP_{2017} [$\mathrm{Mt-CO_2eq/Mpkm}$]	GWP_{2050} [$\mathrm{Mt-CO_2eq/Mpkm}$]
Bus EV	151	126
Bus Diesel	116	116
Bus FC	175	138
Bus NG	116	116
Coach EV	180	133
Coach Diesel	113	113
Coach FC	127	118
Coach NG	113	113
Commuter EV	12	12
Commuter Diesel	12	12
Train Diesel	25	25
Train EV	25	25
Tramway	11	11

Table 2.9: Reference factor parameters for freight mobility

	f_{ref} [tkm/h]	c_p [−]	n_{lpv} [t/vehicle]	d_{annual} [km/year]
Train	38'500	0.34	550	210'000
Truck	450	0.09	10	36'500

on long distances without having to set-up power lines, as in large nations (United States & Canada), developing countries where electric grid stability cannot be guaranteed and not the whole nation is connected to the grid.

The countries studied in this project are assumed being developed such that electricity is guaranteed along all railways.

Trucks Trucks allow to transport freight on the road from the distribution centers to the specific destinations. Regulations regarding prohibition of freight transportation during nights are common. In Switzerland, no freight can be transported by trucks between 22:00 and 06:00. These regulations as the method of transport from the distribution center to the next with loading and delivering makes the V2G option interesting, as the truck is loaded on the stations while being charged with freight and the battery available during night when the driver is forced sleeping.

Freight such as milk, medical equipment and other prioritized goods are allowed to be shipped during night and need therefore alternative propulsion technologies as Fuel Cell vehicles and other thermal engines propulsed vehicles. In order to avoid emitting CO_2, carbon capture trucks are also modelled, capturing the emitted carbon dioxide and liquefying it afterwards [35].

Efficiency

Figure 2.10 depicts the consumption of freight technologies integrated into this projects model. Trains are consuming less than trucks (-40% in the case of electric vehicles), due to their size, less stops and longer distance travels at constant speed, while trucks have to deliver on roads with traffic. Train also have a higher load per vehicle n_{lpv} according to their payload. Efficiency comparison according the fuel allows to observe the same behaviour as for for the previous vehicles: electric powered vehicles are more efficient than thermal powered ones.

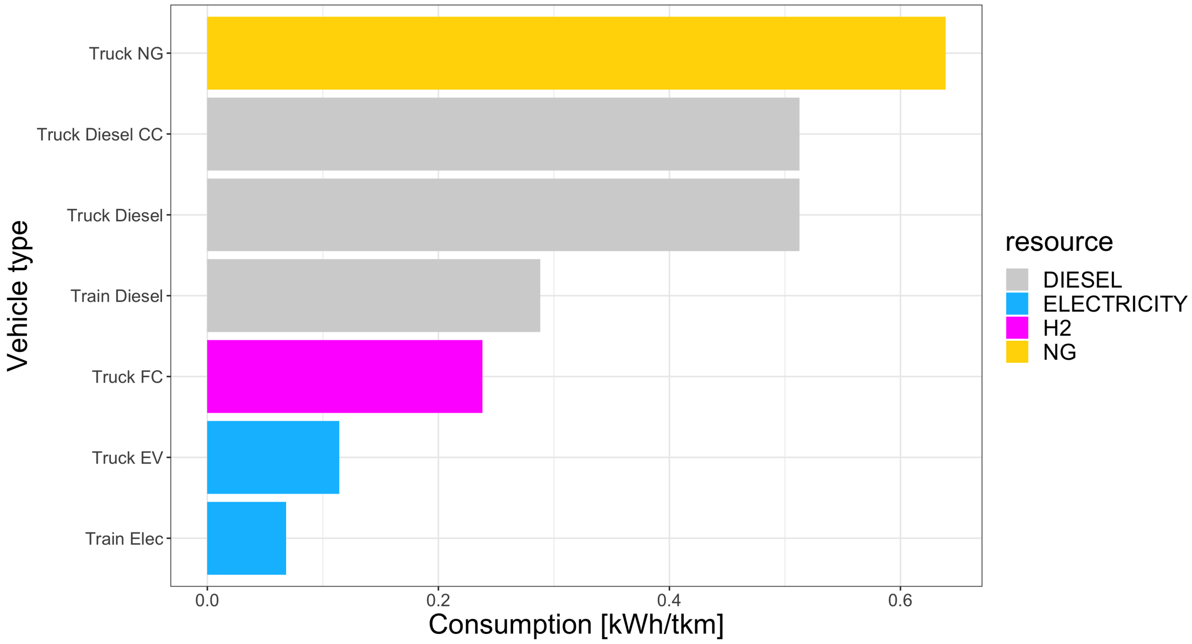


Figure 2.10: Efficiency of Freight Mobility Technologies, represented in Energy consumption of resources by service (person-km).

Cost

Figure 2.11 depicts the investment cost of the different freight mobility vehicles. In absolute terms, trains are more expensive than trucks, but after normalization, the train is cheaper (-54% for the Diesel comparison).

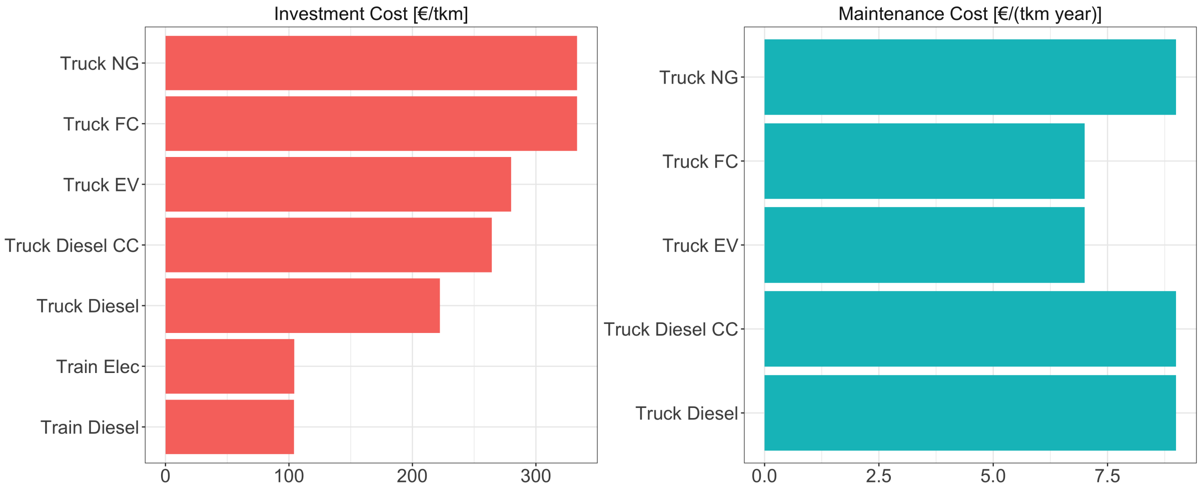


Figure 2.11: Cost of Freight Mobility Technologies, represented in cost by transported unit (tons-km).

2.2.5 Global warming potential

The global warming potential is estimated by using the EcoInvent database. The fragmentation is similar to the cars, where the GWP of the basic vehicle type has been determined, to which the potential of batteries and fuel cells is added. Latter two are subject to the learning curve and result in lower emissions, as visible in Table 2.10. For the same service (expressed in tons-kms), trains emit, on average, 31% less than trucks. In 2017, the most emitting vehicles are electric trucks, having more than double the GWP potential of similar diesel trucks. In 2050, this difference is estimated to shrink to 26% difference, while fuel cells are slightly better with a GWP being 13.7% higher than diesel.

Table 2.10: Global Warming Potential Freight Transport

	GWP_{2017} $[\mathrm{Mt-CO_2eq/Mtkm}]$	GWP_{2050} $[\mathrm{Mt-CO_2eq/Mtkm}]$
Train Diesel	29	29
Train EV	25	25
Truck Diesel	113	113
Truck EV	244	153
Truck FC	160	131
Truck NG	113	113

2.3 Transportation infrastructure

The term *transportation infrastructure* covers fixed installations of waterways, airways, railways and roads, as well as bus stations, charging stations and terminals. The associated costs were not estimated in the previous works dealing with the EnergyScope model.
Firstly, the fixed installation costs with railways and roads were derived based on country-specific and EU reports [36] and encompass:

- the average road and railway infrastructure costs, which include investment, operational and maintenance costs for the existing networks. They are given in monetary unit per unit of transportation service (Mpkm or Mtkm), and sorted by countries and type of vehicles, or are given in monetary unit per unit length (km);
- the marginal infrastructure costs, which correspond to the additional costs for maintaining and renovating the current infrastructures with an increase in mobility demand and traffic.

Secondly, the infrastructure costs with the installation of fuel stations, such as refuelling (liquid fuels) and charging (electricity) stations were considered. The specific investment costs for each station type were derived from both technical and public reports, and the number of stations to install was estimated as a function of the number of vehicles in circulation. For example, the ratio of electric vehicles per charging station is recommended to 10-1 by the European Commission to ensure adequate EV penetration.

2.3.1 Roadways and railways

Roadways

Roads are differentiated into two types, based on their use. For simplification, it is assumed that:

- department and city streets are mostly used for short-distance mobility, while national streets and highways are mostly used for long-distance mobility. This distinction has also been applied for the data mining for the hourly mobility demand;
- the network and characteristics (length, traffic) in 2017 were considered as a basis for estimating the roadway infrastructure costs;
- no additional roads need be built and the additional infrastructure costs are proportional to the increases in mobility demands.

This leads to the definition of the marginal cost c_{marg} expressed in Euro per people-kilometer and depends on the type of mobility s (Table 2.11):

$$c_{marg} = \frac{c_{maint}^{2017} \cdot d_s}{EUD_{Mob}^{2017}}$$

Table 2.11: Marginal costs of the transportation infrastructure

	c_{marg}^{road} [€/pkm]	c_{maint}^{2017} [€/km]	d_s^{2017} [km]	EUD_{mob}^{2017} [pkm]
Long Distance	3.25×10^{-3}	58'200	20'662	3.7×10^{11}
Short Distance	1.11×10^{-1}	58'200	1'082'789	5.66×10^{11}

The marginal cost per people-kilometer for short distance is 34 times bigger than for long distance. Highways need less service as fewer vehicles are driving over latter, visible by the comparison of network length (52 times longer for conventional roads) and the mobility demand (52% more demand).

Railways

Railways are also differentiated into two types based on their use and associated technologies:

- high-speed lines are supposedly used mostly by high-speed trains and for long-distance mobility, while regular train lines are run by conventional trains;
- the network and characteristics (length, traffic) in 2017 were considered as a basis for estimating the railway infrastructure costs;
- no additional railways need be built and the additional infrastructure costs are proportional to the increases in mobility demands.

This assumption is valid for high-speed lines, but could be improved for regular-speed lines as high-speed trains also run on those, if data on railway use were available.

2.3.2 Fueling and Charging

Three different types of fueling stations are considered.

Liquid Fuel

Liquid fuel stations are the stations already installed, consisting of a fuel reservoir under the station with pumps, transporting the liquid fuel from the stations tank to the vehicles tanks on atmospheric pressure. It is assumed that:

- no additional liquid fuel stations need to be installed, as the actual network already guarantees the coverage of the mobility demand, and the number of liquid fuel stations has actually decreased over the last decade;
- additional investment costs associated with the transport and storage of alternative liquid fuels, such as ethanol, were neglected.

Gaseous Fuel

Gaseous fuels as SNG and H_2 need another type of station, where the fuel is stored and transported in pressurized tanks. The daily hydrogen demand per station is estimated to $200\,\mathrm{kg\,d^{-1}}$, with a specific cost of 2000 €/(kg/day), allowing to estimate the investment cost per station to 400000 €. 11’000 refueling stations are installed in France, leading to the investment cost of 440 M €, if each refueling station has a hydrogen station installed.

Electricity

The European Union (EU) suggests a density of 1 charging station per 10 EV, regardless of their power. This ratio was considered for estimating the total number of stations, and the split between slow, fast, rapid and ultra-rapid stations is taken from the current 2017 shares (Table 2.12).

Table 2.12: Electric charging stations (F/D)

	Slow	Fast	Rapid	Ultra-rapid
Cost [€]	1800	2250	5500	30000
Power [kW]	3	22	50	350
Share [%]	26/0	65/88	8/8	1/4

2.3.3 Batteries

Parameters

Using the EV database, it was possible to determine the specific characteristics of the batteries of the EV cars, as visible in Table 2.13.

Types

Two different types of batteries are modelled, where the distinction is made if the vehicle is able to connect to the grid and can be used as storage medium for electricity. The battery will therefore deploy stored electricity not only for mobility, but also for storage purposes of the grid (V2G). The main difference is, as visible in Table 2.13 the lifetime.

Table 2.13: Characteristic parameters EV batteries

Battery	Capacity [kWh]	t_{charge} [h]	$t_{discharge}$ [h]	Lifetime (stan./V2G) [y]	GWP [kg-CO_2-eq]
BEV LR	28.74	4.28	2.12	3.10/2.55	4823
BEV Medium Range (MR)	76.1	8.72	4.94	3.10/2.55	12785
PHEV	12.56	3.28	0.9	3.10/2.55	2110

- *MODIR* batteries are used only as power-supply for the EV. The car is charged in order to satisfy the demand in energy for the mobility. The battery lifetime of a standard vehicle battery is expressed in a distance, which we assume being $300\,000\,\mathrm{km}$. This lifetime expression is misleading, as cycle and calendar ageing have to be taken into consideration [37], which leads to 3.1 years before reaching the end-of-life criterion of 80% remaining capacity[3].
- *BIDIR* batteries allow to direct electricity in both directions when plugged to the grid, enabling V2G. Additional charging and discharging cycles are induced, decreasing the lifetime of the battery. The economical optimum is assumed to be at $18\,\%$ V2G [38], leading to a lifetime decrease of latter value.

2.4 Resources and processes

2.4.1 Fossil Fuels

Fossil fuels such as fossil diesel and gasoline mostly contain hydrocarbons, they are derived and refined from crude oil. They are either imported (cases of France and Germany), or produced in the country itself (case of Norway). The price of these fuels is subject to large variations and high uncertainties [39] and the impact of those will be taken into consideration within sensitivity analysis in Section 3.5. For simplification a constant price for each resource was set at first, as shown in Table 2.14.

Table 2.14: Cost and global warming potential of fossil fuels

	c_{op} $[\mathrm{kCHF/GWh}]$	gwp_{op} $[\mathrm{kg-CO_2eq/GWh}]$
Gasoline	87.95	344.80
Diesel	85.15	314.80
Natural Gas	34.82	266.60

---

[3] In fact, one has to take into consideration the driving-induced charging and discharging cycles as the time the car is not used (calendar ageing)

2.4.2 Synthetic Fuels, biofuels and electrofuels

Synthetic fuels are liquid or gaseous fuels that have been synthesized from syngas, which is a mixture of hydrogen and carbon monoxide. The syngas was derived from gasification of solid fuels (coal or biomass) or from reforming of liquid fuels (natural gas). Biofuels are fuels that are produced through biomass conversion, with or without an intermediate conversion step into biogas. Electrofuels are made by converting excess electrical energy from renewable sources (wind or solar) into chemical fuels.

Examples of synthetic fuels are methanol, second-generation ethanol, hydrogen and ammonia generated from natural gas reforming. Examples of biofuels are ethanol of first (fermentation) or second (gasification) generation. Example of electrofuel is hydrogen produced through water electrolysis.

In the rest of this thesis, the term synthetic fuel will be used for ease of language as a substitute for the three categories above-mentioned.

Synthetic fuels can be processed directly in dedicated conversion engines (e.g. fuel cell for hydrogen), blended with gasoline and consumed in tuned ICEs (e.g. ethanol- and methanol-gasoline blends such as E10 and E85), or further refined into synthetic gasoline and used in conventional ICEs.

The corresponding processes are visible in Figure 2.12, where all modelled processes for each fuel are represented in energetic balance.

Table 2.15: Parameters Synthetic fuels

	HV_m [MJ/kg]	HV_{rho} [MJ/L]	ρ [kg/L]	N_C [−]	gwp_{op} [kg − CO_2eq/MJ]
Gasoline	43.1	32.2	0.745	0.842	0.071
Diesel	43.2	35.9	0.832	0.857	0.073
Natural Gas	42.4	33.9	0.8	0.75	0.065
Ethanol	29.7	23.4	0.789	0.522	0.064
Methanol	22.7	18.0	0.792	0.375	0.061
Hydrogen	142	1.28×10^{-2}	8.99×10^{-5}	0	0
Ammonia	22.5	13.5	0.601	0	0

Ethanol

Ethanol (C_2H_5OH) can be used in two different fuels, blended with gasoline: E10 and E85, where XY within EXY corresponds to the volumetric fraction of ethanol within the blend. Ethanol has a 34% lower heating value than gasoline, leading to an increase in consumption of fuel. Due to the higher octane number, it is possible to increase the compression ratio of the engine, leading to a higher efficiency.

Ethanol can be gained by using Crops-to-Ethanol process, where sugar-cane or starch is converted in ethanol. The production can be described by fermentation, distillation and dehydration. This process consumes 1.78 energy-equivalent plant in order to generate 1 ethanol.

Methanol

Methanol CH_3OH is, similarly to ethanol, a substitute for gasoline. At the moment, methanol is mainly used as fuel in racing series, but not spread widely as fuel for traditional engines. Methanol has a lower volumetric heating value (18.0 [MJ/L]) compared to ethanol (23.4 [MJ/L]). The advantage of methanol over ethanol are the different processes to synthesize methanol. methanol can either be generated using methane or hydrogen and carbon (CO_2 or wood). The processes to synthesize 1 [kWh] Methanol are:

- Wood-to-Ethanol by converting hydrogen (4.54 [kWh]) and wood (2.08 [kWh]), with additional 1 [kWh] high temperature heat and CO_2 generated;
- CO_2-to-Ethanol converts CO_2 and 1.5 [kWh] H_2 to 1 [kWh] ethanol. This process allows to convert captured carbon, as for example in the Carbon Capture (CC) trucks;
- Fischer-Tropsch, while converting CO_2 and 1.19 [kWh] Methane to ethanol at high temperatures (300 °C) and low pressure (1000 Pa);
- Methane-to-methanol allows the synthesis of liquid methanol from methane [1.52 kWh] in a two-stage process. methane is transformed by steam reforming to synthesis gas, which is catalyzed to methanol under high pressure in a second step. Byproduct is CO_2.

Ammonia

The advantage of ammonia (NH_4) is that it can be considered as carbon-free fuel, leading to no CO_2 emissions during combustion. Ammonia ($22.5\,\mathrm{MJ\,kg^{-1}}$) has a comparable mass-based heating value as methanol ($22.7\,\mathrm{MJ\,kg^{-1}}$). Due to the low density, the volumetric heating value is the lowest of the synthetic fuels listed in Table 2.15.

1 [kWh]-eq ammonia can be synthesized by using the Haber-Bosch process, where atmospheric nitrogen and hydrogen (1.2 [kWh]) are converted to ammonia using a catalytic reaction under high temperatures and pressures.

Hydrogen

Hydrogen (H_2) is similar to ammonia a carbon-free fuel, allowing combustion without greenhouse gases emissions. Hydrogen has the highest mass-based heating value ($142\,\mathrm{MJ\,kg^{-1}}$), but being the smallest atom in the periodic table, its density is low ($8.99 \times 10^{-5}\,\mathrm{kg\,l^{-1}}$), leading to a very low volumetric heating value as visible in table 2.15. In order to store hydrogen, high pressure vessels going up to $200\,\mathrm{bar}$ are common, leading to losses in compression and expansion.

Hydrogen is produced according two methods: electrolysis or from fossil fuel resources (95% of hydrogen production in 2018).

- *Electrolysis* allows the separation of water (H_2O) into hydrogen (H_2) and oxygen (O_2) while applying an electric current. Electrolysis can therefore be used in the Power-to-Gas (P2G) principle, where excess or off-peak power generated by intermittent sources is converted into hydrogen.
  Three different electrolysis processes are modelled within this project, differentiating by the set-up of the electrolyser: alkaline, proton membrane and solid oxide. Per unit of energy of hydrogen produced, electrolysers convert between 1.25-1.72 units of electricity, by generating up to 0.26 units of high temperature heat.
- *Steam Reforming* converts natural gas or wood into syngas, composed of hydrogen and carbon dioxide. It was the most used process to synthesize hydrogen in 2018 (95%). The highly endothermic reaction ($\Delta H_r = 206$ [kJ/mol]) is occurring at high temperatures ($900\,^{\circ}\mathrm{C}$) and high pressure ($40\,\mathrm{bar}$) and cannot be scaled down for medium and small applications.
  1.36 [kWh] of NG or 1.59 [kWh] of Biomass are used to generate 1 [kWh] of Hydrogen.
- In biomass *gasification*, heat, steam and oxygen are added to the biomass to convert the biomass into hydrogen and CO_2 without combustion.
  In order to produce 1 [kWh] of hydrogen, 1.92 [kWh]-equivalent of Biomass are needed, emitting the byproduct CO_2.

Synthetic Natural Gas

SNG is a fuel mainly consisting of methane CH_4 and being either produced from fossil fuels (coal, lignite etc.) or renewable resources as biomass or power-to-gas. SNG can be used either as combustible fuel in thermal engines or in fuel cells-driven vehicles. Within this project, SNG will only be used in thermal combustion engines, as fuel-cell applications with SNG imply fuel cell sizes being too large for mobility applications.

The SNG characteristics are comparable to gasoline and diesel with a massic heating value of $42.4\,\mathrm{MJ\,kg^{-1}}$ and a density of $0.8\,\mathrm{kg\,m^{-3}}$ lying in between gasoline ($0.745\,\mathrm{kg\,m^{-3}}$) and Diesel ($0.832\,\mathrm{kg\,m^{-3}}$).

SNG can be synthesized by using different processes:

- *Methanation*, where water is separated in oxygen and hydrogen using P2G. Hydrogen and CO_2 are brought to reaction on chemical or biological way to create methane and carbon-dioxide. One Energy-Equivalent Unit (EQU) of SNG needs CO_2 and 1.2 EQU of hydrogen.

- *Biogas-to-Biomethane* allows to remove impurities of biogas, consisting of 30-45% of CO_2 and other compounds as H_2S. Several biogas upgrading processes exist. The modelled process converts for one energy-equivalent unit of SNG 0.198 CO_2, 0.0224 electricity, 1.191 units of hydrogen to SNG and 0.189 units of waste-heat.

- *Anaerobic Digestion* is a reaction where wet biomass (3.34 [kWh]) is digested with absence of oxygen, in order to produce 1 [kWh] of SNG and CO_2.

- *Gasification* of 1.351 [kWh] wood generates 1 [kWh] SNG, as 0.042 [kWh] electricity, CO_2 and 0.121 [kWh] heat. In a first step, wood is converted to wood-gas with nitrogen, carbon monoxide, hydrogen and methane, which are after being cooled down filtered to obtain SNG.

- The *Hydrothermal Gasification* of 2.36 EQU wet biomass is a process that converts the wet biomass into 1 EQU SNG through thermochemical reactions. This takes place at a lower temperature than in the dry thermochemical reaction, and no drying of the product is required. 0.685 EQU are also generated, with the possibility of producing 0.04 EQU electricity.

Diesel

Synthetic diesel ($C_{10}H_{20}$-$C_{15}H_{28}$) has not been extracted from crude oil using refineries. It has the same properties as fossil fuel diesel and can be used in self-ignition thermal engines.
Two processes are modelled to produce synthetic diesel:

- *Fischer-Tropsch Diesel*, where wood (2.25 EQU) and CO_2 are used to generate 1 EQU diesel, with CO_2 and 0.394 EQU high temperature heat byproducts.

- *CO_2-to-Diesel* allows to convert hydrogen (1.54 EQU) and CC CO_2 to diesel and gasoline (0.387 EQU).

Gasoline

Similarly to synthetic diesel, it is possible to generate synthetic gasoline, which is not produced by refine crude oil. Synthetic gasoline is indifferent to standard gasoline and can therefore be used in spark-ignited engines.

Two processes are integrated to the model, while CO_2-to-Diesel is a hybrid by producing gasoline and diesel, already explained in section 2.4.2

- *Methanol-to-Gasoline* allows to transform 1.1 EQU methanol (CH_3OH) to 1 EQU gasoline with several intermediate processes. In a first step, methanol is converted to light olefins and water, which is separated. Carbon is added to the olefins which then are converted to paraffins, aromatics and napthenes which is gasoline.
- *CO_2-to-Diesel.*

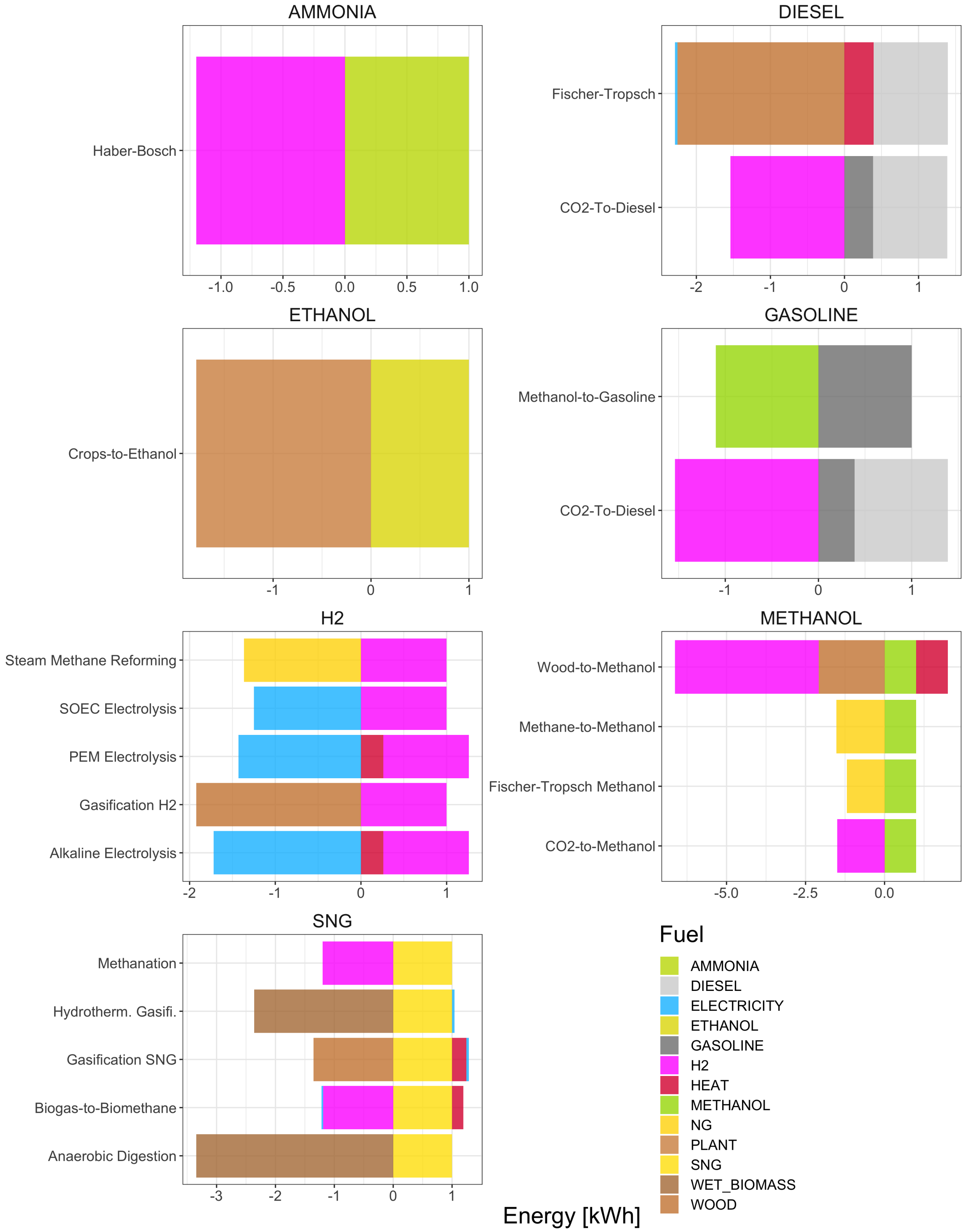


Figure 2.12: Synthesizing fuel processes with resources and products expressed in energy per unit product.

Chapter 3

Methodology

MobES is based on the ES model by Limpens [1] and Moret [39], with additional features regarding mobility. This chapter will in a first instance present the additional Modelling Framework, as sets, parameters & variables, as the additional constraints related to mobility. These modifications will be validated using the 2017 case study of Germany and France. A comparison between the Typical Day (TD) and the monthly model will allow us to point out for which application which model is suitable. The framework of the determination of the countries energy and mobility demands using historical data analysis will be explained at the end. Within this chapter the following research questions will be answered:

- How can we estimate and model the mobility behaviour of the population in 2050? (Section 3.2)
- What are the economic, environmental and energetic impacts on the energy system due to renewable mobility integration? (Section 3.3)
- How can the future demands in mobility and the other sectors be estimated? (Section 3.4)

3.1 Approach

3.1.1 Overview of steps

The computational framework which has been integrated in a R-script procedure is visible in Figure 3.1 and summarised in appendix A.

- As first step, the precalculation (Sections 4.2.2 & 3.4) allow to determine the models demands and times series input.
- The parameters depend on the technologies and the scenario selected (Section 2.2)
- Additional constraints being specific to each case study and vehicle scenario are integrated with an additional model file.

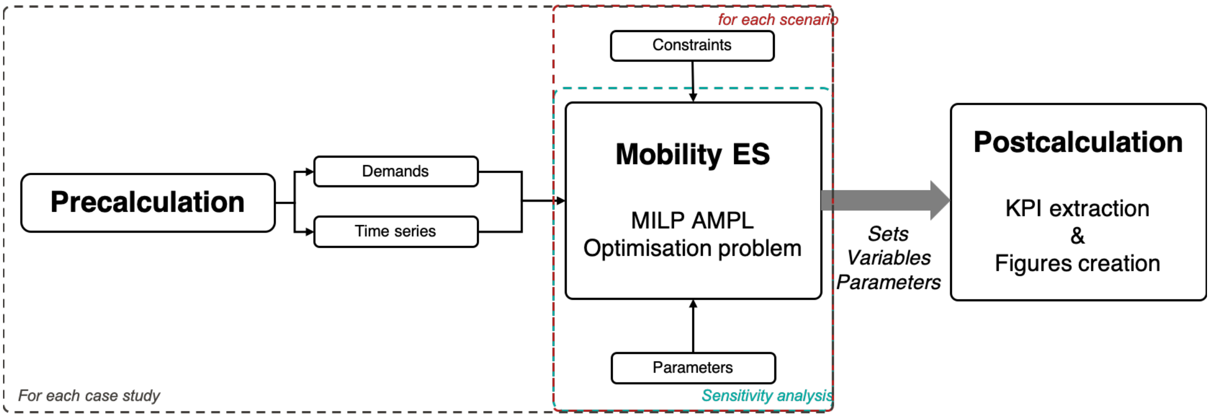


Figure 3.1: Computational framework

- Every file is imported in a R-script and then launched, while for each scenario the sets, parameters and variables of the model are stored. Different running methods can be applied
    - The Pareto curve running allows to run on n parametrized different points between a minimum and maximum objective value, while being optimized on the other one.
    - The Morris simulation takes a set of parameters and varies each one of them individually to asses the impact on the model's objective, which allows to determine the relative sensitivity of each parameter (Section 3.5.1).
    - The Monte Carlo analysis takes as input the set of parameters with their relative distribution and runs for a n iterations the parameter space variations, allowing to determine the uncertainty of each parameter (Section 3.5.2).
- Postcalculation takes the stored data and converts it to exploitable figures, results and key performance indicators being visible in results section (Section 5).

3.1.2 Description of tools

AMPL The modelling language used for modelling and optimization is AMPL (a mathematical programming language). AMPL is a large scale algebraic computational language which is compatible with open-source and commercial solvers. Within this project the solver CPLEX has been used.

The advantage of AMPL is its similarity to the mathematical formulations, allowing to read and code the model within short time. The formulation of an optimization model can be achieved by defining declarative language elements. *Parameter* are single named numerical values, which can be defined as single number, vectors or arrays. *Sets* are defined as combination of parameters, constraints and variables over which can be iterated, commonly used by summing operations. *Variables* correspond to variables in the mathematical formulation which are allowed to change through the solving iterations. *Constraints* consists of combination of sets, variables and parameters and allow to model the mathematical equations. The *objective function* can either be defined as variable or as constraint. The model will apply the optimization based on latter objective.

Energyscope The Energyscope model is a monthly thermoeconomic optimization written in AMPL, allowing to represent the global energy system of a specified region. Energyscope was initially built to determine the impact of uncertainty in strategic energy planning in Switzerland 2035 by applying uncertainty characterization, sensitivity analysis and robust optimisation.

The energy balance has been achieved by defining *End Uses Demand (EUD)*, corresponding to the energy demand of the final customer. EUD are separated in the sectors households, services, industry and transportation, as in the end uses types space heating, hot water demand, high temperature, electricity, passenger mobility and freight mobility.

Different units allow to transform resources (natural gas, electricity, wind etc.) to the EUD. The grouping of these variables and parameters is summarised within the set *layers*, which is forced to be balanced in each period. This can either be achieved by being consumed by the EUD or as input to other technologies.

A second version of EnergyScope allows to increase the temporal resolution by replacing the months by typical days and their respective hours of the day. This increase in resolution allowed to analyse inter and intra day storage, being achieved by adding the variable Storage level. Storage level at time (t) is calculated by the difference in storage in and storage out at the previous time step (t-1).

This storage furthermore allowed the implementation of daily mobility technologies as infrastructure, battery electric vehicles being able to figure as grid battery etc. The time resolution allowed to estimate the hourly peak in power for each technology, by defining the variable $\mathrm{F}_{\mathrm{Mult}}$.

Based on the monthly model, the carbon flows have been added to ES, providing insight in the different CO_2 emissions, captures etc. In addition to the carbon flows, a transition model is under development, taking snapshots at a defined interval, which constrain the characteristics of the following snapshot.

Within this project, the carbon flows have been adapted to the typical day model. Furthermore more resolution has been put on the mobility aspect of both models, by splitting the passenger mobility EUD in short and long distance mobility. Additional vehicle technologies as the respective fuel producing technologies have been defined and added. In order to model battery electric vehicles behaviour, constraints simulating peaks in mobility demand, exchange of charging stations and the vehicles as power steering have been added.

3.2 Modelling

The mobility induced behaviour is modelled by adding new constraints. Therefore several thematic groups of constraints are added to model. Latter are optional and can be deactivated to reduce the calculation time. The influence of latter constraints will be shown in Section 5.4.1.

3.2.1 Sets, parameters and variables

Figure 3.2 shows the technologies added to the TD model by Limpens [1]. The addition of new vehicles implied new fuels, which needed to be synthesized as batteries with different behaviours as conventional battery storage modelled by Limpens. The additional vehicles (Section 2.2) and synthesizing fuel processes (Section 2.4.2) have been added to the existing categories and are highlighted in red.
The addition of new vehicles and the separation of passenger mobility in two categories implied modifications in changes of sets. The adapted figure by Limpens [1] is visible in Figure 3.3.

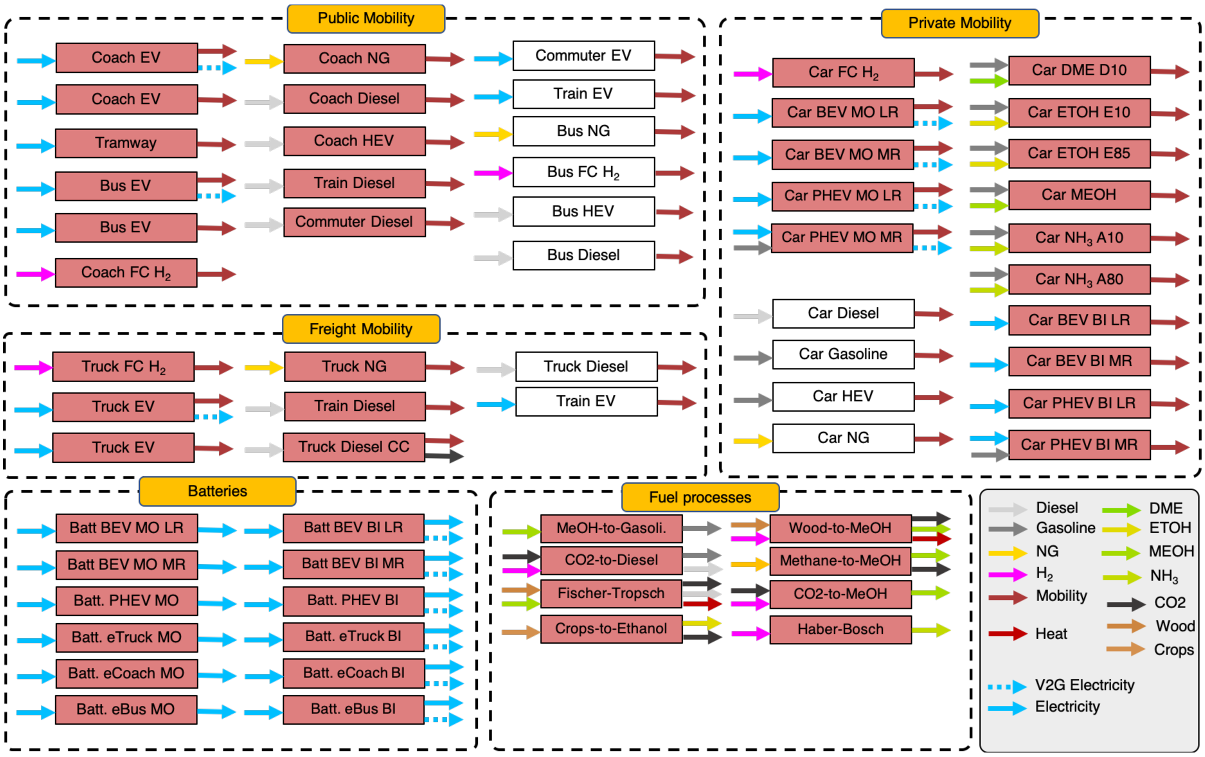


Figure 3.2: Application of the LP modelling framework to the European energy system. Additional technologies to Limpens Figure 5 [1]. White boxes represent existing technologies, while red boxes are the additional technologies,

The parameters are summarised in the appendix in Table D.1.

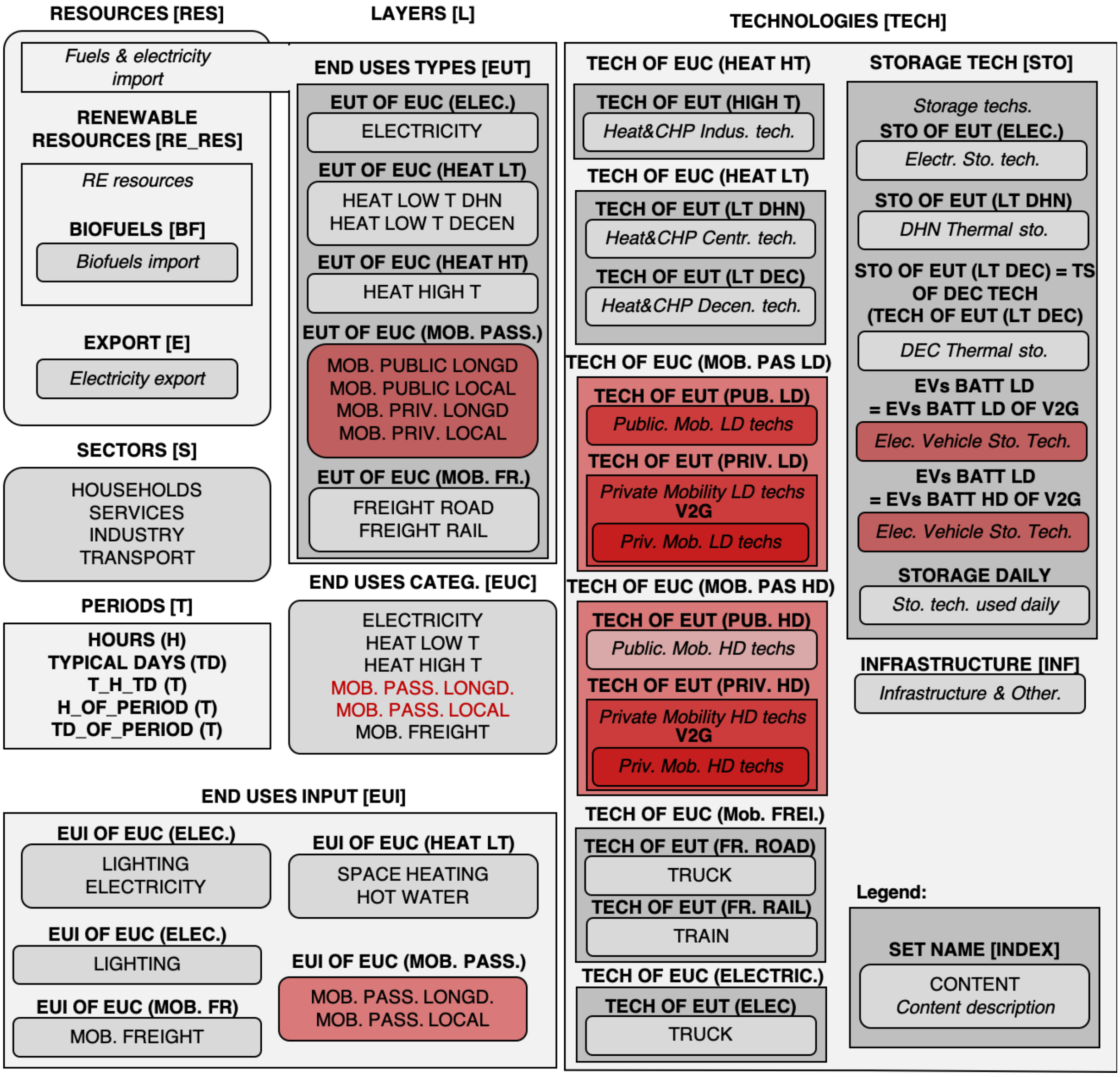


Figure 3.3: Graphic representation of the sets and indices of the MILP framework. Abbreviations: space heating (SH), hot water (HW), temperature (T), mobility (MOB), vehicle-to-grid (V2G), thermal storage (TS), low distance (LD) and high distance (HD). Red entries are the modifications done on Limpens [1].

3.2.2 Constraints

End-uses demand

In Energyscope, the final energy demand is divided into three types, namely heating, electricity and mobility, the latter being divided into passenger and freight mobility. Passenger mobility was further divided into long-distance and short-distance categories as the demand profiles, types of technologies and required infrastructures are different.

Table 3.1: MobES specific variables.

Variable	Unit	Description
C_inf_avrg	M€	Infrastructure cost
C_inf_marg	M€	Marginal infrastructure cost
C_inf_marg0	M€	Initial marginal infrastructure cost
F_Mult_Mob_Infra	-	Factor of growth mobility infrastructure
Max_Elecmob_Demand	Mpkm	Maximum electric mobility demand
Max_ElecV2Gmob_Demand	Mpkm	Maximum V2G mobility demand
Max_Mobility_Demand_**X**	M**x**km	Maximum mobility demand of **X**
Max_Share_Mobility_EV_**X**	-	Maximum share electric mobility demand of **X**
Number_of_Cars_per_Type	cars	Number of cars per type
Share_Mobility_**X**	-	Mobility share of **X**
Shares_Average_**X**	-	Average mobility share of **_X**
Shares_Mobility_**X**	-	Mobility share at a given hour of **X**

The end-use demands correspond to the energy that is delivered to the consumer's door to satisfy his needs. A given energy conversion technology, such as a power plant, can be used to satisfy different demands (e.g. power and heat) in different sectors (e.g. industrial and residential). This separation between the end-uses demands and end-uses inputs has been adapted for mobility (Figure 3.4).

EV storage

The total battery capacity is calculated as the sum of the batteries of all electric vehicles. The battery size is therefore assumed to be proportional to the amount of electric cars, assuming, after discussion with PSA, that, on average over a day, only 4% of cars ($f_{car,circulation}$) are in circulation (Equation 3.1).

The sets i and j are adapted to cover all EV classes: private, public & freight for V2G and V1G.

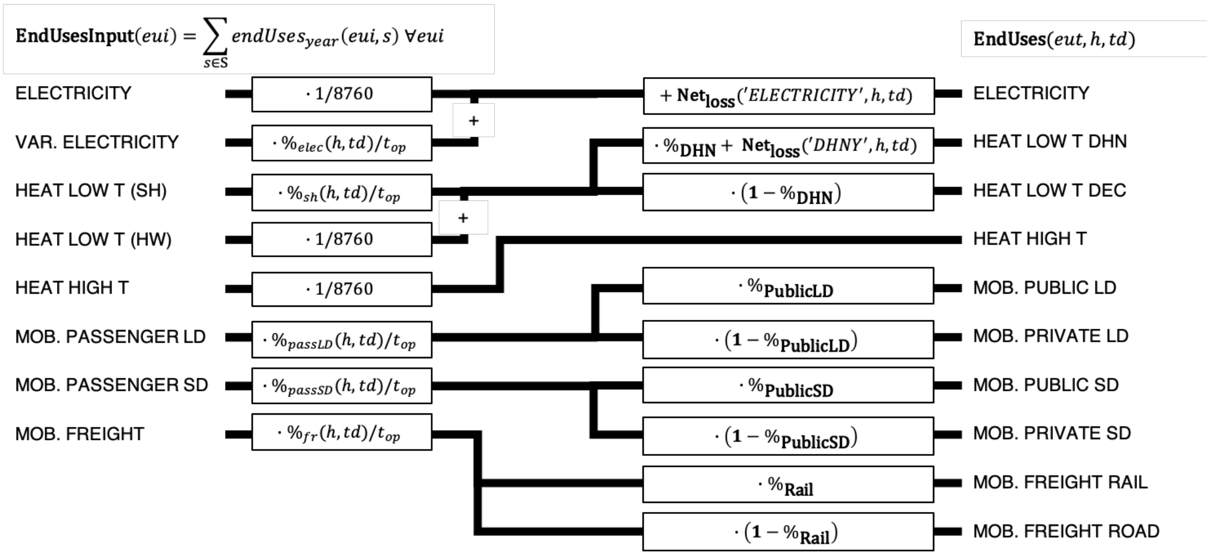


Figure 3.4: End-uses calculation starting from yearly demand model inputs (*endUsesInput*). Adapted from [1]. Abbreviations: space heating (sh), district heating network (DHN), hot water (HW), passenger long distance (passLD), passenger short distance (passSD) and freight (fr).

For simplicity reasons, only the first combination of sets has been represented.

$$\mathbf{F_{mult}}(i) = \frac{\mathbf{F_{mult}}(j) \cdot Batt_{per,Car}(j)}{f_{car,circulation} \cdot Power_{per,Car}(j)} \tag{3.1}$$

$$\forall \quad j \in EVs\_NO\_V2G$$

$$\forall \quad j \in EVs\_NO\_V2G$$

V1G vehicles cannot, by definition, be used by grid operators for frequency or load control. The electricity out of the battery should be strictly equal to the energy required to drive the car, neglecting transmission losses (Equation 3.2).

$$\sum_i \mathbf{Storage\_Out}(i,'ELEC', h, td) = -\sum_k layers\_in\_out(k,' ELEC') \cdot \mathbf{F_{mult,t}}(k, h, td) \tag{3.2}$$

$$\forall \quad i \in EVs\_BATT\_OF\_NO\_V2G \setminus EVs\_NO\_V2G\_LD$$

$$\forall \quad k \in MODELS\_OF\_TECHS\_ALL\_DISTANCES(j)$$

$$\forall \quad h \in HOURS$$

$$\forall \quad td \in TYPICAL\_DAYS$$

On the contrary, the batteries V2G-vehicles are used for mobility purposes and can be used as storage medium. The electricity out of the battery $\mathbf{Storage_{Out}}$ has to be bigger or equal to the energy required to drive the car.

$$\sum_i \mathbf{Storage\_Out}(i,'ELEC',h,td) \geq -\sum_k layers\_in\_out(k,'ELEC') \cdot \mathbf{F_{mult,t}}(k,h,td) \quad (3.3)$$

$$\forall \quad i \in V2G \setminus V2G\_LD$$
$$\forall \quad k \in MODELS\_OF\_TECHS\_ALL\_DISTANCES(j)$$
$$\forall \quad h \in HOURS$$
$$\forall \quad td \in TYPICAL\_DAYS$$

The penetration of V2G vehicles among electric vehicles can be constrained as:

$$\mathbf{F_{mult}}(i) = \frac{share\_v2g}{1 - share\_v2g} \cdot \sum_j \mathbf{F_{mult}}(j) \quad (3.4)$$

$$\forall \quad ev \in EVs$$
$$\forall \quad i \in MODELS\_OF\_EV(ev)$$
$$\forall \quad j \in MODELS\_OF\_EV(ev) \setminus MODELS\_V2G\_OF\_EV(et)$$

with $share\_v2g$ being the parameter defining the fraction of V2G vehicles.

Charging points

The number of charging stations and their total power can be determined knowing the power rating of a station, the number of electric vehicles and the ratio of installed stations per electric car. (Equation 3.5) states the constraint for electric vehicles. The constraint is similar for hydrogen stations, assuming a given hydrogen demand per day. We assume that charging stations for gasoline and diesel are already built, setting equation 3.5 to zero for latter fuels.

$$\mathbf{F_{mult}}(i) = \sum_j Numbers\_of\_Cars\_per\_Type(j) \cdot Stations\_per\_Car(i) \cdot Power\_per\_station(i) \quad (3.5)$$

$$\forall \quad i \in TECHNOLOGIES\_OF\_EV\_CHARGING$$
$$\forall \quad j \in V2G \cup EVs\_NO\_V2G$$

Peak demands

To compare the impacts of local and long-distance mobility demands on the energy system, it is necessary to know the demand profiles for each type and the resulting peaks in electricity and fuel demands.

The challenge with electric mobility is the possibility of simultaneous charging of the batteries, creating volatile and spiky loads in the absence of load control. The electricity demand profile does therefore not depend only on the mobility demand, but also on the number of charges per day (usually assumed to 1 for private cars, up to 2-5 for public transport technologies) and on the charging strategy (constant power steering over night, direct charging when plugging the car, etc.). Taking in consideration the peak demands is important to adequately dimension the network of charging stations, power plants and electric batteries.
In the absence of power steering, the peak demands in mobility and electrical mobility are directly correlated. For example, for short-term mobility, a peak in mobility demand in the afternoon is followed by a peak in electric demand. The maximum peak demands can thus be derived for each non-V2G mobility type X from the following constraint (Equation 3.6):

$$\mathbf{Max_{Xmob,demand}} \geq -\sum_{i} layers\_in\_out(i,'ELEC') \cdot \mathbf{F_{mult,t}}(i,h,td) \tag{3.6}$$

$$\forall \quad i \in TECHS\_OF\_XMOB$$
$$\forall \quad h \in HOURS$$
$$\forall \quad td \in TYPICAL\_DAYS$$

For V2G-mobility, the amount of electricity used for V2G has to be added for calculating the maximum peak demand (Equation 3.7).

$$\mathbf{Max_{Xmob,demand}} \geq -\sum_{i} layers\_in\_out(i,'ELEC') \cdot \mathbf{F_{mult,t}}(i,h,td) + \sum_{j} \mathbf{Sto_{in}}(i,'ELEC',h,td) \tag{3.7}$$

$$\forall \quad i \in TECHS\_OF\_XMOB$$
$$\forall \quad j \in BATTS(V2G\_VEHICLES)$$
$$\forall \quad h \in HOURS$$
$$\forall \quad td \in TYPICAL\_DAYS$$

This constraint is expected and was revealed to be trivial when analysing the energy system of an entire country and minimizing the total costs.

Greater peak loads result in oversizing of infrastructure (charging points, electricity suppliers), or the need for importing greater amounts of electricity or producing it from peaking power plants such as CCGTs. This induces extra investment or operational costs, which can be minimized by avoiding charging of the V2G batteries. In practice, peak demands can be specific to a specific region - there may be a localized peak of electrical demand around highways in week-end/vacation days, and electricity excess in other regions.

Charging stations

Exchanges between electric vehicles and charging stations can be modelled by applying conventional energy balances, formulated as equality constraints. Adding those is necessary to design and/or verify that the network of charging stations can handle the electricity demands, both considering energy and power aspects.

Neglecting transmission losses, the electricity delivered by all batteries is equal to the electricity transferred from the charging station to the batteries, and from the grid to the charging stations, as described in Equations 3.8 and 3.9. This approach implies that all batteries are modelled and agglomerated as a single battery receiving electricity from numerous charging stations, which are themselves connected to a single power grid.

A thinner model of each single car battery and of the electric infrastructure was judged out of scope of this thesis, increasing significantly the computational time for a limited gain in information.

$$\sum_i \mathbf{F_{Mult,t}}(i,h,td) \cdot t_{op} = \sum_j \mathbf{Sto_{In}}(j,'ELEC',h,td) \cdot t_{op}(h,td) \tag{3.8}$$

$$\forall \quad i \in TECHS\_OF\_EV\_CHARGING$$
$$\forall \quad j \in EV\_BATTERIES$$
$$\forall \quad h \in HOURS$$
$$\forall \quad td \in TYPICAL\_DAYS$$

$$\sum_i \mathbf{Transfer}(i,j,h,td) = \mathbf{Sto_{In}}(j,'ELEC',h,td) \tag{3.9}$$

$$\forall \quad i \in TECHS\_OF\_EV\_CHARGING$$
$$\forall \quad j \in EV\_BATTERIES$$
$$\forall \quad h \in HOURS$$
$$\forall \quad td \in TYPICAL\_DAYS$$

Limitations regarding the global power and the stations characteristic power are modelled following Equations 3.10 and 3.11.

$$\sum_i \mathbf{F_{Mult}}(i,h,td) \geq \sum_j \mathbf{Sto_{In}}(j,'ELEC',h,td) \tag{3.10}$$

$$\forall \quad i \in TECHS\_OF\_EV\_CHARGING$$
$$\forall \quad j \in EV\_BATTERIES$$
$$\forall \quad h \in HOURS$$
$$\forall \quad td \in TYPICAL\_DAYS$$

$$\mathbf{F_{Mult}}(i) \geq \sum_j \mathbf{Transfer}(i,j,h,td) \tag{3.11}$$

$$\forall \quad i \in TECHS\_OF\_EV\_CHARGING$$
$$\forall \quad j \in EV\_BATTERIES$$
$$\forall \quad h \in HOURS$$
$$\forall \quad td \in TYPICAL\_DAYS$$

Slow charging stations are installed at households, where cars are parked during night. During the day, cars are either in transit and need ultra-rapid stations for recharging on highways, or stopped in public areas where fast and rapid chargers are available. During the night, cars are mostly parked in households and their batteries are therefore charged mostly through slow-charging stations.

To avoid inconsistent solutions, where, for example, all cars would be charged through ultra-rapid stations on highways, an additional time-dependent parameter $c_{access,t}$, was added (Equation 3.13).

$$\mathbf{Transfer}(j,i,h,td) \leq \sum_j \mathbf{Sto_{In}}(j,'ELEC',h,td) \cdot t_{op}(h,td) \tag{3.12}$$

$$\forall \quad i \in TECHS\_OF\_EV\_CHARGING$$
$$\forall \quad j \in EV\_BATTERIES)$$
$$\forall \quad h \in HOURS$$
$$\forall \quad td \in TYPICAL\_DAYS$$

$$\mathbf{Transfer} \leq c_{access,t}(h,td) \cdot F_{Mult}(i) \tag{3.13}$$

$$\forall \quad i \in TECHS\_OF\_EV\_CHARGING$$
$$\forall \quad j \in EV\_BATTERIES)$$
$$\forall \quad h \in HOURS$$
$$\forall \quad td \in TYPICAL\_DAYS$$

The latter equation ensures a more realistic model and solutions, as it limits the quantity of electricity that can be transferred at a given type of power station.

Charging strategies

Scheduling strategies for charging electric vehicles allow for partially decoupling the mobility and resulting electric demands. Various scheduling strategies have been suggested in the literature to minimize the charging costs and minimizing the peaks. They consider, for instance, load and price forecasting across various sectors, as well as the EVs power demand.

The "worst case" charging strategy is an uncoordinated charging strategy "first come first served (FCFS)" - electric vehicles are charged as they are plugged, regardless of their battery level or electricity cost. This unscheduled strategy is expected to result in the greatest peak demands, occurring as vehicles are parked at households after working hours.

A smarter charging strategy is based on electric tariffs - electric vehicles are mostly charged during the night, when the electricity demand in other sectors (households and industry) is smaller and prices lower. Charging is avoided during specific periods of the day, as for example during midday, when the peak of electricity consumption is occurring for cooking-reasons or in the evening when everyone is arriving home and proceeds to leisure-activities. In addition, to prevent peak demands, the charging curve is smoothed by averaging the demanded load in smaller loads over long time periods, typically over a night.

$$\mathbf{Sto_{In}}(i,'ELEC',h,td) = 0 \tag{3.14}$$
$$\forall \quad i \in EV\_BATTERIES)$$
$$\forall \quad h \in h_{end} \geq h \geq h_{start}$$
$$\forall \quad td \in TYPICAL\_DAYS$$

Systematic charging allows to avoid trivial charging and discharging of the battery, such as to have a fixed charging load during a defined period, as for example, what should be charged in this battery when people go home should be at least equal to what was discharged in the afternoon [40].

$$\sum_{h=18}^{22} \mathbf{Sto_{In}}(i,'ELEC',h,td) \geq \sum_{h=12}^{16} \mathbf{Sto_{Out}}(i,'ELEC',h,td) \tag{3.15}$$
$$\forall \quad i \in EV\_BATTERIES)$$
$$\forall \quad td \in TYPICAL\_DAYS$$

These two strategies are taken as a basis for comparison when investigating the integration of electric vehicles in the energy system, but others could be investigated and implemented. For example, electricity price forecasts may be integrated [41].

3.3 Optimization

3.3.1 Problem definition - MILP

The energy model was translated in a multi-periodic mixed-integer linear programming (MILP). The key variables of the model are $\mathbf{F_{Mult}}$ and $\mathbf{F_{Mult_t}}$, which determines the size of the technologies. $\mathbf{F_{Mult}}$ is located within the integer defined by the parameters f_{min} and f_{max}. The MILP model optimizes the energy system of each case study according to two objectives.

Economic optimization The model is generally optimized according to the total costs (Equation 3.16), consisting of the sum of the annualized investment costs $\mathbf{C_{inv}}$, the annual maintenance costs $\mathbf{C_{maint}}$ and the costs of the consumed resources $\mathbf{C_{op}}$ (Equation 3.19). The investment costs results from the multiplication of the specific investment cost c_{inv} and the difference of the installed capacity $\mathbf{F_{Mult}}$ and existing capacity f_{ext}, which is determined according the end-uses output type (Equation 3.17). The annualization is done with the annualization factor $\boldsymbol{\tau}$ depending on the technologies lifetime and the interest rate. Similarly the maintenance costs are determined without annualization by multiplying the technology specific maintenance cost c_{maint} with the installed capacity $\mathbf{F_{Mult}}$ (Equation 3.18). The operating costs of the resources are determined by multiplying the resources specific operating cost with the operating time t_{op} and the temporal capacity $\mathbf{F_{Mult,t}}$.

$$\mathbf{C_{tot}} = \sum_i \mathbf{C_{inv}}(i) \cdot \boldsymbol{\tau}(i) + \mathbf{C_{maint}}(i) + \sum_j \mathbf{C_{op}}(j) \tag{3.16}$$

$$\forall \quad i \in TECHNOLOGIES$$

$$\forall \quad j \in RESOURCES$$

$$\mathbf{C_{inv}}(i) = c_{inv}(i) \cdot (\mathbf{F_{Mult}}(i) - f_{ext}(i)) \tag{3.17}$$

$$\forall \quad i \in TECHNOLOGIES$$

$$\mathbf{C_{maint}}(i) = c_{maint}(i) \cdot \mathbf{F_{Mult}}(i) \tag{3.18}$$

$$\forall \quad i \in TECHNOLOGIES$$

$$\mathbf{C_{op}}(j) = \sum_{h,td} c_{op}(j) \cdot \mathbf{F_{Mult,t}}(j,h,td) \cdot t_{op}(h,td) \tag{3.19}$$

$$\forall \quad j \in RESOURCES$$

$$\forall \quad t \in PERIODS$$

$$\forall \quad h \in HOUR\_OF\_PERIOD(t)$$

$$\forall \quad td \in TYPICAL\_DAY\_OF\_PERIOD(t)$$

Environmental optimization The second objective is the minimization of the greenhouse gases emissions, which are estimated using a LCA approach for the technologies and resources. The emissions can be classified in three emission categories.

- CO_2^A are emissions which can be captured, such as emissions from heavy industry, trucks etc.
- CO_2^C are the captured CO_2 emissions, which either can be stored or reused for fuel production etc.
- CO_2^E are the emissions which cannot be captured directly and are emitted in the atmosphere.

The GWP impact expressed in kt CO_2/yr can be determined by summing the emissions the total GWP of CO_2^A and CO_2^E (Equation 3.20, being specific to each technology and resource.

$$\mathbf{GWP_{tot}} = \sum_i \mathbf{GWP_{CO_2^A}}(i) + \mathbf{GWP_{CO_2^A}}(i) \tag{3.20}$$

$$\forall \quad i \in TECHNOLOGIES \cup RESOURCES$$

$$\mathbf{GWP_{CO_2^x}}(i) = gwp_{CO_2^x}(i) \cdot \mathbf{F_{Mult,t}}(i,h,td) \cdot t_{op}(h,td) \tag{3.21}$$

$$\forall \quad i \in TECHNOLOGIES \cup RESOURCES$$

$$\forall \quad x \in A, E$$

Alternatively, the total emissions can be estimated by splitting the $\mathbf{GWP_{tot}}$ similarly to the total cost calculation in construction $\mathbf{GWP_{construction}}$ and operating GWP $\mathbf{GWP_{op}}$ (Equations 3.22-3.24).

$$\mathbf{GWP_{tot}} = \sum_i \mathbf{GWP_{constr}}(i) + \sum_j \mathbf{GWP_{op}}(j) \tag{3.22}$$

$$\forall \quad i \in TECHNOLOGIES$$

$$\forall \quad j \in RESOURCES$$

$$\mathbf{GWP_{constr}}(i) = gwp_{constr}(i) \cdot \mathbf{F_{Mult}}(i) \tag{3.23}$$

$$\forall \quad i \in TECHNOLOGIES$$

$$\mathbf{GWP_{op}}(j) = \sum_{h,td} gwp_{op}(j) \cdot \mathbf{F_{Mult,t}}(j,h,td) \cdot t_{op}(h,td) \tag{3.24}$$

$$\forall \quad j \in RESOURCES$$

$$\forall \quad t \in PERIODS$$

$$\forall \quad h \in HOUR\_OF\_PERIOD(t)$$

$$\forall \quad td \in TYPICAL\_DAY\_OF\_PERIOD(t)$$

Within this project the separation according the CO_2 categories has been selected.

Multi-objective optimization The multi-objective optimization allows the decision making in optimization problems where more than one objective function is to be optimized simultaneously. Within both projects the economic and ecological objectives are set, which are to be optimized at the same time. The model is optimized for the economic objective, while the ecological objective is integrated by parametrized constraints.

Due to the simultaneous optimization of both objective functions, it is not possible to improve one property without worsening the other. These solutions can be displayed on a coordinate system with the target functions as axes. The set of all optimal solutions can be summarized on a curve. Figure 3.5 shows such an example curve, where all points within the gray zone can be replaced by more efficient solutions lying on the curve (red) and the blue zone is infrasible.

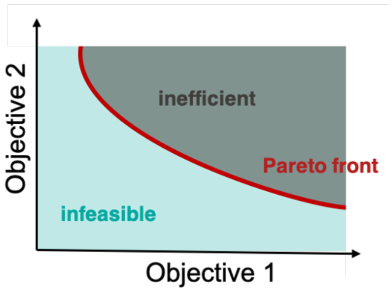


Figure 3.5: Pareto front of a two-dimensional multi-objective minimization problem

3.3.2 Key performance indicators

The comparison of solutions and scenarios can be normalized by defining KPI, summarizing the impact of different constraints on the energy system by representing the desired objectives. Within this project, the KPI can be split in four categories, as summarised in Table 3.2.

Economic

EnergyScope has been developed to obtain thermo-economical optimisation. The main objective function is the *total cost* ($\mathbf{Ctot}$), which estimates the annual costs for the energy system under the assumption of acquiring all technologies from scratch. Total cost is calculated by operating $\mathbf{C_{op}}$ and investment cost $\mathbf{C_{inv}}$, which both can be taken as KPI (Equations 3.16-3.19).

Environmental

The to the economic objective opposed objective is the *GWP*, estimating the environmental malus of the system. Similarly to the cost, the total $\mathbf{GWP_{tot}}$ can be split on operational $\mathbf{GWP_{op}}$ and construction $\mathbf{GWP_{constr}}$ (Equations 3.22-3.24).

Energetic

The characterisation of the energy system can be determined by calculating the*primary energy consumption* of selected resources. The annual consumption of the following resources can be calculated and allows to characterize the renewable fraction of the system. The primary energy consumption $\mathbf{E_i}$ of resource i can be calculated as

$$\mathbf{E_i} = \sum_{h,td} \mathbf{F_{Mult,t}}(i,h,td) \cdot t_{op}(h,td)$$

The renewable resources are::

- Geothermal
- Waste
- Wet Biomass
- Wood
- Solar
- Wind
- Hydro

The non-renewable resources are:

- Gasoline
- Diesel
- LFO
- Coal

The *heating* KPI share give insight about the heating technologies installed. Three different KPI are calculated by summing all technologies within these classifications over the year as

$$\mathbf{Q_i} = \sum_{h,td} \mathbf{F_{Mult,t}}(i,h,td) \cdot t_{op}(h,td)$$

where i corresponds to the following hetaing technologies

- Heat pumps
- Cogeneration
- Boilers
- Electric heating

The *district heating share* allows to represent the distribution between decentralised and centralised heating technologies and are constrained within the interval

$$f_{DHN}^{min} \leq \mathbf{f_{DHN}} \leq f_{DHN}^{max}$$

3.3.3 Mobility

In order to represent the impact of mobility, the annual mean *share by vehicle type* defines the penetration of different mobility technologies, defined in Section 2.2. Another parameter defining mobility is the *share of public transportation* for long and short distance. These shares can be calculated for each vehicle type i within the mobility category $mob-cat$ as

$$\mathbf{f^i_{mob-cat}} = \frac{\sum_{h,td} \mathbf{F_{Mult,t}}(i,h,td) \cdot t_{op}(h,td)}{\sum_i \sum_{h,td} \mathbf{F_{Mult,t}}(i,h,td) \cdot t_{op}(h,td)}$$

Table 3.2: Summary of KPI

Type	Name	Unit	description
Econom.	$\mathbf{C_{inv}}$	[M€/yr]	Investment cost
	$\mathbf{C_{op}}$	[M€/yr]	Operating cost
	$\mathbf{C_{maint}}$	[M€/yr]	Maintenance cost
	$\mathbf{C_{tot}}$	[M€/yr]	Total cost $\mathbf{C_{tot}} = \mathbf{C_{inv}} + \mathbf{C_{op}} + \mathbf{C_{maint}}$
Environ.	$\mathbf{GWP_{constr}}$	[Mt-CO_2^{eq} /yr]	Construction GWP
	$\mathbf{GWP_{op}}$	[Mt-CO_2^{eq} /yr]	Operating GWP
	$\mathbf{GWP_{tot}}$	[Mt-CO_2^{eq} /yr]	Total GWP $\mathbf{GWP_{tot}} = \mathbf{GWP_{inv}} + \mathbf{GWP_{op}}$
Energy System	$\mathbf{E_i}$	[TWh/yr]	Primary Energy consumption by type i
	$\mathbf{f_{renewable}^{primary}}$	[%]	Renewable share on primary energy
	$\mathbf{Q_i}$	[TWh/yr]	Heat produced by technology type i
	$\mathbf{f_{DHN}}$	[%]	District heating share
	$\mathbf{W_{el}^{peak}}$	[GW]	Peak electricity demand
Mobility	$\mathbf{f_{pass}^{i}}$	[%]	Share of technology i within passenger mobility
	$\mathbf{f_{public}^{local}}$	[%]	Share public mobility within LD passenger mobility
	$\mathbf{f_{public}^{longd}}$	[%]	Share public mobility within HD passenger mobility
	$\mathbf{f_{freight}^{i}}$	[%]	Share of technology i within freight mobility
	$\mathbf{f_{train}^{freight}}$	[%]	Share train mobility within freight mobility
	$\mathbf{E_{el}^{Mob}}$	[TWh/yr]	Electricity consumed by mobility technologies

3.4 Future demands and typical days

3.4.1 Future demands

"Prediction is very difficult, especially if it's about the future." (Niels Bohr)

The estimation of future demand has to be based on historical data. To be consistent with available data for the countries of Germany and France, a unique open-acces database has been searched, containing socio-economic data. Latter was found with the Organisation for Economic Co-operation and Development (OECD)-economonic database [11], consisting of a collection of over 40 data series as population, income, households etc.

Some demands, as for example the mobility demand per year, are not available within databases projecting the future. In order to estimate latter future demands, they have to be constructed with outscoping databases with similar behaviour. Following assumptions are made for the demands, following as much as possible Codina-Girones methodology [42]:

- Industry demands are correlated with the countries Gross Domestic Product (GDP);
- Demands in service sector is assumed being proportional to the population number of the country;
- Household demands are proportional to the number of households in the country. Note that in Codina-Girones method, the households demand was made proportional to the dwelling surface. Latter time series is not available in the OECD database and a replacing time series had been found with the number of households.

Passenger mobility demand is assumed to follow the population number, as the demographic movement. While latter movement is directly linked to the short and long distance mobility. In order to determine the effect of either time series on the mobility, the weighting factors w_n have been determined by applying a minimization problem such as

$$\min \sum_t |f_t^{Mob} - \sum_n w_n \cdot f_{n,t}| \qquad \text{s.t} \sum_n w_n = 1$$

where f_t^{Mob} is the mobility demand of the year t, $f_{n,t}$ the time series entry of either population or demography of year t. This allows to minimize the difference of historical data and the mobility demand. This methodology allowed to determine the weighting factors on which the mobility demand has been able to be estimated. Freight mobility is correlated with the GDP under the assumption that the countries economies are mainly industry-based and affecting the goods transport.

3.4.2 Typical days

To model the hourly behaviour of the energy system based on these future demands, the typical days model was adapted to the mobility characteristics. The model works with 12 typical days, modelling the 365 days of the year as close as possible by minimizing the model resolving time. This improvement in resolution allows to take into consideration hourly variations and the induced extreme combinations of demand and production.

The selected clustering method, as in previous works on Energy Scope, apply the method for Combined Heat and Power (CHP) MILP optimization presented by Dominguez-Muñoz [43]. As input to the clustering, different time series in hourly resolution were normalized and weighted according to their importance.
The time series by Limpens [1] were taken as basis, with the mobility time series being replaced by the short and long distance mobility time series. To ensure the different day types, a weighting factor of 5 was added to the mobility time series.

3.5 Sensitivity and uncertainty analyses

The developed model aims at analysing the potential energy systems in 2050, based on estimates of costs and demands for 2050. These parameters, such as the natural gas and electricity prices, present, by definition, a high uncertainty and may as well vary greatly from one year to another. Sensitivity analyses help in understanding the relations between the model inputs (costs, efficiencies, demands, potentials) and outputs (total cost and global warming potential). They can be used as well, as desired here, to simplify the model by ranking the various parameters according to their importance.

Local sensitivity analyses (one-step-at-a-time or OAT methods) consist of varying only one input factor at at time to induce changes in the outputs, and are useful in identifying important model parameters for given sets of parameter values. On the contrary, when parameter values vary in search spaces, global sensitivity analyses are more efficient, as they tackle the problems of model non-linearities and dependencies between input parameters. The main global sensitivity analysis tools are either screening (Morris) or sample-based (Sobol) methods.

3.5.1 Morris screening

The Morris method [44] was used to identify which costs, efficiencies, potentials and energy demands have the greatest effect on the optimised total costs. A strong advantage of this method is the small number of simulations to run, compared to Sobol-based methods, to get an overview of the influential and non-influential factors. A main drawback is its qualitative nature, for the exactly same testing conditions, different rankings of parameters can be obtained. The Morris method involves discretizing the model inputs, generating samples of parameter values using random OAT designs and consists of seven steps:

1. the complete space of possible values of the k input parameters x is discretised in a p-levels grid - the higher the number of levels p, the thinner the discretisation of the search space;
2. a certain number of initial values is generated for each of the k input parameters - these values take only a value of the p-levels grid;
3. the subsequent model outcome (optimal total cost) y is calculated based on the set of initial values;
4. a new set of parameter values is generated - all parameters but one are kept at their start values, and one input parameter only changes value within its $p$levels;
5. these steps are repeated r times, the higher the number of repetitions r, the more accurate the final ranking;

6. the variations in the model output y due to the input x are determined by calculating the elementary effect (EE) and calculated for the j-th variable and the i-th valuation:

$$\mathrm{EE}_j^{(i)} = \frac{\partial y}{\partial x_j} \simeq \frac{y(x_1, x_2, x_j + \delta x_k) - y(\mathbf{X})}{\delta}$$

7. as each parameter varies over different magnitudes - for example, the potential for wind power varies between 100 and 300 GW, while the demand for mobility varies between 1,000,000 and 1,500,500 Mpkm, which corresponds to a difference of magnitude of 10^4 - it is necessary to scale these elementary effects by the standard deviations of the model inputs and outputs:

   These elementary effects are scaled to calculate the non-dimensional deviation of the model outputs σ_{y_i}, and the factors σ_{x_j} & $\mathrm{SEE}_j^{(i)}$;

8. the approximate distribution of the local derivatives of the solutions are compared to define the sensitivity of the model. Two indicators are used:

   - μ^*, the mean values of the distribution of the standardized absolute elementary effects SEE [45]. The larger μ^* is, the more sensitive the output of the j-th input is. μ^* is defined as:

   $$\mu_j^* = \frac{1}{r}\sum_{i=1}^{r} \mid \mathrm{SEE}_j^{(i)} \mid$$

   - σ, which is the standard deviation of the distribution of the elementary effects SEE. σ measures the nonlinear effects of the jth input on the model output, as well as the effect on the other $k-1$ parameters. σ is defined as

   $$\sigma_j = \sqrt{\frac{1}{r}\sum_{i=1}^{r}\left(\mathrm{SEE}_j^{(i)} - \frac{1}{r}\sum_{i=1}^{r}\mathrm{SEE}_j^{(i)}\right)^2}$$

Based on these indicators, the input factors can be categorised as:

- Non-influential factors are the group of points being close to the origin (small μ^* and σ). Their effects can be neglected on the models output result in comparison to the other factors;
- less-influential factors are values which are located close to the line $\sigma = \mu$;
- influential non-interacting, are factors below the separation line $\sigma = \mu$. Their influence on the optimisation result is more of additive nature;
- influential interacting factors are above the separation line and have a non-linear effect on the result.

Morris screening has been applied to MobES by integrating 193 parameters (Table F.1).

3.5.2 Monte-Carlo simulations

Monte Carlo methods are a class of computational algorithms used to model a range of possible outcomes and estimate their probabilities. They rely on repeated random (or near-random) sampling and are used in cases where analytical solutions do not exist or cannot be easily found.

For example, they were applied in this project to determine how frequently electric vehicles are more competitive than fuel cell ones, under which conditions and at which costs. This problem cannot be solved analytically and performing a high number of simulations with random input values (e.g. natural gas price, wind potential, efficiency of an electric vehicle) can help estimating the probability of this outcome.

These techniques are therefore particularly useful to identify the impact of technical and economic uncertainties and the resulting risks. They consist of the following steps [46]:

- identify the input parameters that are likely to have a significant impact on the model output;
- determine the statistical properties (mathematical distribution, such as uniform, normal, beta, etc.) of these input parameters;
- generate a large number of input sets which represent adequately the parameter space;
- for each set of input values, perform a deterministic calculation of the model outputs;
- analyze statistically the results in terms of average values and distributions.

For example, in a country such as Germany, which imports natural gas for heating, the natural gas price is likely to have an impact on the total cost of the energy system. The possible price range in 2050 is difficult to estimate and is assumed to vary uniformly around the current price with an uncertainty of $\pm 30\%$.
This methodology has been applied to the case studies of France and Germany with the parameters being identified by the Morris screening and summarised in Tables G.1 & G.2. For simplification, in this work, uniform distributions were taken - beta distributions could have been derived based on historical values, but may not have been appropriate as the time horizon is 30 years.

Chapter 4

Case studies & scenarios

Two countries were selected, representing the European energy system. Latter countries are characterised according their geographic, economic social situation, before the modelling important parameters are listed. In a second step, the future demands of latter countries are estimated, as the typical days are characterized, based on historical time series. In a last step different scenarios influencing the energy system are generated. These steps allow to answer the research questions:

- What are the characteristics of representative European countries? (Section 4.1)
- How can extreme scenarios in mobility demand be taken into consideration? (Section 4.2)
- What are the scenarios allowing to take into consideration different mobility fleet technologies? (Section 4.3)

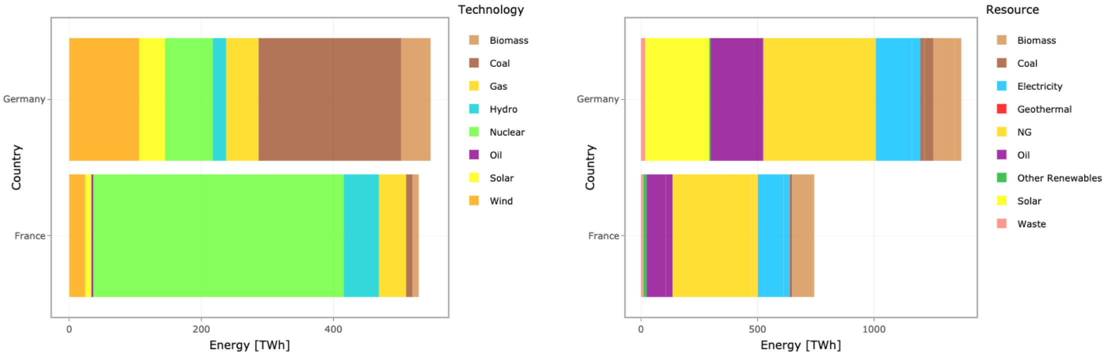
4.1 Case studies

The MILP framework was applied as an example to two countries of Europe for a 30-years horizon. EU presented in 2019 the "Green Deal 2050" in order to elaborate a framework for its member nations to reach the carbon neutrality in 2050. Germany and France were selected due to their different strategies to reach these policies, as for their different mobility-behaviour. Those two countries furthermore are the biggest countries in term of population (33.5% of EU population) and primary energy consumption (38.8% of EU primary energy consumption.) [11].

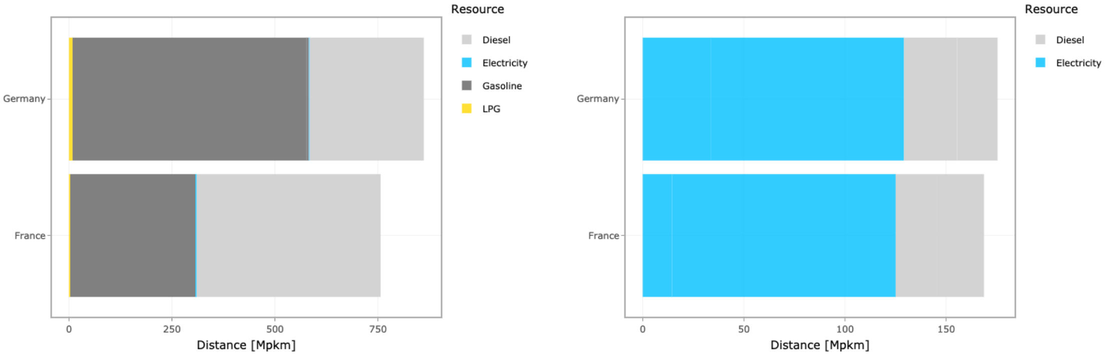
4.1.1 France

Background

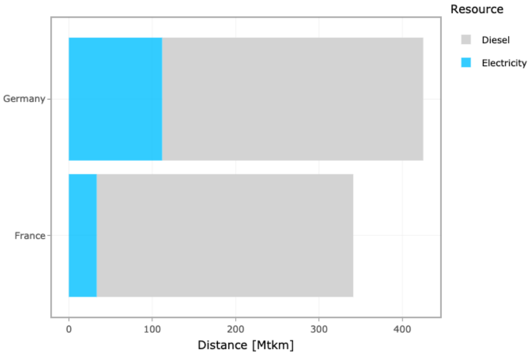
France is a densely populated country with a population of 123 people per square kilometer, and a total of 67 million inhabitants for a surface of 545’000 square kilometres. It had large



(a) Electricity (b) Heating



(c) Private Mobility (d) Public Mobility



(e) Freight Mobility

Figure 4.1: Primary Energy consumption for Electricity, Heating and Mobility 2017.

gas and coal reserves which were exploited for both heat and electricity production until the 1950s. After the 1974 oil crisis, France mostly developed nuclear power for energy security reasons and is the country in Europe with the largest share of nuclear in the electricity mix. The energy and electricity mixes changed little in the following decades. France played a pioneering role in the development of hydropower (15% of the hydroelectricity generated in Europe). Wind power and photovoltaics have only been developed in recent years, resulting in 13% of electricity from renewable sources in 2017.

In 2014, the Energy Turnaround Act was passed, which was intended to reduce the share of nuclear energy in the electricity mix from 75% in 2014 to 50% in 2030 by capping the total output at 63.7 GW. Other measures include the renovation of buildings and the expansion of the electric fleet.

Heating

The total heating demand amounts to 745 TWh and is mainly fossil fuel based (65.8%) of which NG takes the highest share (75% of the fossil fuel consumption in heating). Renewable energy ranks second with 112 TWh (15.1%). The use of solar energy for thermal purposes is negligible (0.2‰), despite high potentials in the southern regions.

Electricity

Figure 4.1(a) shows that the major part of France's electricity production originates from nuclear power (71.6% of 529.2 TWh). Fossil fuels represent 10.18%, with NG-cogeneration taking 41.1 TWh. Renewable energy sources mainly consist of hydropower (53.2 TWh), followed by wind power (24 TWh).

Mobility

The yearly mobility demand for passenger transport amounted to 925.2 Bpkm in 2017, with a ratio of about 4-1 for private and public mobility (Table 4.1 and Figure 4.1(d)).
Private mobility is dominated by fossil-fuel powered vehicles with a share of 59% of diesel vehicles and of 40.1% gasoline. The contributions of electric vehicles (3.03 Bpkm) and Liquified Petroleum Gas (LPG) vehicles (3.04 Bpkm) are negligible in comparison.
Public transportation consists of both road (85.7%), rail and water transport. The main technologies are electric and diesel-powered vehicles (Figure 4.1(d)), the former (trains and tramways) dominating (74.1% against 25.9%) the latter (diesel coaches and buses).
Freight transport is dominated by road transport, rail transport representing only 9.3%. The diesel-electricity ratio in freight transport amounted to 10:1. Maritime and pipeline transport (5%) is neglected within this project.

Table 4.1: Uses and shares of passenger & freight mobility technologies in France (2018) [3])

	Absolute	Relative
Private cars	757.3 [Bpkm]	82%
Public transport (excl. airplanes)	168.7 [Bpkm]	18%
Rail	33.4 [Btkm]	9.3%
Road	307.7 [Btkm]	85.7%
Others	18.0 [Btkm]	5.0%

Policies 2050

Introduced by the Energy Transition Law for Green Growth (LTECV), the National Low-Carbon Strategy (SNBC) is France's roadmap to combat climate change. It provides guidelines for implementing, in all sectors of activity, the transition to a low-carbon, circular and sustainable economy. It defines a trajectory for reducing greenhouse gas emissions until 2050 and sets short- and medium-term objectives: carbon budgets. It has two ambitions: to achieve carbon neutrality by 2050 and to reduce the carbon footprint of French consumption.

In order to achieve latter objectives, policies for carbon emissions and Energy transformation were defined.
Within SNBC, three carbon levels, named "budgets" were defined, allowing a gradual transition towards carbon-neutrality being summarised in Table 4.2.
In 2050, carbon neutrality should be achieved, with 80 MtCO2-eq of emissions and 80 MtCO2-eq carbon capture, being achieved by decreasing the emissions by 11.5 Mt/year starting after the third budget in 2035.

Table 4.2: Three upcoming carbon-budgets of SNBC

				Budget 1	Budget 2	Budget 3
Period	1990	2005	2015	2019-2023	2024-2028	2029-2033
Annual Emissions [Mt CO2-eq]	546	553	458	422	359	300

Two main objectives were defined for the Energy system 2050

- $f_{RE}^{heat} \geq 62$ [%]
  The target of 38% renewable energy in final heat consumption by 2030 was set. After that intermediate budget, the rate of growth of the renewable heat rate must be accelerated to an average of 1.2% per year, i.e. a rate 1.5 times faster than before, resulting in a minimum of 62% share in 2050.

- $f_{RE}^{Elec} \geq 40$ [%]
  The target of 40% renewable energy in final electricity consumption by 2030 was set by the "loi relative à la transition énergétique pour la croissance verte". No further thresholds were set for the year 2050, as the role of nuclear power has not yet been fully defined.

France also decided not to expand nuclear power, which means that the current capacity of 62.3 GW will be maintained in the future.

Potential

The potential of continental France has been analysed in detail by the "groupe développement durable" of France's environment ministry [47]. They are summarised in Table 4.3 where the minimum value (policy or existing potential) and the maximum (real potential) are represented.

Table 4.3: Primary energy potential France 2050

Resource	Minimum	Naximum
Geothermal	0.73	1.39 [GW]
Hydro Dam	19	23.354 [GW]
Hydro River	6.33	6.33 [GW]
Plant	-	131 [TWh/yr]
Solar thermic	2.63 [GW]	10.52 [GW]
Solar PV	107 [GW]	350 [GW]
Waste	-	157 [TWh/yr]
Wet biomass	-	40 [TWh/yr]
Wind onshore [48]	25.4	813 [GW]
Wind offshore [48]	6	175 [GW]
Wood	-	120 [TWh/yr]

4.1.2 Germany

Germany is a country in Central Europe and lies between the Alps in the south and the Baltic Sea in the north. In 2017, Germany had 82,521,653 inhabitants living on an area of 357,376 square kilometres, which is one of the most densely populated countries in the world with a population of 230 people per square kilometre.

Energy System 2017

The German energy system 2017 consists of conventional thermal power plants (coal, natural gas, oil), nuclear power plants and renewable energies. The "13. Gesetz zur Änderung des Atomgesetzes" of 2011 [49], which regulates the end of the use of nuclear energy and the acceleration of the energy turnaround, dictates the trend of the last few years (2011-2017) with a reduction in the share of nuclear power plants and an increase in renewable energies such as wind and solar.

Electricity The production of electricity in Germany is strongly influenced by the 13th law on nuclear phase-out. Due to the Fukushima catastrophe, the German Bundestag decided to end the use of nuclear energy and accelerate the energy turnaround in 2011. As a result, eight power plants were taken off the grid and the remaining stations will be shut down in stages until 2022. Thus until 2017 it was necessary to compensate the reduction of 10 GW by coal and gas power stations.

The German electricity production is mainly dominated by coal, which amounts to 216 TWh, respectively 39.5% of the electricity production. Nuclear power was reduced to 72.2 TWh. Renewable energy already takes 38.2% of the German electricity production in 2017, where wind with 105.7 TWh takes more than half of the renewable shares.

Heating Heating demand in Germany amounts to 1374.8 TWh in 2017, from which 55 % are generated from fossil resources. NG takes 54% of the fossil fuel part, while coal (4.8%) can nearly be neglected in comparison to its role in electricity production. With 618.7 TWh, renewable resources take almost half of the German heat production, where the biggest contribution comes from solar thermal with 274.4 TWh.

Mobility Table 4.4 lists the shares and the demands in mobility for Germany in 2017, where it is split between passenger and freight mobility. Passenger mobility in 2017 was 1111 Bpkm, which is split in private (78%) and public (22%) transport. Figure 4.1(d) shows the share of the different private vehicles, separated according to their powering resource. It is visible that the major part of the private mobility (98.1%) is running standard ICE cars, which is split in 65.9% gasoline and 32.2% Diesel. Public mobility is mainly electric-powered dominated, as 54.4% of the passenger-distance in public mobility was done in trains. On the other hand, freight transport is Diesel based as road-transport (62.8%) is almost fully Diesel-powered. 22.4% are transported on rails. Maritime and pipeline transport is neglected.

Table 4.4: Uses and shares of passenger & freight mobility technologies in Germany (2017) [4])

	Absolute	Relative
Private cars	868 [Bpkm]	78%
Public transport (excl. airplanes)	243 [Bpkm]	22%
Rail	111.9 [Btkm]	22.4%
Road	313.1 [Btkm]	62.8%
Others	73.7 [Btkm]	14.7%

Policies 2050

The German government established the "Energiewende"-strategy, aiming to reduce carbon dioxide emissions and to reduce fossil fuel consumption. The main objectives of Germany can be summarized as:

- Reduce greenhouse gas emissions to 250 Million tons CO_2 equivalent
- Primary energy consumption should be reduced to 50%
- Fossil fuels represent at maximum 20% of the primary energy consumption
- Renewable Energies take the remaining 80% of primary energy shares
- Nuclear power will be completely shut down
- Heating demand should be reduced to 20% of 2012 by increasing efficiency of heating processes and renovation of building stock

In order to fulfill the electricity production share policies, renewable energy will strongly be developed. The potential of the different renewable energy resources was estimated, resulting to the feasible potential values:

- Hydro Dams 11 GW
- Hydro River 5 GW
- PV 320 GW
- Wind 280 GW
- Biomass (Wood, Waste, Plant, Wet Biomass) 335 TWh

4.2 Future demands & typical days

With the assumptions presented in the previous chapter, it was possible to estimate the end-use demands. Validation of the methodology was applied to the case of Germany, where the Fraunhofer Institute also has generated estimations about the electricity consumption. The comparison of the EUD is visible in Table 4.5. While households and industry have a low relative error, differences are visible in low temperature heating and electricity demand of the industry & services sector. The electricity demand is overestimated by 11.7% for the sum of the latter sectors, but corresponding to 4.8% error of the overall electricity consumption. The understimation by 40 [GWh] for the low temperature heating of the industry and services sector also represents an acceptable relative error of 4.7% of the total heating demand. By summing the total energy demand for heating and electricity, the difference between both methods lies at 2.1%.

4.2.1 Future demands

Heating and Electricity

Having validated the approach, it is possible to estimate the demands for France also. The EUD for electricity and heating are represented in Table 4.6.

Table 4.5: Comparison of the energy demands outlook 2060 for Germany calculated by the Fraunhofer ISE and the ones presented in this work with EnergyScope.

Demand Germany	Value ISE [GWh]	Value ES [GWh]	Difference [%]
Heat LT Households	525000	546000	3.9
Electricity Households	48000	49900	3.8
Heat LT Industry & Services	320000	$212000 + 68000$	-14.5
Electricity Industry & Services	37500	$152000 + 273000$	11.7
Heat HT Industry	445000	$722000 - 273000$	1.0
Total	1713000	1749000	2.1

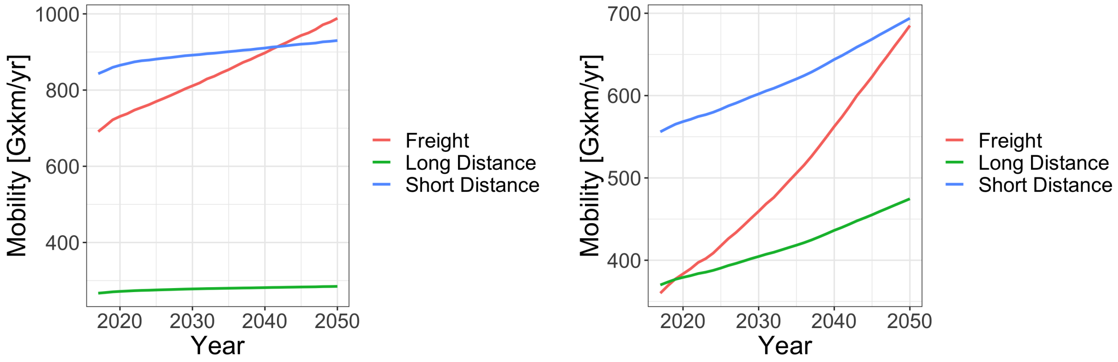
Table 4.6: EUD Heating and Electricity Germany and France 2050 [TWh]

	Households		Services		Industry	
	Ger	Fra	Ger	Fra	Ger	Fra
Electricity	35.0	54.0	152.4	112.4	272.5	192.2
Heat High T	0	0	0	0	722.0	297.1
Heat Low T SH	312.6	291.2	193.1	123.8	61.2	79.2
Heat Low T HW	69.2	44.7	18.8	31.0	6.4	19.8

Different effects are visible. While the heating demand in the households is higher for Germany, the electricity demand shows the contrary. The industry sector is striking with the difference in high temperature heating demand of Germany, being 2.43 times the demand of France, while France has the higher low temperature demands. These differences in the sectors can be explained by the correlation assumptions. France is expected to have the higher population growth than Germany, leading to an increase in services demand. The same phenomena is expected for the industry, where France is to be expected to have the higher GDP growth.

Mobility

Figure 4.2 illustrates the estimated mobility demand evolution, using the method stated in section 3.4. While long and short distance mobility are following similar slopes, freight transport has the highest slope, due to the direct correlation to the GDP. It is visible that France is expected to have the higher GDP growth than Germany, starting in 2025. Passenger mobility is attenuating for Germany, while France is expected to increase, which can be brought back to the population growth estimations according to the OECD [11].
The mobility demands for 2050 are reported in Table 4.7. The evolution of long and short distance mobility is visible throughout the shares. While the short distance is taking higher shares in Germany, high distance is increasing in France. This phenomena can be brought



(a) Germany (b) France

Figure 4.2: Mobility demands evolution outscoping ([x]: [people] for passenger mobility and [t] for freight).

back to the decentralisation strategy of France, where people prefer living outside the centers and are commuting to the work, rather than living on the workplace. Germany has on the other side several centers of industry and services, which allows people to live close to the workplace.

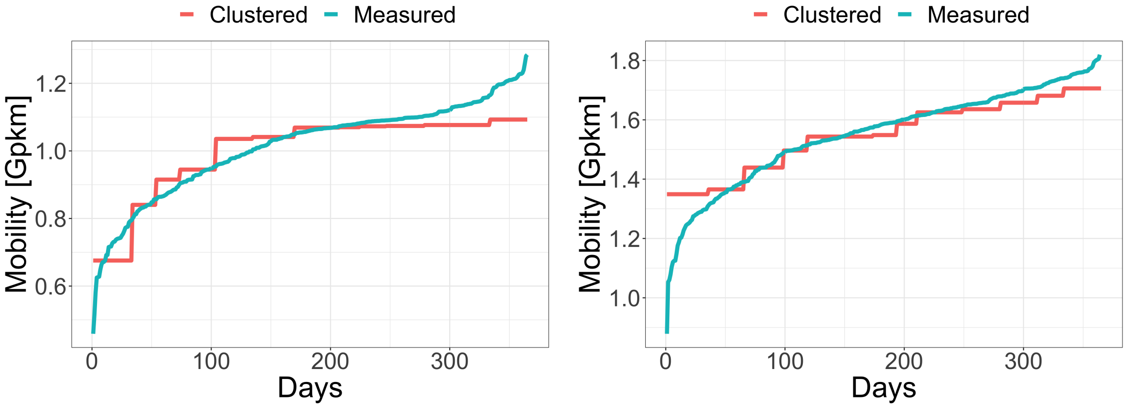
Table 4.7: EUD Mobility Germany and France 2050

	Transportation		Share	
	Germany	France	Germany	France
Mobility Passenger LD [Gpkm]	930.1	693.9	76.56%	59.38%
Mobility Passenger HD [Gpkm]	284.8	474.7	23.44%	40.62%
Mobility Freight [Gtkm]	988.4	685.1		

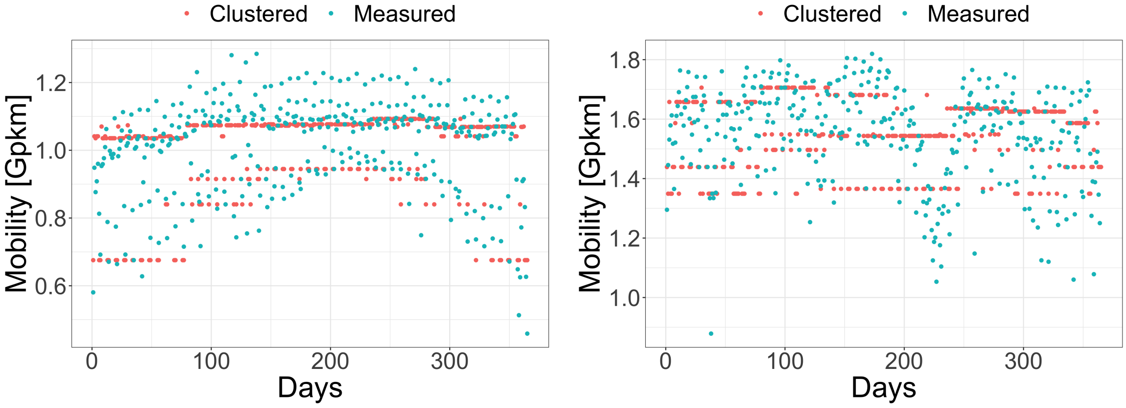
4.2.2 Typical Days

Mobility Having applied the clustering, the resulting typical days are visible in Figure 4.3. The 12 typical days can be observed by the plateaus. Figures 4.3(a) and 4.3(b) show the ordered demands on which the difference between clustering and real value can be observed. By following Limpens clustering methodology, no extremal values were added.

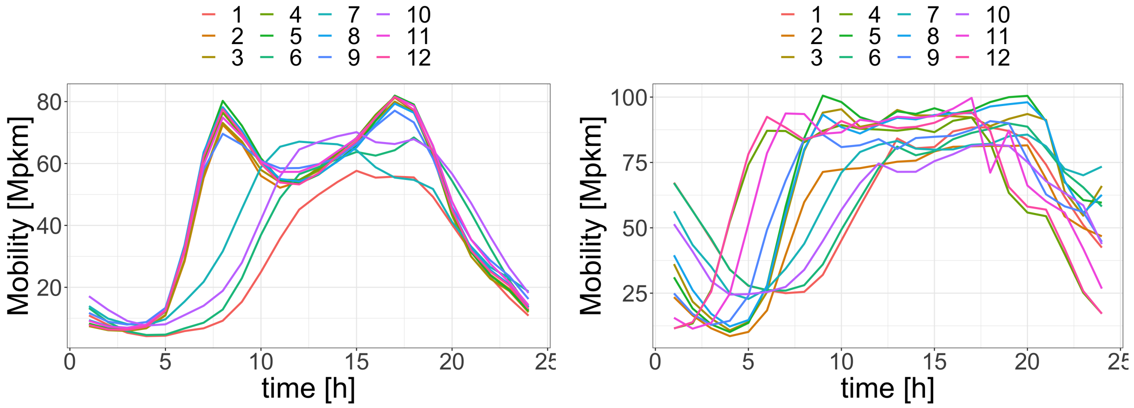
Figures 4.3(e) & 4.3(f) represent the hourly mobility demands of the clustered days. Long distance mobility is clustered 8 days corresponding to workdays, while TD 1, 6, 7 & 10 are weekends. LD mobility is more ambiguous to graphically identify the day types. The weekend TD are characterized by an increased sink in the morning and lower peak during the afternoon compared to the weekday local mobility.



(a) Ordered HD (b) Ordered LD



(c) Daily HD (d) Daily LD



(e) Hourly HD (f) Hourly LD

Figure 4.3: Clustering and measurements comparison on mobility Germany 2017.

Seasonal variation Table 4.8 summarises the parameters of each typical day. The hourly time series were summed up to obtain the dayly sum. Wind and Solar have the relative variance added

$$var = \frac{\max_h x_h^{TD} - \min_h x_h^{TD}}{\sum_h x_h^{TD}}$$

in order to characterize variations during the day.

The simplest distinction between the TDs is to group by seasons. Three TDs (1,2,3) are in *Winter*, being characterized by the highest heating demand, varying between $3038\,\mathrm{GWh}$ and $4337\,\mathrm{GWh}$. Due to low temperatures, less water is available leading to low hydro power production, being $7.3-14.84\,\mathrm{GWh}$ daily electricity production by hydro power. The incident angle of the sun is lower in winter, explaining the low irradiance.
TDs in *Summer* (9,10,11) are the opposite of the Winter TDs, being characterized by low heating demand as the average temperture is above the ambient temperature of $20\,°\mathrm{C}$. The solar incidence angle is highest in summer, resulting in the highest solar irradiance (2.9-$5.3\,\mathrm{kWh/m^2}$). The high temperatures are melting the ice and snow, leading to higher water volumes in rivers and lakes, which allows to produce higher hydro powered electricity (63.85-$115.17\,\mathrm{GWh}$). *Spring* and *Autumn* are the transitory seasons with intermediate heating demands and solar irrdiance. The major difference is in the hydro potential, as spring follows winter, allowing to melt more ice and leading to single peaks in hydro potential, as the TD 8 with $154.67\,\mathrm{GWh}$.

High distance Mobility demand is not affected by the seasons by comparing the Figure 4.3(e) and Table 4.8. No differences in seasonal TDs are visible for the mobility curves. The only visible distinction is according the weekdays, which follows the pattern described in Section 2.1.1. *Low distance mobility* is affected by seasonal variations as visible in Figure 4.3(f). In fact, people prefer using light mobility for short distance travels when the weather allows. Sunny and warm days are therefore leading to a decrease in mobility demand as the TDs of Summer and Spring (5-11).

4.3 Scenarios

The simulation of different results within the results space of cost minimization can be shown by evaluating extreme scenarios. These scenarios are selected in order to take into consideration the major possible impacts on the energy system, as the composition of the vehicle fleet.

4.3.1 Reference scenario

The reference scenario is defined in order to take into considerations all policies, strategies as the renewable energy potential of the corresponding countries (Sections 4.1.1 and 4.1.2) for the year 2050. It serves as baseline for all scenarios, where additional constraints are added.

Table 4.8: Typical Days clustering parameters characterization case study Germany 2050.

TD	Date	Season	Daytype	Heating [GWh]	Elec. [GWh]	Hydro [GWh]	Wind [GWh]	Wind [%]	Solar $[\frac{\text{kWh}}{\text{m}^2}]$	Solar [%]
1	04.02	Winter	Weekend	4059	1395	14.84	284.1	6.6	1.514	17.83
2	08.02	Winter	Weekday	3038	1408	14.08	166.7	8.9	1.572	18.41
3	14.02	Winter	Weekday	4337	1407	7.30	140.0	7.5	1.283	16.54
4	05.12	Autumn	Weekday	4177	1478	22.90	506.4	4.3	0.473	22.45
5	10.04	Spring	Weekday	1540	1304	36.97	176.8	8.8	3.424	15.49
6	22.04	Spring	Weekend	1465	989	53.75	371.0	6.0	3.887	12.90
7	05.05	Spring	Weekend	1176	1272	83.28	240.2	7.3	4.996	12.55
8	05.06	Spring	Weekday	59	1248	154.67	284.0	3.9	3.087	10.94
9	31.07	Summer	Weekday	0	1176	107.55	132.8	5.6	5.295	12.02
10	22.07	Summer	Weekend	6.6	1217	115.17	312.2	6.7	2.980	11.97
11	05.09	Summer	Weekday	552	1273	63.85	198.7	6.0	2.806	15.12
12	14.11	Autumn	Weekday	2124	1388	30.45	179.9	9.7	0.868	16.67

The GWP of each country was defined. As France wants to be Carbon-Neutral in 2050 and within this project no carbon capture was taken into consideration, the GWP limit of France is set to the emissions estimated without carbon capture corresponding to 80 Gt-equ CO_2. Germany is more sceptic about carbon capture technologies and has not planned integrating latter technologies. Their target is to reduce the GWP to 250 Gt-equ CO_2.

The end uses demands are estimated according the outscope results from Section 3.4, visible in Tables 4.6 and 4.7.

Fossil Fuels import is limited according to the country's policies. France and Germany both decided to delete the LFO and coal import. Gasoline and diesel are kept available, while NG import is limited to $420\,\mathrm{TWh}$ for the case of France. Germany restricted the consumption of imported NG to the fraction of the consumed primary heating Energy to 50%. Latter constraint is not modelled for the German case and therefore kept available.

While the biomass potential of France clearly was defined and separated in waste $(15.7\,\mathrm{TWh})$, wet biomass $(40\,\mathrm{TWh})$, wood $(120\,\mathrm{TWh})$ and plant $(131\,\mathrm{TWh})$, Germany only estimated the total biomass potential $(335\,\mathrm{TWh})$. In order to split latter potential, the shares of France were applied to Germany, resulting in waste $(17.15\,\mathrm{TWh})$, wet biomass $(43.85\,\mathrm{TWh})$, wood $(131\,\mathrm{TWh})$ and plant $(143\,\mathrm{TWh})$.

The power generation technologies were modelled by defining their minimum (f_{min}) and maximum (f_{max}) installed capacities. The minimum is defined by the already existing technology size for renewable energies, while the maximum corresponds either to a regulated maximum (nuclear power in France) or the economic potential of the resources.

The shares limitations of public transport was adapted such that the evolution towards more public transport can be taken into consideration. The upper limit is set to 40%, where the minimum is at 20%, corresponding to an estimation of the actual share. The district heating minimum limitations correspond similarly to the public transport shares to the actual shares of district heating (15%). The maximum was defined to 75%, being the extreme case of Sweden in 2020.

4.3.2 Vehicle technologies scenarios

The influence of the penetration of different vehicle types with the relative influence on the energy system analysis is the aim of the vehicle technologies scenarios. The base scenario is selected and different vehicle technology shares are constrained within an interval of 100% to 0% with 20% steps.

- *BEV* induce high charges on the electric grid, due to the recharging power needed at similar times. The behaviour of these vehicles was modelled and explained in Section 3.2.2. BEV have the possibility to be connected to the grid (V2G). This fraction is defined as parameter and set to 5%. Accordingly, the minimum and maximum fraction of the BEV had to be adapted for mono- or bidirectional vehicles.

  The maximum power of all non-electric freight and public transport vehicles had been set to zero, forcing the solver to select pure electric freight and public transportation solutions.

- *Hydrogen vehicles* force the system to produce H_2, as the import of latter was set to zero. For each transportation mode, a fuel-cell powered vehicle is available, allowing to set the penetration of hydrogen vehicles on each sector.

- *Synthetic fuel* is used in conventional ICE. The share of gasoline and diesel vehicles, as the technologies available for freight and public transportation are defined as available in 2017.

  The variation of penetration of the synthetic fuel is controlled by varying the share of produced synthetic fuels. Note that the problem is infeasible for a synthetic fuel share of 100% Diesel, leading to a share of 95% Diesel for the 100% synthetic fuel case.

4.3.3 Extreme scenarios

The extreme scenarios are created to model the extreme points within the search space, allowing to analyse the influence of different policies and their corresponding activated technologies. Two extreme scenarios are modelled

- *Energy independence* is modelled by setting all imports to zero, forcing the system to exploit all indigenous resources;
- *Minimization of environmental impact* is obtained by changing the objective function from total cost minimization to GWP minimization. To avoid the appearance of trivial solutions, such as exploitation of infeasible storage inducing extreme costs etc, the minimum GWP is determined by rounding up by 1% the GWP computed after optimization, and constraining the GWP to latter value and minimizing the total cost.

4.3.4 Summary of the implemented scenarios

All scenarios are implemented to the case studies of Germany and France. Furthermore, the extreme scenarios as the vehicle scenarios with 100% share are run with the monthly model for comparison purposes. Table 4.9 summarises all scenarios with the main characteristics.

Table 4.9: Summary of the considered scenarios.

Scenario	Type	Energy policy		Vehicle technology
		GWP	Import	
0	Reference	limited	NG, Diesel, Gasoline, Uranium	ICE Gasoline & Diesel
1	Fleet	none	NG, Diesel, Gasoline, Uranium	EV and open
2	Fleet	none	NG, Diesel, Gasoline, Uranium	Hydrogen and open
3	Fleet	none	NG, Uranium, Diesel, Gasoline	open
4	Fleet	none	NG, Uranium, Diesel, Gasoline, Ethanol	E85 and open
5	Extreme	limited	none	open
6	Extreme	Minimization	none	open

Chapter 5

Results

Within this chapter, the different results on the impact of various mobility technologies are presented and the main differences between Germany and France are analysed. In Section 5.1, the model and assumptions for the two case studies are validated based on the available data for the year 2017. Based on the policies and end-use demands expected for 2050, the resulting costs, impacts and shares of renewable sources in the energy and power mixes are estimated (Section 5.2) for a few scenarios.

In the subsequent sections, the detailed impact of the integration of different mobility technologies (synthetic fuels, electric vehicles, ethanol, etc.) is discussed. It is illustrated with Pareto borders, showing the trade-off between costs and emissions, as well as the needs for implementing new technologies.

A global sensitivity analysis based on a Morris screening approach was conducted to identify which parameters, such as costs, efficiencies, demands and potentials, have the greatest impact on the system costs. Finally, an uncertainty analysis was carried out on the parameters judged influential by the Morris screening to investigate which mobility technologies were the most promising to integrate, and what would be their impacts in terms of costs and environmental impacts.

This procedure allows to respond to the following research questions:

- What are the economic, environmental and energetic impacts on the energy system due to renewable mobility integration? (Sections 5.2-5.6)
- Which parameters are subject to highest impact on the energy system? (Section 5.7)
- How does uncertainty impact green mobility technology penetration in thermo-economic optimisation? (Section 5.8)

5.1 Reference scenario (2017)

The models and assumptions for the two case studies were validated based on the data for the year 2017. The objective of this step was to compare the results obtained by running the two models (monthly and typical days) against the official statistics. The model outputs used for comparison are the primary energy use, sorted by source (e.g. gasoline, coal, solar, etc.) and the total greenhouse gas emissions.

The used model is based on linear programming and returns a solution judged optimum with respect to the total costs or emissions. The retrieved solution is particularly sensitive to variations in the input parameters (chaotic behaviour) and additional constraints were added to best reproduce the energy system designs of France and Germany in 2017. For both models, a constraint on the minimum shares of district heating, boilers and cogeneration units for heat generation was added, as well as on the shares of the main energy sources (such as nuclear for France and natural gas for Germany). The efficiencies of the coal and natural gas power plants were further adjusted to 40% and 55%.

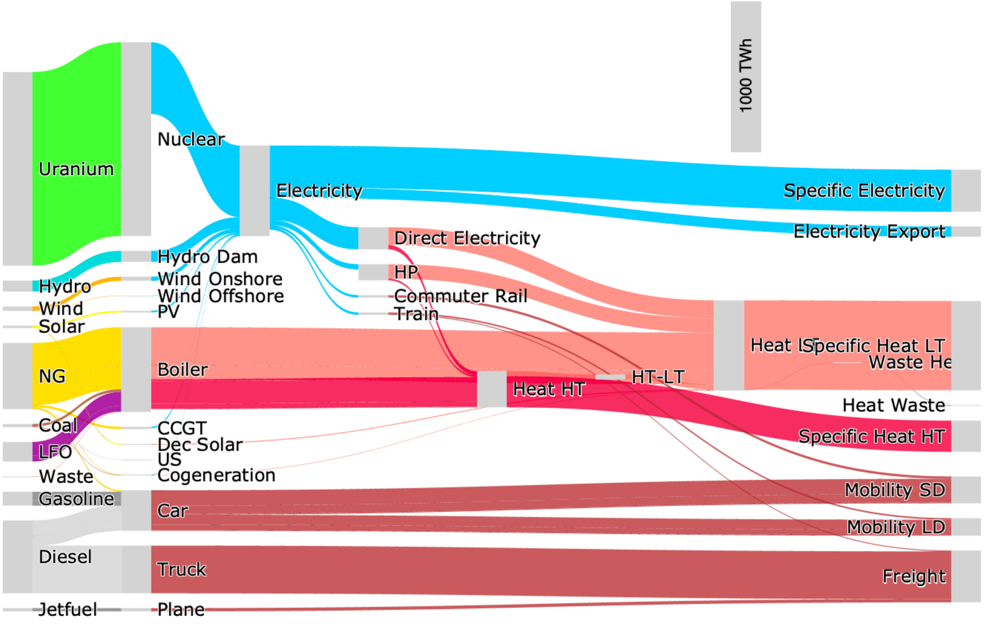
The main differences between the two countries (Figures 5.1(a)-5.2(b) & Table 5.1), are the demands for thermal energy (higher in Germany, resulting in a greater consumption of gas and coal) and the electric power mix (mainly driven by nuclear facilities in France).

A comparison between the TD and the monthly models illustrates some differences in terms of system design and operation. They are more marked for the German energy system than for the French one. The former is characterized by a higher share of renewables (wind and solar) in the electricity mix.

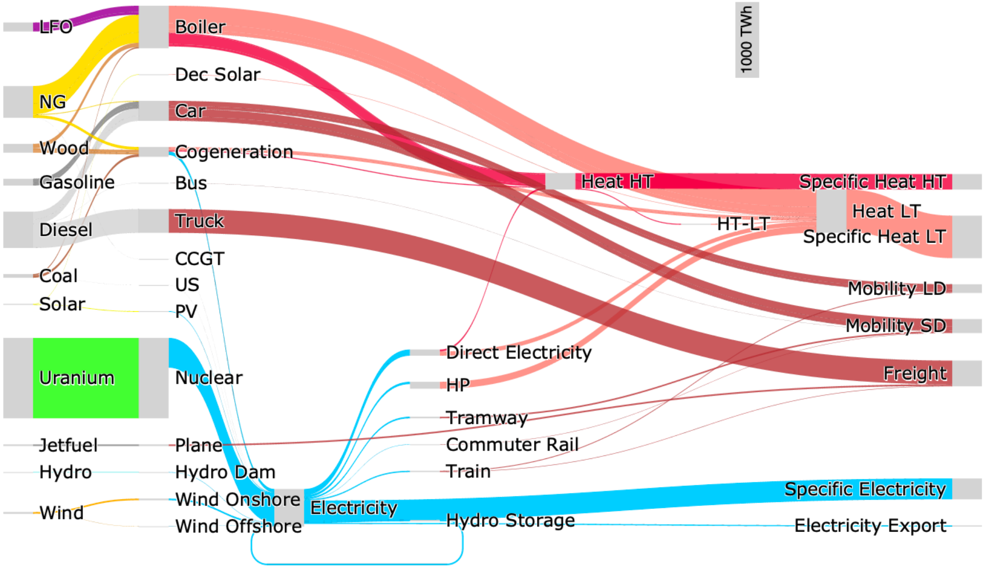
The impact of renewable intermittency at an hourly or daily time scale are not easily visualized when using a monthly-based model as the power fluctuations are averaged over a month and attenuated. The energy system seems to rely on higher/smaller electricity generation from conventional thermal power plants and on long-term storage with hydro dams to balance the grid.

On the contrary, the TD Model inherently has a thinner temporal resolution and a larger panel of storage technologies, such as short-term thermal and electricity storage. The hourly and daily variations of wind and solar power are captured and addressed differently. Short- and medium-term storage units such as batteries and compressed air energy storage are used in parallel with imports and exports for grid balancing.

Interestingly, the proposed system designs for the case of Germany are almost equivalent in the monthly and TD models in terms of global warming potential and costs. This demon-

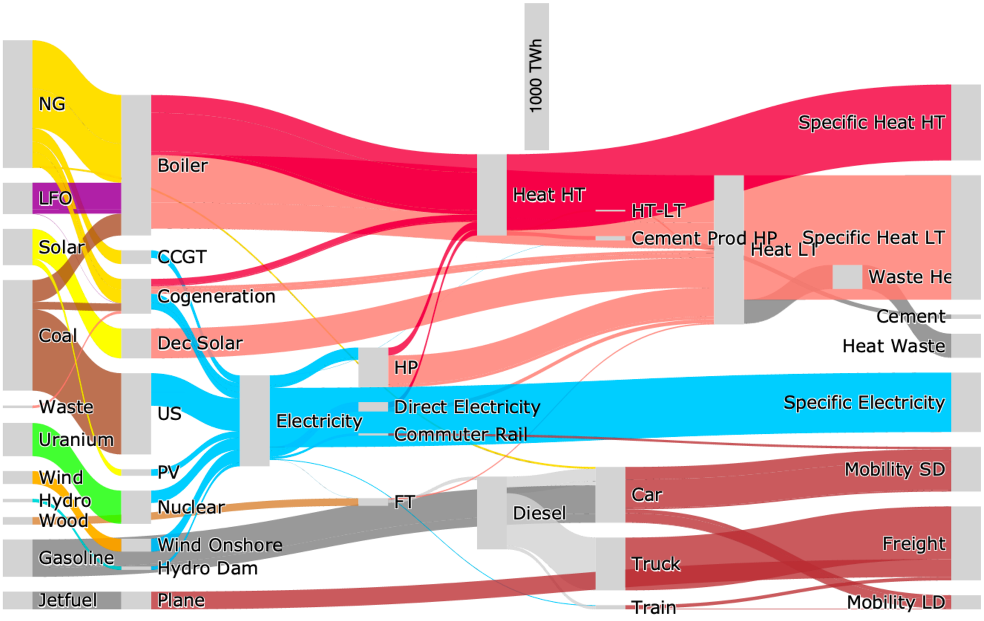


(a) Monthly

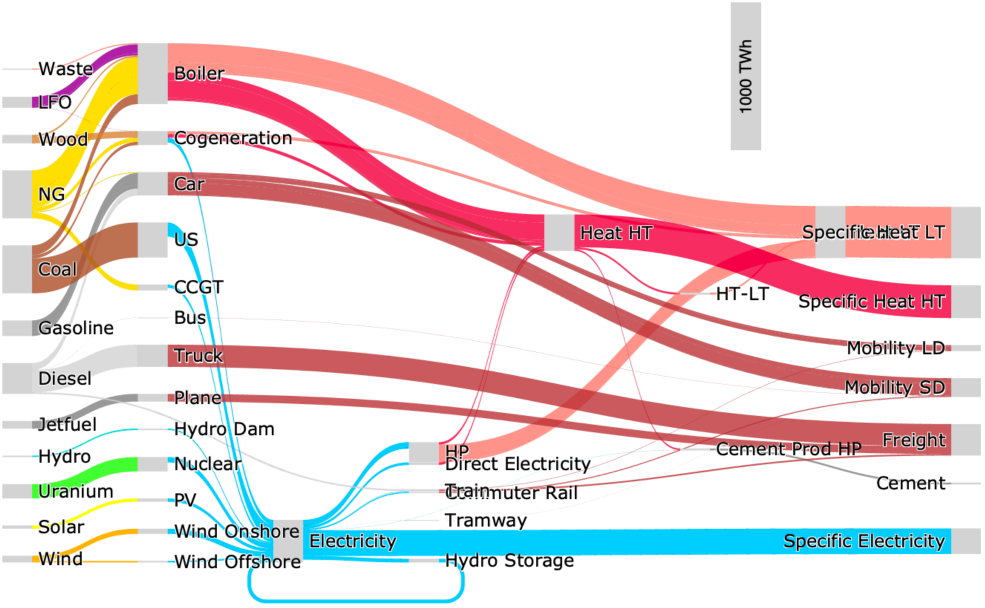


(b) Typical Days

Figure 5.1: Sankey diagrams France 2017 model comparison and validation.



(a) Monthly



(b) Typical Days

Figure 5.2: Sankey diagrams Germany 2017 model comparison and validation.

strates the chaotic behaviour of linear programming problems, where near-equivalent solutions (in terms of optimization objective) can be found for significantly different inputs (decision variables).

Table 5.1: Model validation: MILP model output vs. actual 2017 values for the France and Germany energy systems. (TD / Monthly)

		Actual 2017		MILP		Δ	
		GER	FRA	GER	FRA	GER	FRA
Primary Energy [TWh]	Coal	834	114	730 / 728	23 / 50	-104/-106	-91/-64
	Gasoline	236	92	246 / 248	102 / 90	10/11	10/-2
	Diesel	501	414	483 / 426	450 / 425	18/-75	-36/10
	NG	890	446	825 / 829	479 / 492	-65/-61	33/45
	LFO	205	75	172 / 190	127 / 120	-33/-15	52/45
	Nuclear	229	378	221 / 221	386 / 316	-8/-8	8/-62
	Solar PV	41	9	48 / 43	8 / 10	0/2	7/1
	Onshore wind	86	26	78 / 86	21 / 27	-8/1	-5/0
	Offshore wind	24	2	24 / 25	2 / 2	0/0	0/0
	Geothermal	3	0	0 / 0	0 / 0	-3/-3	0/0
	Waste	37	3	17 / 17	3 / 3	-20/-20	0/0
	Wood	131	117	130 /130	115 / 115	1/1	-2/-2
Heating [TWh]	Boilers	858	503	905 / 850	508 / 500	43/-8	5/-3
	HP	94	90	91 / 85	90 / 90	-3/-9	0/0
	Cogeneration	89	53	85 / 85	50 / 50	-97/-13	-3/-3
Mobility [Mpkm]	Car diesel	228	520	230/231	512/523	-2/3	-8/3
	Car gasoline	462	256	462/461	251/253	0/-1	-5/-3
	Car BEV	71	80	0/0	0/0	-	-
	Train	225	311	231/229	310/312	6/4	-1/1
Objs.	Total cost (MCHF/y)	-	-	290/288	208/188	-	-
	Total GWP (MtCO2/y)	-	-	556/555	448/303	-	-

The differences between the actual statistics and model outputs are:

- in the case of France, the consumption of coal, diesel and natural gas, which is underestimated (up to 15%), and the production of electricity from wind and solar, which is overestimated (about 5%);

- in the case of Germany, the consumption of coal, waste and biomass, which are underestimated (10 to 50%).

These can be attributed (i) the efficiencies of thermal power plants and diesel cars, which may be overestimated in the MILP model, as they are based on future projections and not on actual plant data, (ii) the simplified modelling of biomass feed and conversion units, (iii) the lack of data on fuel use and carbon emissions for non-energy, agriculture and aviation purposes, and (iv) the non-inclusion of power curtailment for photovoltaic panels and windmills.

These differences do not alter the order of importance of each source in the current energy systems of Germany and the model was deemed satisfactory to reproduce the relations between the energy demand, conversion units and resources.

Firstly, the values entered in the model were deemed reasonable to represent the 2050 energy systems based on the scientific literature and on the previous works conducted with EnergyScope. Secondly, the integration of batteries and other storage units to balance the intermittency of renewables is expected to reduce the need for curtailment. The two models (typical day and monthly) show the same trends, with small differences in terms of solar and wind power production, due to the averaging and use of clusters for typical days.

5.2 General results

The different simulations were run for different scenarios (Section 4.3) with the monthly and the TD models. The aim was to analyse the impact of scenarios with full penetration of a given type of vehicle (e.g. 100% full electric, 100% fully synthetic fuels), named afterwards "extreme points". A selection of extreme points of the different scenarios (Table 4.9) is visible in Figure 5.3. Each scenario will be presented and analysed in details in a dedicated section. Figure 5.3 shows the extreme points of each scenario represented within a GWP-Cost graph, such that for each vehicle scenario, the vehicle share of the corresponding vehicle technology is at 100%. Furthermore, the reference and the import-limited scenarios were added. Two points per scenario are represented, where one point is the result of the total cost minimization and the other one corresponds to the total GWP minimization. Certain points are located at the same spot, as the reference scenario (0) in France and the electric vehicles. A full integration of battery electric vehicles corresponds to the economic optimum for the reference scenario. Neither hybrid electric nor plug-in hybrid vehicles (PHEV) appear in the cost- or GWP-optimized solutions. This suggests that, for the costs projected in 2050, turning to fully-electric vehicles instead of hybrid ones is both the most sustainable and economic path.

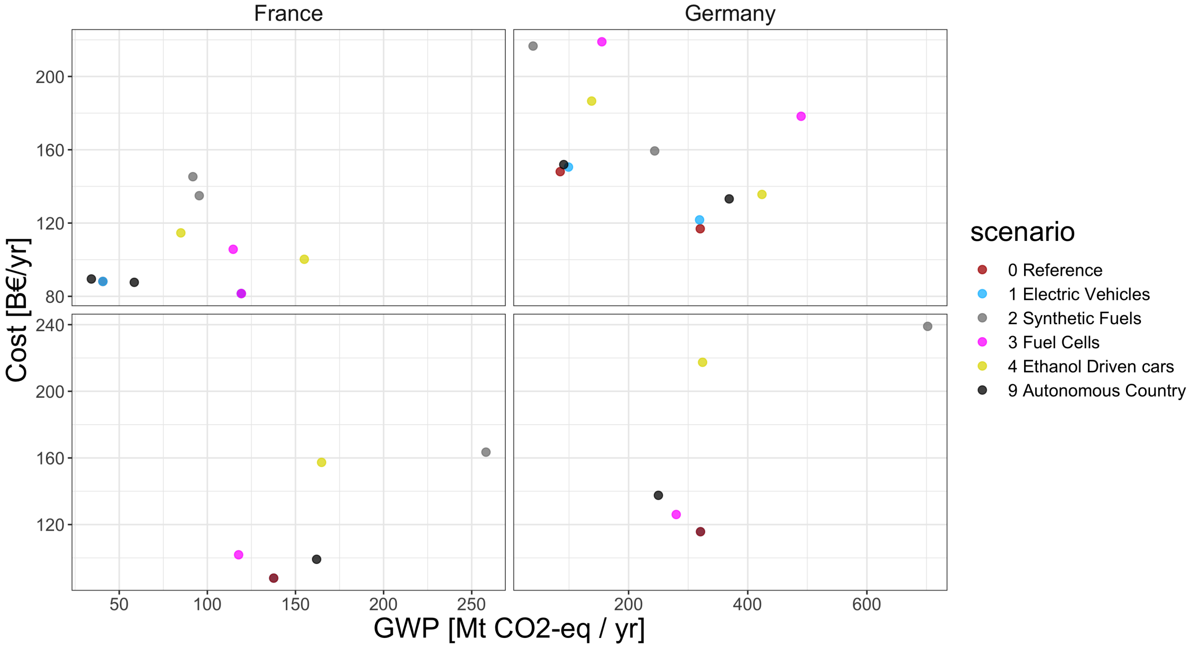


Figure 5.3: Trade-off between environmental impacts (GWP) and total costs for various scenarios, for the cases of France of Germany (top: TD, bottom: Monthly)

The total costs, shown on the vertical axis, include annualized investment, maintenance and operating costs (Figure 5.4). The scenario with 100% electric vehicles is apparently the cheapest one for both France ($91.5\,\mathrm{BEur/yr}$) and Germany ($112.4\,\mathrm{BEur/yr}$). This trend is confirmed with both types of models.

On the contrary, a 100% deployment of vehicles with synthetic fuels (synthetic diesel and gasoline) appears to be the first or second expensive solution for both countries, with $161.4\,\mathrm{BEur/yr}$ in France and $235.4\,\mathrm{BEur/yr}$ in Germany. Neither France nor Germany have enough biomass resources (wood, waste, crops, etc.) for production of synthetic fuels replacing fossil fuel based gasoline & diesel. The missing carbon needs to be recovered either from reforming of natural gas or from conversion of carbon dioxide captured from air. The higher costs in Germany compared to France result from the smaller biomass potential.

The differences between both models in terms of economic costs range between 13% and 23%, the smaller total costs being predicted with the monthly model. This difference is likely imputable to the higher penetration of intermittent renewable energies. The variations are captured on a daily basis and the costs associated with backup electricity sources (peak power plants), electricity import and storage units are more accurately predicted. The maintenance-investment-operation ratio is nearly constant throughout the models, indicating similar technologies chosen for the same scenario.

In contrary to the cost composition, major differences (Figure 5.3) between the models are visible when the GWP emissions for each scenario are compared. While the highest emis-

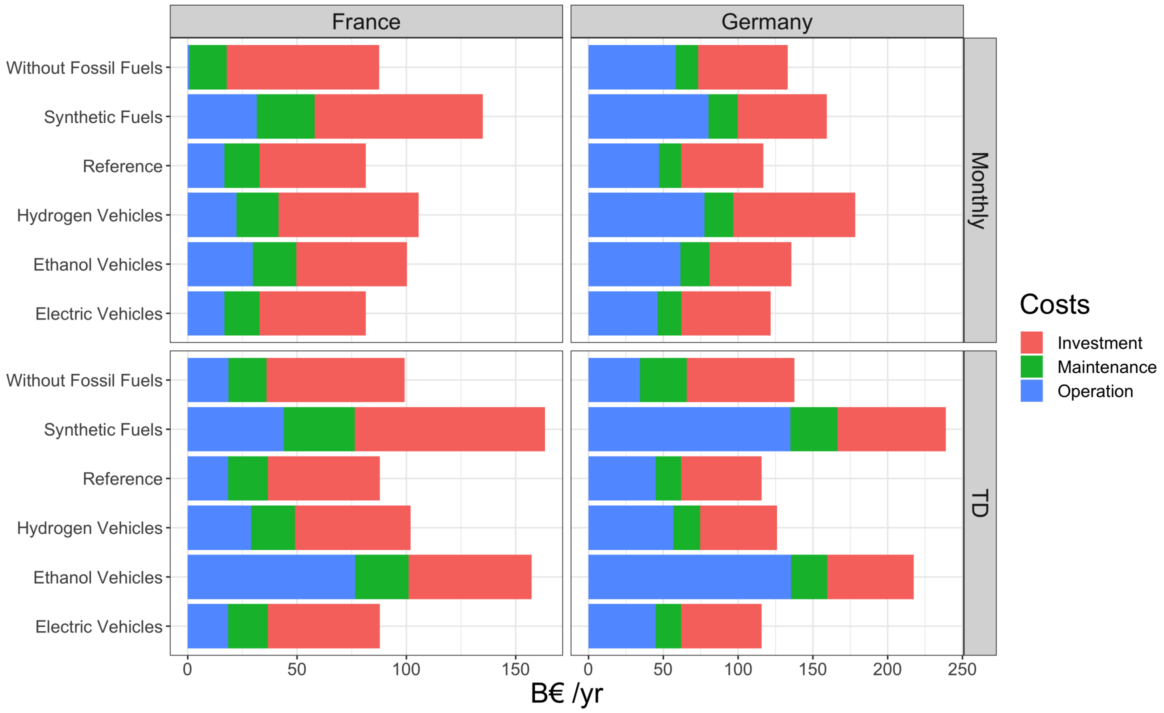


Figure 5.4: Decomposition of the total costs into annualised investment, maintenance and operation costs for each scenario

sions are caused by synthetic fuels in TD model, most GWP is caused by ethanol (France) or hydrogen (Germany) vehicles in the monthly model, by varying in between 85%-135% according to the model. The remaining scenarios have a relative difference of 12-18%. The differences in the stored CO_2 in the synthetic fuels scenario is a hint to different implemented technologies. The lack of CO_2 atmosphere emissions is a sign for different definitions of primary energy use.

Figure 5.6 represents the consumption of primary energy for latter scenarios. While no major differences between the models is visible for France, Germany has two scenarios behaving in a different manner. The monthly model suggests the import of hydrogen for the generation of synthetic fuels, whilst the TD model indicates the integration of large-scale electrolysis to produce the required hydrogen. A different trend is also observed for the fossil fuel free scenario. The TD model indicates a need for twice the imports of electricity than the monthly model does, which relies heavily on power production from both onshore and offshore wind.

All scenarios are within the same range (1500-2000 TWh/yr), with the exceptions of the synthetic fuel scenario (24%-36% more than the average) and the scenario without fossil fuel import (54%-60% less than the average). The fossil fuel free scenario must recur to renewable energy producing electricity, without having additional, more economic intermediate

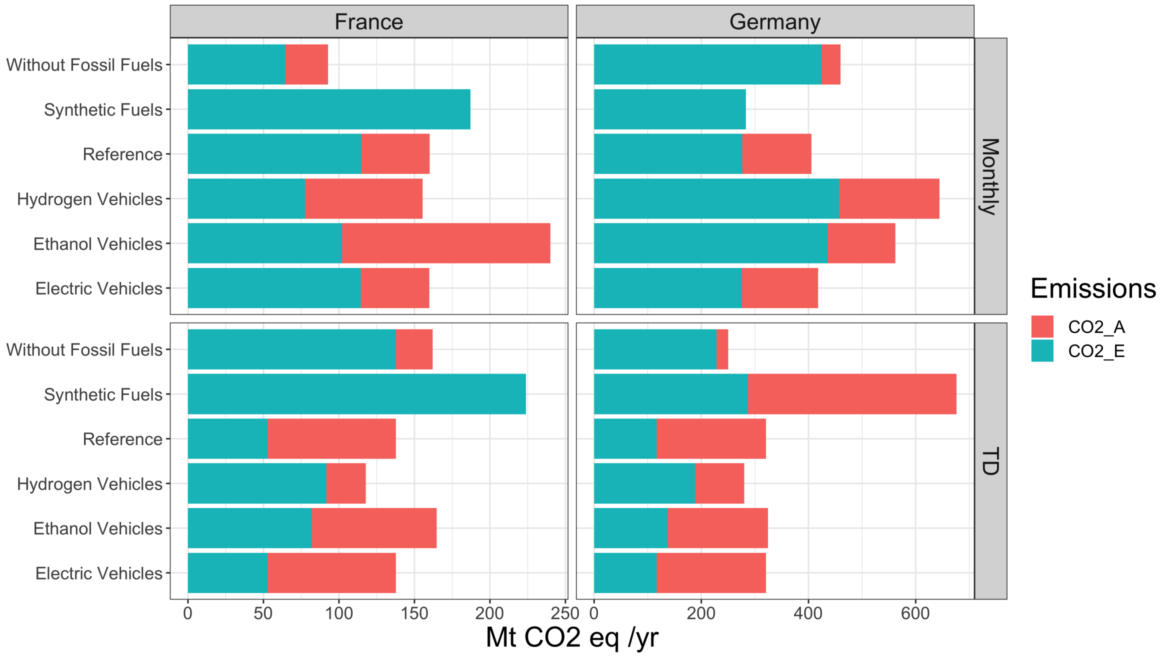


Figure 5.5: Decomposition of the total CO_2 emissions from large stationary sources (CO_2-A, e.g. power plants and biorefineries) and, small emission points (CO_2-E, e.g. cars) for each scenario

processes in between. The opposite is occurring with the synthetic fuel scenario, where the system is forced to convert biomass resources into gasoline and synthetic fuels, leading to a higher energy demand.

Another distinction is visible by comparing France and Germany. The large deployment of nuclear power in France, combined with a large exploitation of wind resources and balancing with hydroelectric storage, guarantees its energy independence.

On the opposite, Germany has a more limited potential for offshore wind and biomass, which prevents a large electrification of its energy system. The import of either natural gas or electricity for heating technologies is therefore necessary. Germany's electricity-producing renewable energy technologies are, independent of the scenario and model, at its maximum potential of $430\,\mathrm{TWh/yr}$. In theory, Germany could go beyond this maximum potential, which is the potential judged economic and with the current installation restrictions by studies of the European Commission.

5.3 Reference scenario (2050)

Different cases for the reference scenario were simulated (Table 5.2) and the constraints were selected to represent the major impacts on the energy system for each country. Figure 5.7 shows the Pareto curves of the scenarios.

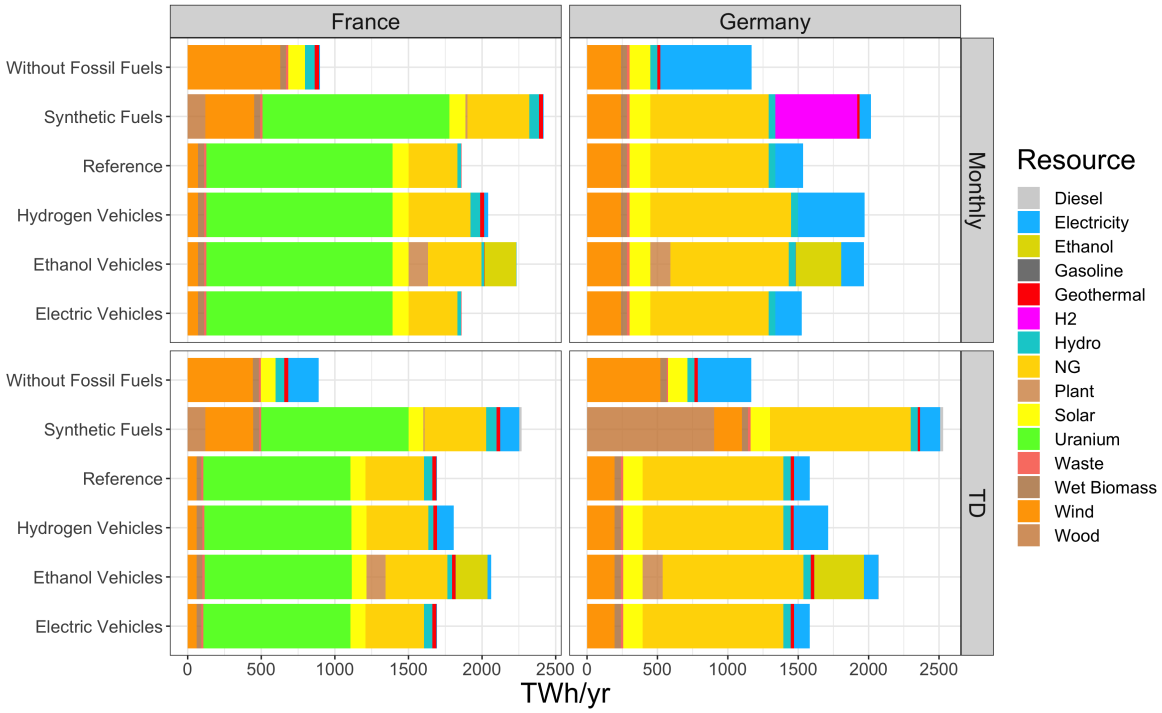


Figure 5.6: Decomposition of the main sources of primary energy for each scenario

Two curves are visible in Figure 5.7 for Germany, while the red curve corresponds to the economic potential and the green curve the technical potential for photovoltaic, onshore and offshore wind. Both curves are parallel to each other with similar inflection points. While the technical potential reaches 60% less emissions, the relative difference in costs amounts to 6%[1].

France has three curves represented, where the left-most curve corresponds to the reference scenario 0 without constraints. The environmental optimum of all three curves is in the interval $87\text{-}88\,\mathrm{BEur/yr}$ at $40\text{-}45\,\mathrm{MtCO2-eq/yr}$, while the economic optimum of each curve lies at $120\,\mathrm{MtCO2-eq/yr}$ for a cost varying between $81\text{-}86\,\mathrm{BEur/yr}$. While the nuclear scenarios have similar inflection points at the same emissions, the nuclear-free curve (blue) decreases nearly linearly with a slope of -35 Mt CO_2-eq/B€.

Table 5.2: Summary of the reference scenarios 2050.

Index	France	Germany
0	no constraints	no constraints, economic potential (wind and solar)
1	no electricity import	no constraints, economic potential (wind and solar)
2	no nuclear, no electricity import	-

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[1] The definition of "economical" potential is therefore questionable and has to be reviewed potentially.

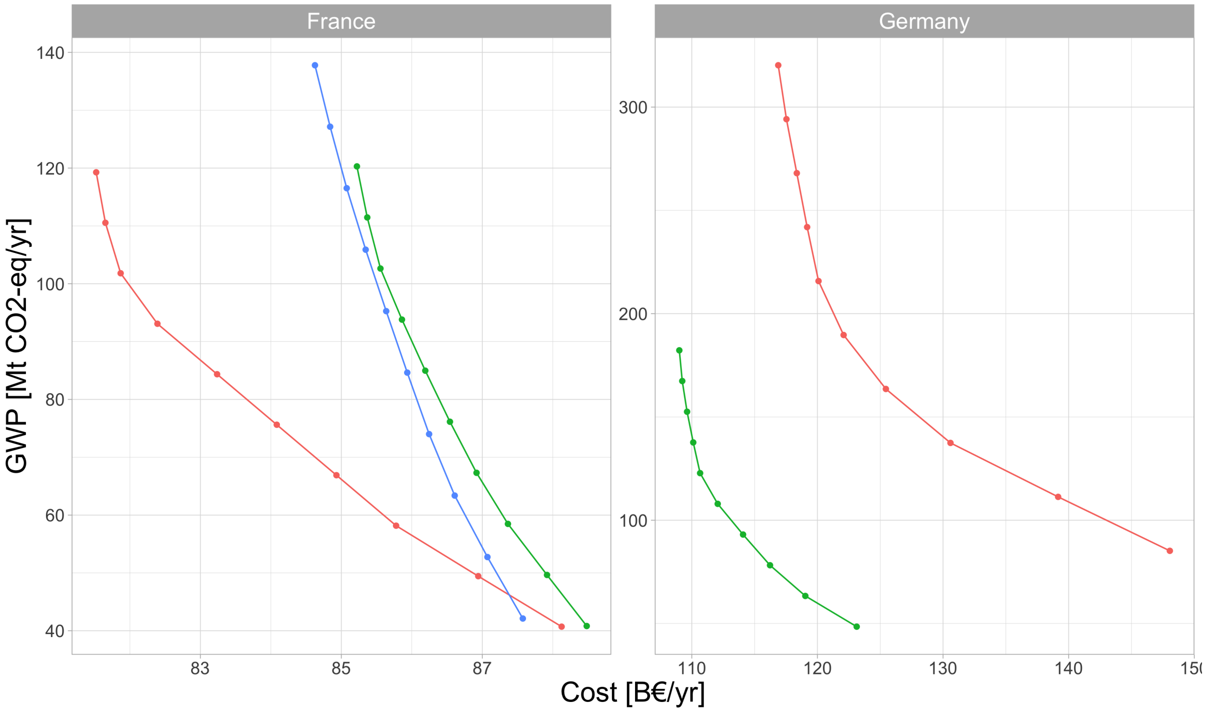

Figure 5.7: Pareto Reference scenario

Figure 5.8 illustrates the evolution of 10 points within the Pareto-curve. This figure allows to determine that the inflection points of Germany's Pareto curve are due to the use of biomass & waste on the economic optimum and the increase in geothermal resource for the environmental aspect. Wind Power and NG are balancing each other out, as the most environmental friendly solution has a Wind-to-NG ratio of 5:1 which is moving towards the economic optimum of 5:9.

France's inflection points are located at 30% between the GWP-cost optimum interval. In fact, the decrease in Biomass and switching to electricity-powered heating systems such as heat-pumps, allows to reduce the primary energy consumption as the GWP, which induces higher costs. The share in Heat Pumps (HP) gradually increases, which leads to higher electricity demand which is provided by higher wind powered electricity production, allowing to reduce the NG consumption by 85%. Solar, hydro and nuclear power are constant throughout the Pareto.

Renewable resources as hydro and solar power are both on the respective highest shares for Germany and France. The deployment of wind power is necessary for replacing NG as the constraints on CO_2 emissions are more stringent. France's base electricity production is satisfied with nuclear power, and renewable resources such as wind and solar power can be used through HP. Germany reaches its potential and switches towards more expensive but "greener" heating technologies as geothermal heating.

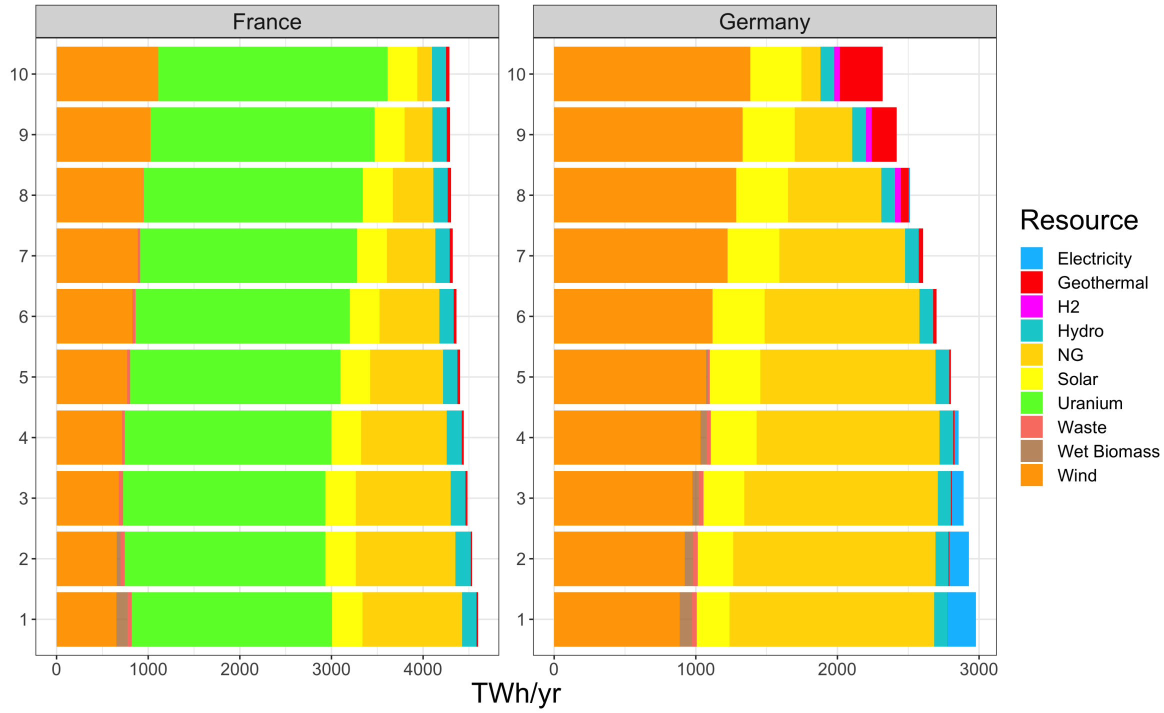

Figure 5.8: Primary energy consumption Pareto points reference scenario

5.4 Impact of vehicle type penetration

The characterisation of the impact of the vehicle fleet composition on the energy systems is modelled by constraining the model to implement a fraction of selected vehicle technologies on the vehicle fleet. Throughout this section, the impact of different shares of specific vehicles are shown, by constraining one single vehicle technology at the time.

5.4.1 Battery Electric Vehicles (BEV)

Different electric vehicle shares were modelled and summarised in Table 5.3. The respective Pareto curves are visible in Figure 5.9.

Table 5.3: Summary of the BEV scenarios 2050.

Index	0	1	2	3
Penetration	100%	75%	50%	25%

As visible in Figure 5.3, battery vehicles and the reference scenario are overlapping in all countries and models. This observation leads to the statement that BEV are the economic minimal optimum, but, depending on the technologies used in other sectors for heating and electricity generation, may also correspond to high emission scenarios.

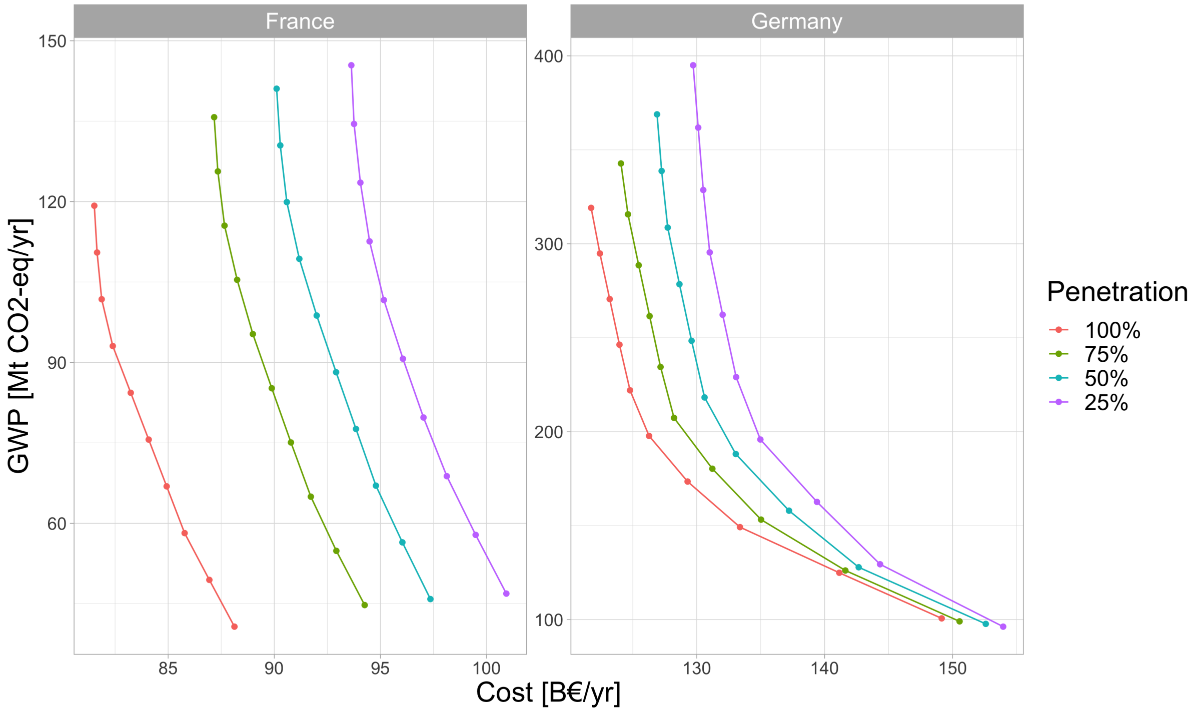

Figure 5.9: Pareto BEV penetration

In all cases, for both France and Germany, battery electric cars seem in *competition* with fuel cell cars - in other words, a 50% penetration of BEV corresponds as well to a 50% penetration of FCVs for private mobility. The demand for public mobility, whichever scenario, is always satisfied by a combination of electric commuters, buses and trains. The Pareto curves of France's BEV shares are parallel and evenly distributed, where the real Pareto-front corresponds to the 100% BEV penetration. With a relative difference of 5-7.5% in cost between the economic and the environmental optimum, the curves are nearly cost-insensitive. While the shares of 25%-75% are distributed by 0.5 B€/yr price reduction per 10% penetration increase independent of the GWP effect, the gap between 75% and 100% amounts to the double of the previous value.

The Pareto curves can be split in two parts, separated by the main inflection point at 75% of the GWP and 25% of the emissions. This inflection points are due to the switching in heating system (Figure E.1). Biomass and waste are replaced by electric heat pumps for industrial and district heating purposes, and the use of fossil fuels is substituted for wind energy with decreasing GWP.

Germany's Pareto curves are distributed evenly at the economic optimum and are converging towards a unique point at the GWP optimum after the major inflection point located at $150\,\mathrm{MtCO2/yr}$. Similarly to France, the pure BEV fleet composition is the left-most Pareto curve, while decreasing fraction, the Pareto fronts moves towards less optimal solutions.

The charging demands need to be covered by renewable resources or nuclear, which forces the system, if the electricity is constrained to switch to less efficient heating technologies (Figure E.1).

Figure 5.10 displays the primary energy consumption for the economic and environmental optima of each penetration level (Table 5.3). The low difference in cost between the economic and environmental optimum for each BEV penetration level in France's energy system is visible by comparing the primary energy shares. Solar and nuclear power remain constant throughout the objectives and shares. The higher electricity demand for the BEV fleet is compensated by boilers (increase in NG and Biomass) for the economic minimization and geothermal energy for the GWP minimization.

Germany's Pareto curves expansion towards the economic optimum is due to the limitation in renewable energy resources. With high BEV share, the electricity is used in the vehicles and alternative heating systems must be installed. While the economic optimum is reached with fossil fuels, the environmental optimum is reached by installing geothermal heating. The differences between the shares for the GWP minimization is the increasing amount of hydrogen import in fuel-cell driven trucks for freight transport.

An interesting trend is shown here: it may be more environmental-friendly, for Germany, to import hydrogen than to import electricity to produce it on-site, under the condition that

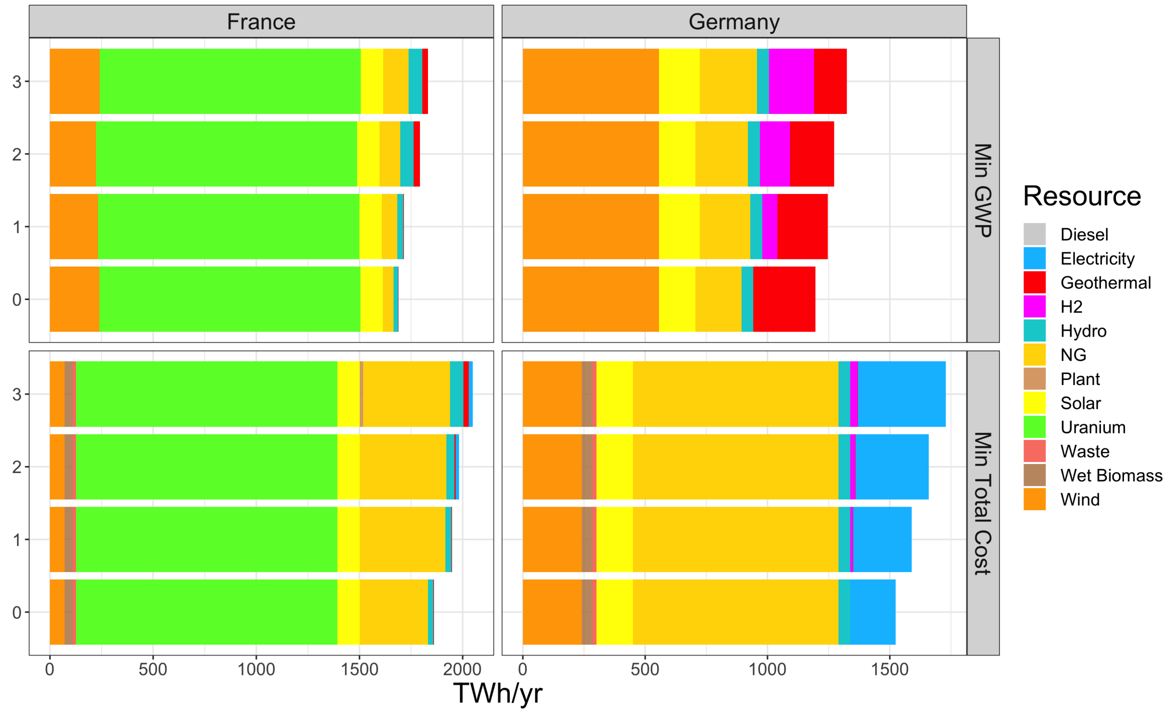

Figure 5.10: Primary energy consumption extreme points BEV

imported electricity has a higher carbon footprint than imported hydrogen. This may be the case, for example, if hydrogen is produced from water electrolysis and if electricity is generated from fossil thermal power plants. This conclusion is therefore very sensitive to hourly variations and situations in neighbouring countries.

Smart charging

Smart charging allows to avoid car charging during high electricity demand times and to spread the charging demand through the night. Figure 5.11 depicts the in and outflows of the EV vehicles, where the negative part corresponds to the battery charging. For the night time the charging remains constant such that the cars are charged in the morning where charging is reduced to a minimum amount.
The charging peak in the evening (18:00) can be attenuated to 5-20% of the maximum value. Electricity peaks in the morning (09:00) are due to limitations in the constraints definitions, as the charging periods have to be defined manually, leading to an explosion in demand after the constant charging.

Vehicle-to-grid

As shown in the modelling section, EV are subject to charging times of several hours with conventional charging stations, which pushes the people to connect their vehicle whenever

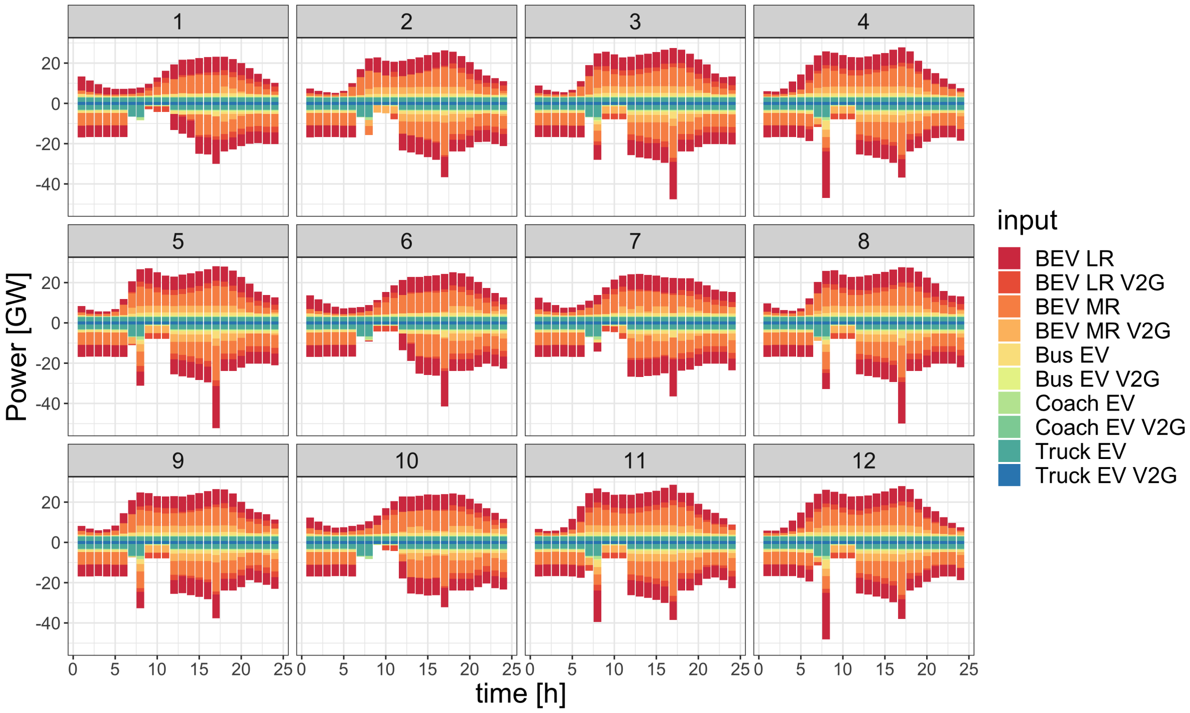

Figure 5.11: Daily profile of charging and discharging of EV batteries for each typical day.

possible to the electric grid[2].

Figure 5.12 represents the fraction of cars in circulation for a pure electric fleet composition with an assumed annual cars in circulation mean of 4%, corresponding to the mean vehicle utilisation in France 2017. With these assumptions, the cars connected to the grid are varying between 93-99%. With a mean battery capacity per car [3] of 67 kWh and a storage availability of 45%[4], the storage capacity can be estimated to 13-15 TWh in 2050[5].

Within the simulations, a V2G share of 5% was assumed at first, reducing the V2G potential towards 650-750 GWh. The higher this potential is, the more renewable intermittent electricity can be produced to be restored later to the grid and used during the day. This behaviour is visible in Figure 5.13, where the vertical axis shows the different V2G-shares within the EV fleet for a 100% electric scenario of Germany. 10% V2G vehicles within the fleet have almost similar composition as the 5% V2G share visible in Figure 5.10. The main difference is the installed capacity of geothermal heating, as discussed earlier.

By increasing the V2G share, the amount of carbon content resources can be reduced, promoting the use of intermittent renewable resources and of this generated electricity for heat-

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[2] This behaviour is similar to any daily use electronic device, as smartphones or laptops nowadays.

[3] According to the BEV database Appendix H.1.1

[4] By taking into consideration 8 hours charging time, 4 hours discharging time and 1 hour circulation

[5] Estimated number of cars: 480 Million cars in Germany and 430 Million cars in France [11] [50]

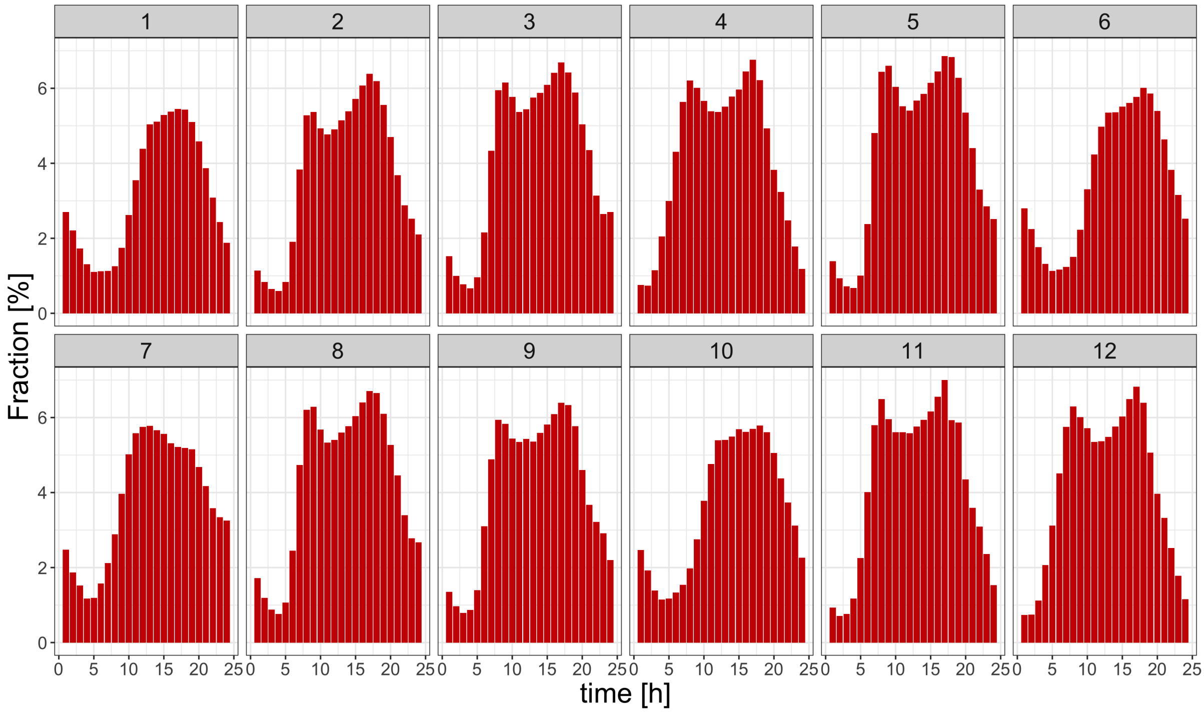

Figure 5.12: Daily profile of percentage of electric vehicles in circulation for each typical day.

ing purposes. In addition, the installation of heat pumps also allows to reduce the primary energy consumption, by about 15% for the case represented in Figure 5.13.

The increase of V2G battery capacity furthermore allows to reduce electricity import towards no import at 90% V2G share. The other side of the equation is the additional use of batteries which reduces the battery lifetime. Figure 5.11 allows to estimate that 20% of the vehicles have an additional cycle per day. In a global approach, the total EV batteries therefore see a reduction of their lifetime of 20%, corresponding to 2.8 years total lifetime.

5.4.2 Synthetic fuels (gasoline and diesel)

Figure 5.14 depicts the Pareto curves of the Synthetic Fuels (SF) scenario with different characteristics of penetration.

High SF shares are located at higher costs and emissions. This phenomena is due to the lack in CO_2 being needed for the fuel synthesizing. The main CO_2 sources are NG and biomass. To provide enough CO_2, CC technologies such as CO_2-capture from power plants (coal and natural gas) and industries (cement), and direct air capture need to be activated. However, as these sources of emissions are also limited with increasing penetration of renewables, direct air capture is necessary to achieve a high penetration of synthetic fuels, which drastically increases the costs (curves 0-2, where the respective Pareto curve has a nearly right inflection point angle).

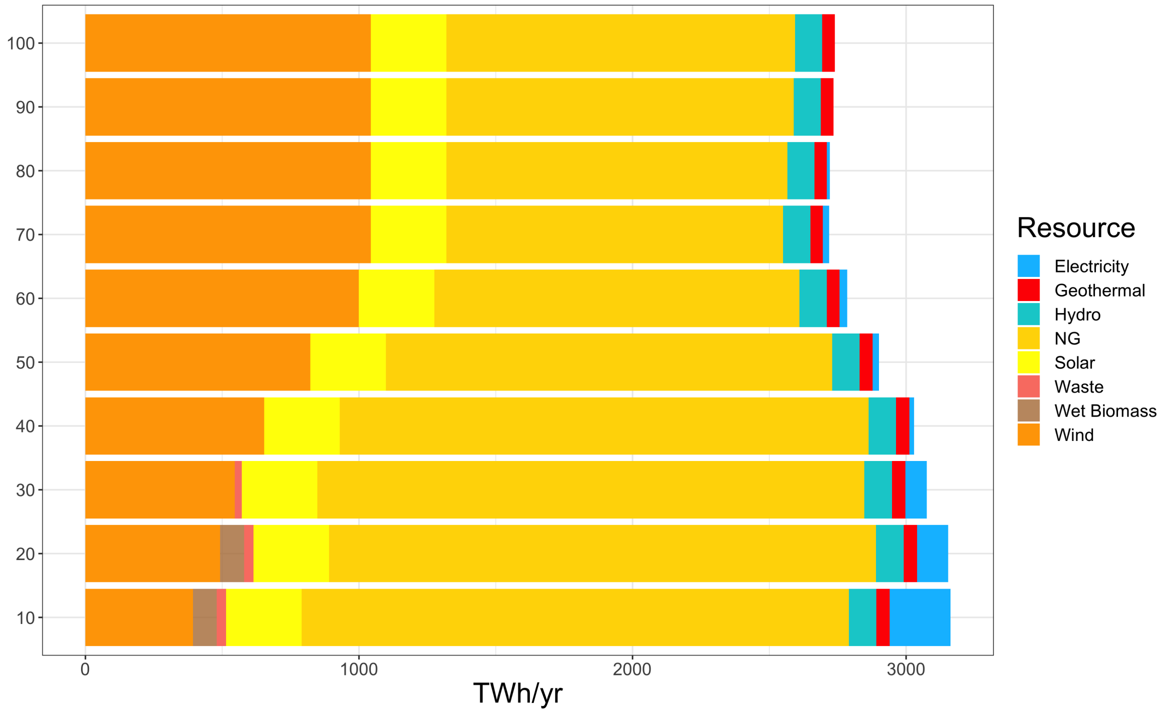

Figure 5.13: Primary energy consumption for different V2G penetrations [%] (cost minimization).

Figure 5.14 depicts in the right plot the Pareto curves of Germany. The curves can be grouped by taking the Pareto front as basis (50%). Curve 0 corresponds to the optimal front, which can be split in two parts by the inflection point at 100 MtCO_2 and 200 B€. The primary energy consumption is visible in Figure E.3. Starting from the economic optimum, the inflection point is characterized by the installation of Fischer-Tropsch processes to convert biomass into liquid fuels. Wind power grows continuously from the beginning until reaching its potential at point 7 of the curve.

The pareto curves of 100% and 50% are almost parallel, with the curve without NG import shifted towards more expensive solutions. The difference between the curves is that NG is not available and the system is forced to use different heating technologies, which in this case is geothermal heating. Furthermore CC technologies need to be installed after the consumption of all biomass at 200 MtCO_2

The carbon-neutrality aspect of biomass has been debated [51]. The use of forest biomass for energy has been argued to be carbon-neutral only if best practice measures are implemented in forest management and biodiversity protection. In other words, the use of bioenergy is seen as CO_2-neutral only with the right incentives, and it is interesting to analyse the impact of this assumption.

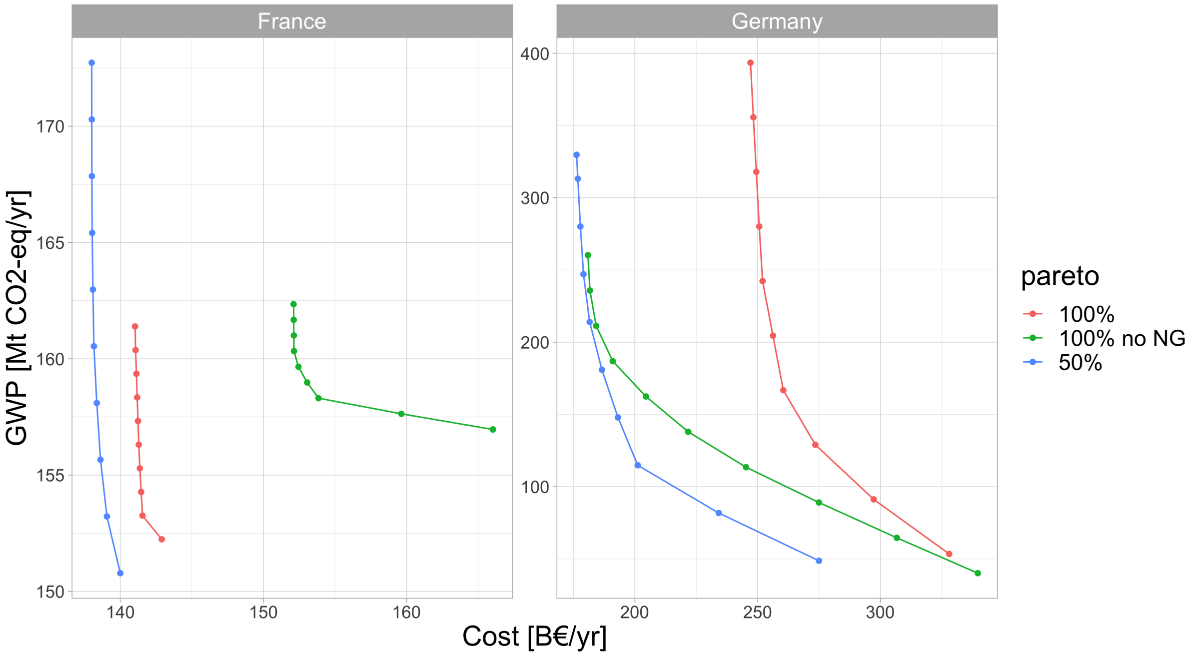

Figure 5.14: Pareto SF penetration

In modelling practice, biomass was either considered as CO_2-neutral, and a negative CO_2 content was considered to compensate for the emissions associated with the combustion of synthetic diesel and gasoline, or non CO_2-neutral, and emissions from the consumption of hydrocarbons are similar to those as if these fuels were originating from fossil oil.

Three processes to synthesize fuel are modelled (Section 2.4.2 where the preferred process is CO_2-to-X, using hydrogen and CO_2 instead of methanol. In the case of France, CO_2 is the restraining resource pushing towards CC and direct air capture, as enough electricity can be made available to generate hydrogen through electrolysis. On the contrary, in Germany, the limited potential in indigenous electricity production forces the import of hydrogen or of methane for steam methane reforming.
Synthetic fuels are thought to replace fossil-source gasoline and diesel. The production of SF include the installation of additional technologies which cannot concur on a thermoeconomic point of view with fossil fuels. Higher shares in SF lead to higher prices, and possibly higher emissions if biomass is not harvested in a sustainable manner.

5.4.3 Hydrogen

Figure 5.16 depicts the Pareto curve for different penetration levels of FCV. All curves are regularly distributed and parallel. While in France the jumping between shares amounts to a cost of 1 B€ per 5% share increase of FCV, Germany almost halves this cost (1 B€ per 3%).

The Pareto curves correspond to the BEV curves of Figure 5.9, while with the BEV have their optimum at high penetration, where FCV behave in the opposite manner. The similarity of the vehicle types Pareto curves can be brought back to the energy vector. Both technologies rely on electric power, which forces the system to spend electricity for mobility purposes. This leads to different heating technologies for each country, being recognizable by the different shapes between the countries as in the primary energy consumption in Figure 5.16.

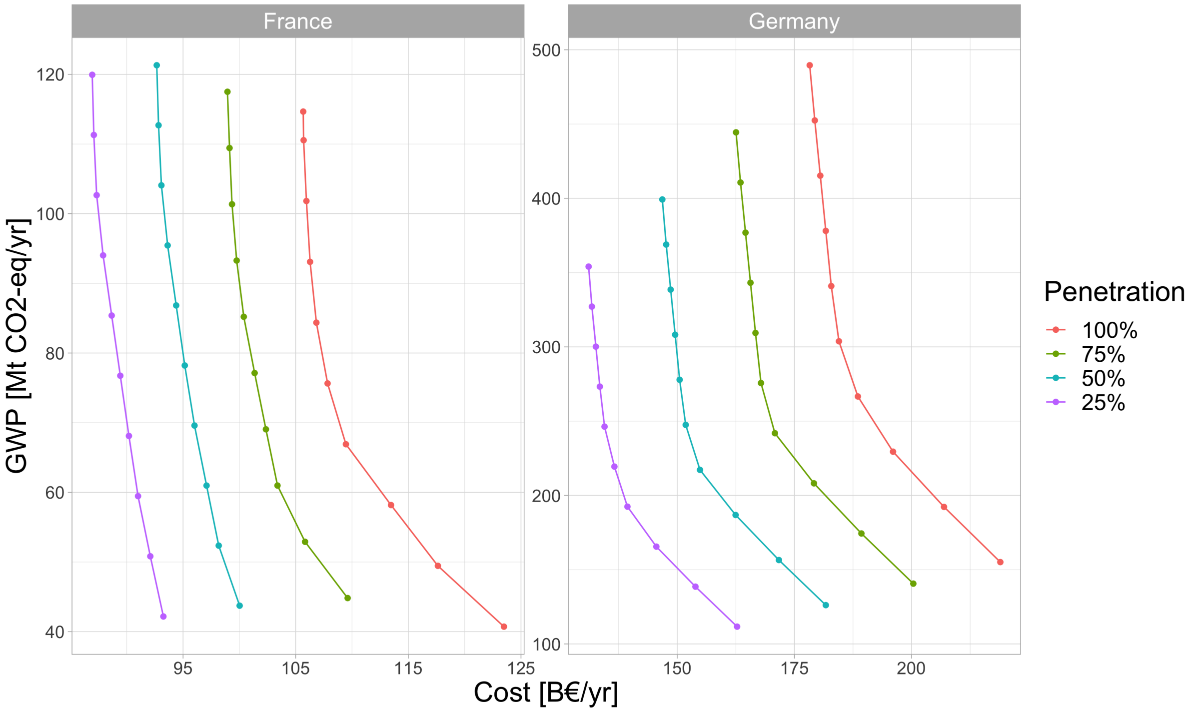

Figure 5.15: Pareto FC penetration

Germany exploits the renewable electricity potential of onshore wind, solar and hydro power for the economical optimum. Electricity is used in first instance to satisfy the demand of specific appliances (e.g. lightning). hydrogen being used for the FCV is produced by steam methane reforming before reaching the maximum NG import limit. The remaining hydrogen is generated by SOFC electrolysis, whose electricity is imported (Figure 5.16).

Germany's Pareto curves are characterized by an inflection point at 40% of the minimum GWP point. This inflection point is due to the installation of HP and geothermal direct/indirect heating to replace boilers gradually, to reduce the emissions with the malus of increasing the costs. Once geothermal and HP installed, the cost per $MtCO_2$ reduction is changing from 10 $MtCO_2$ per B€ to 4 $MtCO_2$ per B€.

Another factor increasing the price is the installation of offshore wind. The environmental optimum is reached by further installing electricity generating renewable resource for hydrogen production. The heating mix is impacted by the FCV share, as direct geothermal heating reduces the need of electricity for heat pumps in favour of electric HP, as less hydrogen needs to be generated with lower FCV shares.

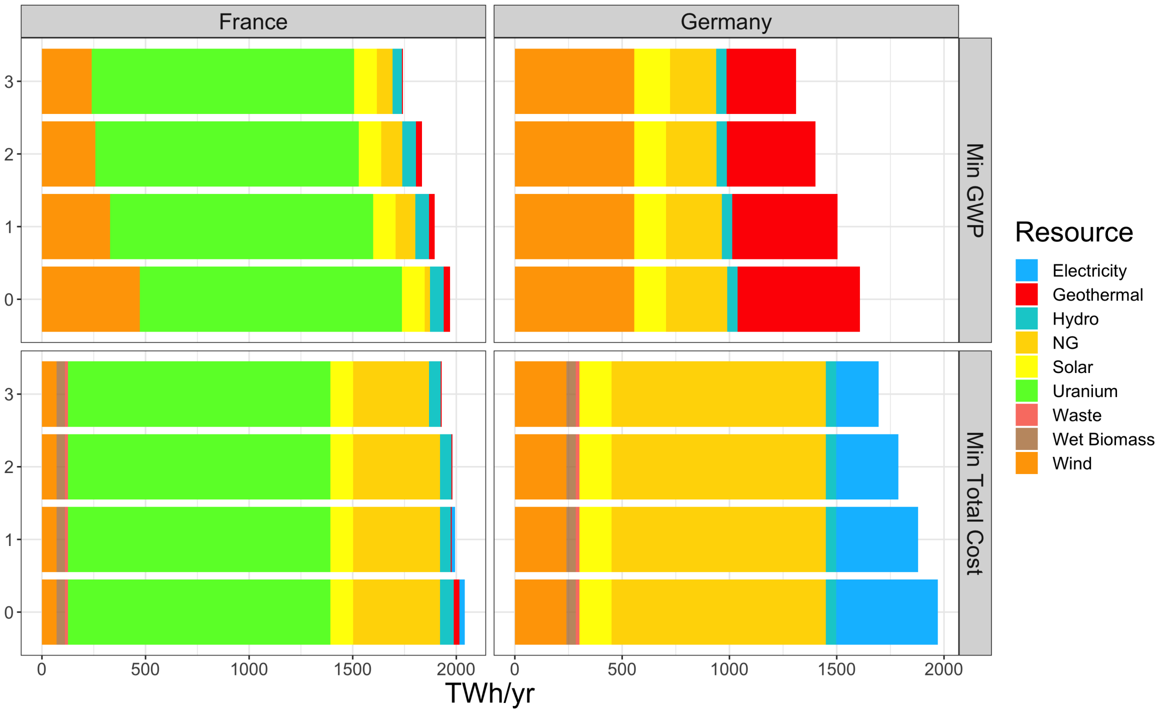

Figure 5.16: Primary energy consumption extreme points hydrogen powered vehicles

The nuclear baseline visible in Figure 5.16 allows France to produce hydrogen without constraints according to the respective Pareto point. This linear change is represented in Figure E.4 for the 100% FCV scenario and visible by the nearly linear curves of Figure 5.15.
The primary energy consumption of the economic optimum is almost unchanged (2.5% difference between the extreme scenarios in Figure 5.16). The main changes in energy systems is visible by the expansion of wind power for the GWP emissions for high FCV shares.
The trade-off between steam methane reforming and electrolysis can be observed by comparing the environmental and economic optimization in the same figure. The slope of the curves is due to the reduction of hydrogen production technologies (SMR vs. electrolysis) leading to higher electricity demands (increase of factor 10 in wind power) and reduction of fossil fuels for heating (NG division by factor 20).

5.4.4 Ethanol

In these simulations, ethanol vehicles are powered with 85% of ethanol and 15% gasoline. Their environmental impact can be compared to ICE vehicles and induce therefore high emissions, unless ethanol is produced from fermentation of agricultural biomass. Within these scenarios, ethanol-powered vehicles are in concurrence with all other vehicle types, leading to be compensated by battery electric vehicles which are more efficient, less expensive and less polluting. By increasing the share of ethanol vehicles, the emissions as the costs increase.

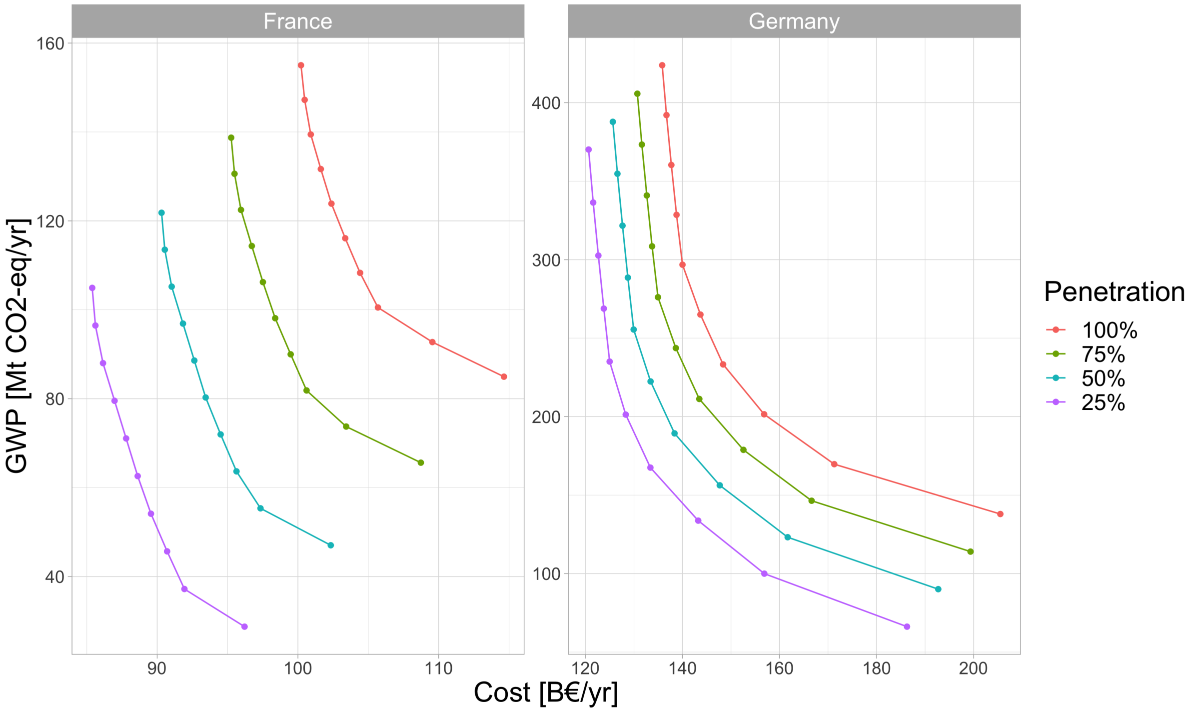

Figure 5.17: Pareto autonomy scenario

Figure 5.17 illustrates the Pareto curves for different penetration levels of ethanol cars. The Pareto frontier is located at low penetration levels with a regular distribution of the parallel curves. The extremes of the curves follow a linear relationship (Figure 5.18).

Table 5.4: Summary of the ethanol scenarios 2050.

Index	0	2	4	6
Penetration	100%	75%	50%	25%

Figure 5.18 shows the extreme points of each of the Pareto curves of Figure 5.17 and summarised in Table 5.4. However, both France and Germany have limited potential for producing ethanol from crops, and ethanol needs to be imported for penetration rates greater than 25% (Figure 5.18). This demonstrates that full penetration of ethanol-driven vehicles is sustainable and economically-plausible only in specific cases, such as Brazil where large amounts of indigenous sugarcane are available. The competing technologies are FCV and EV for France

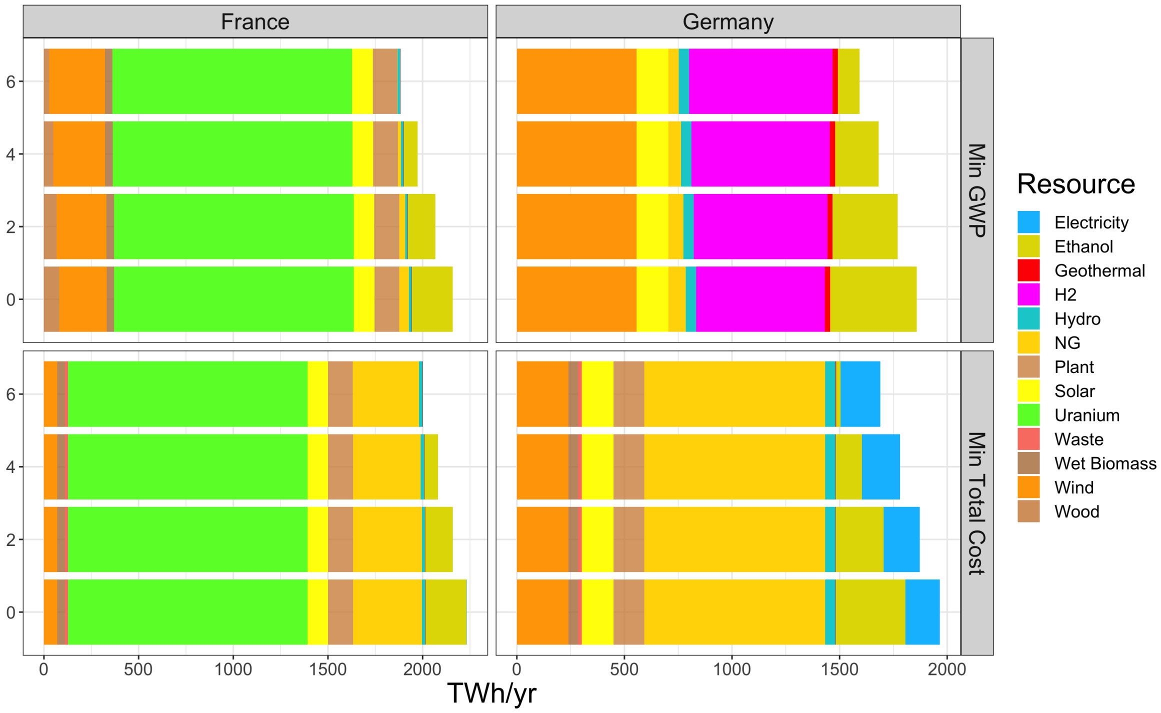

Figure 5.18: Primary energy consumption extreme points ethanol powered vehicles

and Germany, respectively (Figure E.8).

Similar simulations were carried out considering the integration of other biofuels, such as DME and methanol. Those were considered of interest in the frame of the project, as they were also subject to studies in California and in China for large-scale deployment. Although the exact figures differ, since the production processes are different, the same issues and trends (lack of carbon sources) were identified. For conciseness, the corresponding plots are not presented here.

5.5 Comparison of the case studies

Germany and France both move towards the same general direction, which is (i) a greater implementation of onshore wind, photovoltaic and offshore wind and (ii) a competition between fuel cell and electric vehicles. In both cases, the integration of synthetic gasoline/diesel or of alternative biofuels (ethanol/DME) does not seem to present significant advantages regarding the minimisation of the total emissions or costs, due to the limited biomass potential and few available carbon sources.

However, two factors were mainly differentiating France from Germany in the previous results:

- Germany has a smaller *potential for development of wind and solar energy*, as well as greater end-use demands. Germany therefore reaches its economical potential and is forced to import other forms of energy

- The other major difference is the availability of *nuclear power* in France. Germany decided to quit nuclear power and planned to reach that goal in 2023, while France decided (at the moment[6]) to keep its installed power. The high nuclear power allows France to go towards higher BEV and HP shares.

5.5.1 Primary energy demand

To compare the different KPIs, the extreme points of the main scenarios were normalized according to the population estimation.

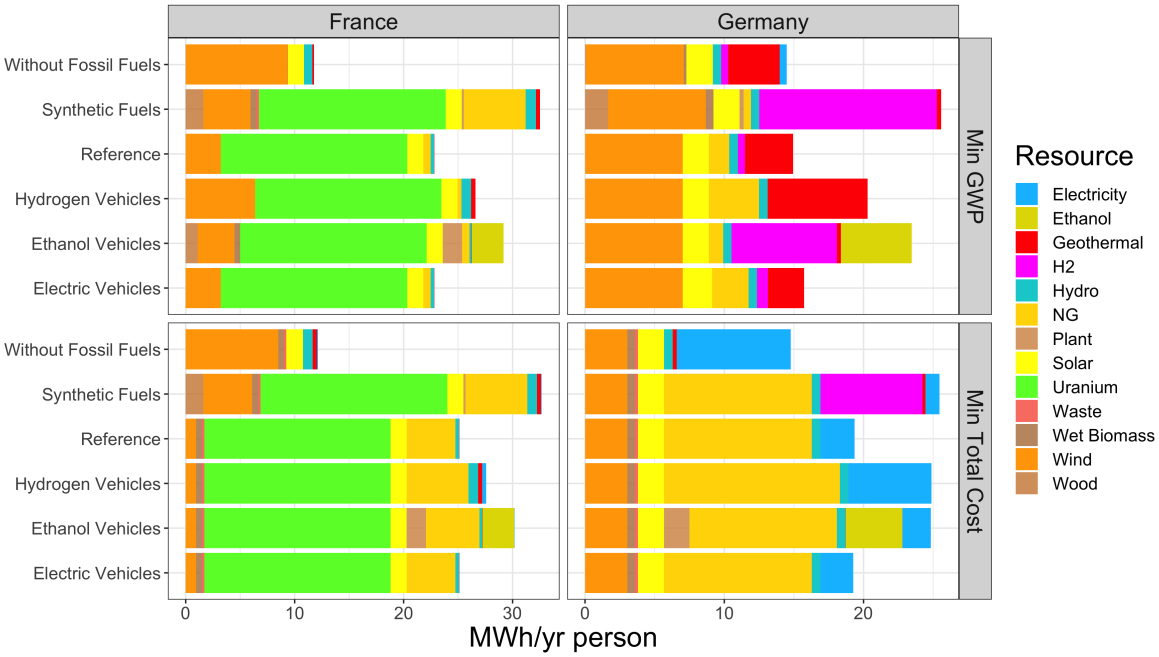

Figure 5.19: Relative primary energy consumption by country for the extreme points.

The specific primary energy consumption is represented in Figure 5.19. The reference scenario allows to compare the models solutions without scenario constraints. Germany has a renewable energy share of 19-88%, while France share varies between 27-42%. This difference is mainly due to the nuclear baseline in France, defining already 58% of the reference scenarios primary energy consumption.

The lowest consumption is for all objectives and countries is the scenario without fossil fuel import. The nuclear baseline of France was replaced by more efficient renewable energy technologies generating electricity. This results in a primary energy consumption of 10 MWh

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[6] France's nuclear policy changed several times in the last four years and is still subject to modifications due to the green wave results in the municipal elections. (28.06.2020)

per year and person for France and 15 MWh/ppl yr. The difference is due to the limited renewable energy potential in Germany, which can be summed to 10 MWh/yr ppl for electricity generating resources, including 4 MWh/yr ppl of offshore wind which is appearing by moving towards the environmental optimum.

Highest primary energy consumption are the ICE driven scenarios with SF with 40% higher consumption for the GWP optima and 20% for the GWP minimization than the reference scenario. This increase can be brought back to the SF conversion technologies.

5.5.2 Economic costs

Figure 5.20 allows to identify 41% higher mean relative costs of Germany compared to France. Differences in the reference scenario can be brought back to the nuclear baseline in France, inducing an investment cost of 62 % of the total cost, compared to 56% in Germany.

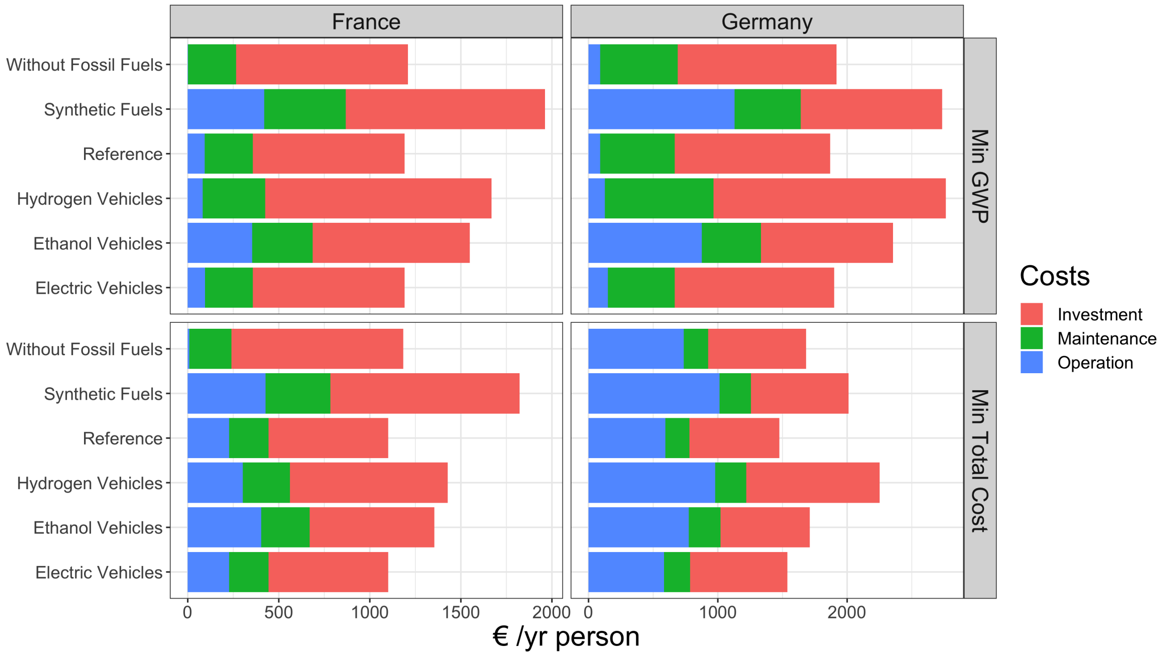

Figure 5.20: Relative cost by country for the extreme points.

The comparison of the peaks in total costs furthermore shows the influence of the main differentiating factors. While SF induce the highest costs for France (1850-200 €/yr ppl), it is the hydrogen vehicles which are peaking in Germany. In fact the import of hydrogen increases the operational costs share by 61% compared to France, where large-scale electrolysis for hydrogen production is more easily implemented.

5.5.3 Environmental impacts

The biggest difference in KPIs is visible in Figure 5.21, where the GWP are represented. While in Germany in 0.75-6.2 tCO_2-eq are emitted by person and year, France's emissions are on average 62% smaller.

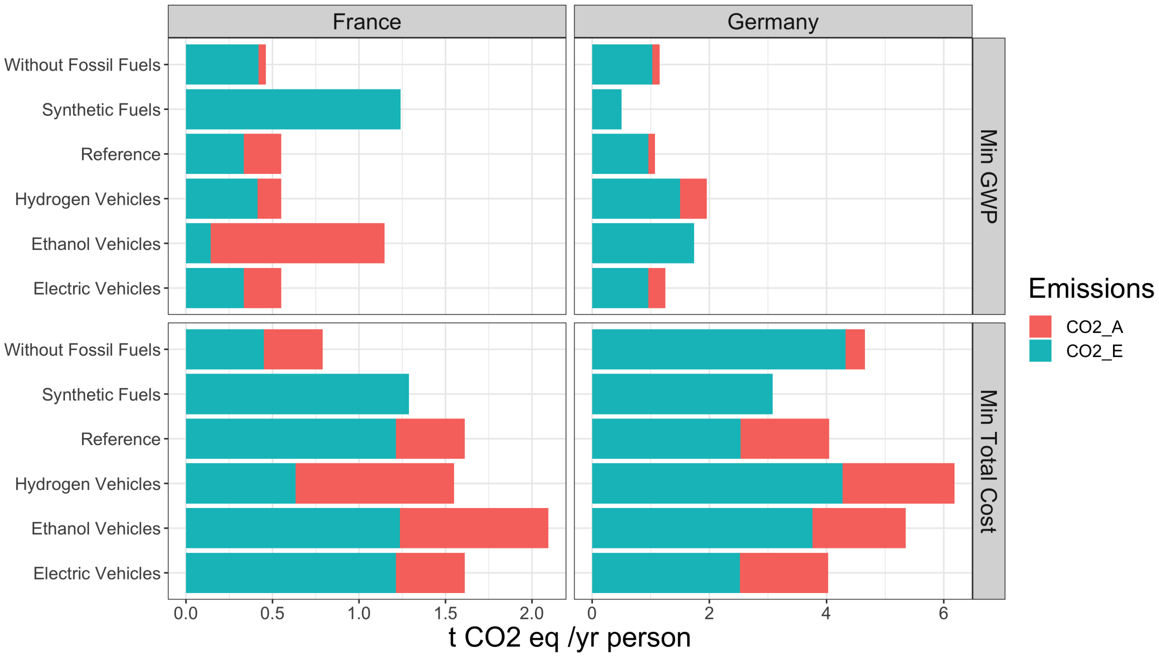

Figure 5.21: Relative GWP by country for the extreme points.

The differences in emissions from large (CO_2-A) and small (CO_2-E) stationary sources can be explained by the technologies installed and resources consumed by the different countries. CO_2-A corresponds to emissions that can be reduced with demonstrated capture technologies (e.g. carbon capture on power plants).

Synthetic fuel scenario has no CO_2-A emissions, as latter was compensated with negative CO_2-A emissions of biomass being synthesized (Figure 5.21). While Germany emits 0.45 tCO_2-eq per person, France's emissions are doubled for the GWP minimization. This relationship is reversed for the cost minimization and can be explained by the resources used to generate SF (hydrogen and NG for Germany and NG only in France, where hydrogen does not produce CO_2-A being carbon-free).

The differences in CO_2-A and CO_2-E is also different for hydrogen vehicles when comparing possibilities for minimizing the total costs. CO_2-A takes a 34% share of the total emissions in Germany and of more than 50% in France. The higher shares of CO_2-E are due to the deployment of steam methane reforming processes, whilst France recurs to electrolysis. This difference in share is not visible in GWP minimization (31% France and 28% Germany) as NG is replaced by hydrogen import in Germany, being "carbon-neutral".

Regardless of the scenarios, a main difference is the installed capacity of the fuel generation technologies and heating systems. While France can recur to electricity-based heating systems (heat pumps) without importing additional resources, Germany needs to import natural gas or electricity to satisfy its heating demand.

5.6 Comparison of the models

The comparisons of the Pareto curves and of the associated data show that both models show the same trends, the main difference being the predicted installed capacities of electricity, heating and mobility technologies. In fact, the hourly resolution allows to take into account higher variations that are averaged within the monthly model. This underestimation in installed power induces lower estimations of environmental (GWP) and economic (cost) impacst.

These differences are particularly striking for higher shares of renewable energies, as illustrated by the comparisons of the 2017 and 2050 reference cases. The size and use of the storage units are to be increased, which is visible with higher storage levels and greater number of storage cycles.

From the mobility point of view, the same tendencies as within the thermo-economic parameters is visible. The mobility variations through the day are neglected, leading to an averaged mobility demand, which can be satisfied by less vehicles. The major difference is with BEV vehicles, whose charge and discharge was modelled in detail (Section 3.2.2). The charging of the batteries, induced by the hourly peaks in mobility influences the magnitude of the electricity peaks and can be attenuated partly by smart charging or V2G technologies.

5.7 Sensitivity Analysis

The Morris screening method proved to be efficient to conduct a preliminary identification of influential and non-influential parameters. The exact outputs may change from run to run as it is a qualitative global sensitivity analysis method, and several runs with different numbers of levels, repetitions and parameters were conducted to verify the consistency of the simulations.

The application of the Morris screening showed some limitations inherent to the method and to the development of the EnergyScope MILP model. For example, the mean of the distribution of the absolute values of the standardised elementary effects (μ^*) is generally comprised between 0 and 1, which is the case for all but one distribution. Based on private communication with developers of the standardised Morris screening, these issues do not affect the validity of the results, and can be explained by the facts that:

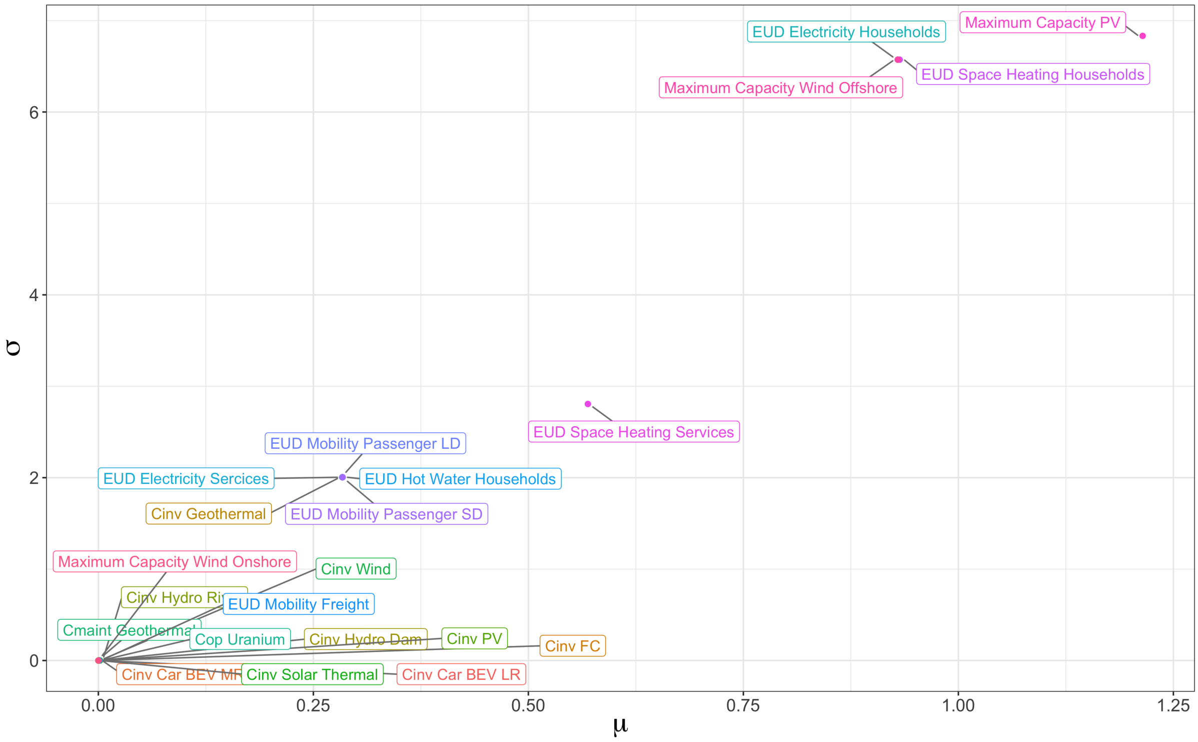

Figure 5.22: Standardised Morris analysis results on selected 10% most important parameters.

- the Morris screening method is qualitative, and performs a relatively small number of experiments (of about 15,000 in the present case) to infer the two main indicators;
- the standard deviation σ_{yj} of the model output (e.g. of the total cost) may be several orders of magnitude bigger or smaller than the standard deviations of the model inputs, which can cause outliers and affect the effect distributions.

Two Morris analysis were run. The first one included all parameters which were expected to be submitted to uncertainty, visible in Table F.1. This allowed to determine the 20 most influencing parameters. The result of this screening are visible in Figure F.1, where the main parameters were labelled.

During a Morris screening the relative influence of the 20 parameters identified in screening one as the potential of the renewable energy was determined (Table 5.5 and Figure 5.22).

Table 5.5: Morris analysis input parameters and results - the term "Cinv" refers to the specific investment cost of a technology, "Cop" to the cost of a given resource, "Cmaint" to the maintenance cost, "Demand" to the actual demand (in GWh for energy or pkm for mobility) and "fmax" to the maximum potential/installed capacity of renewable energies

Parameter	Min	Max	Base	μ	σ	μ^*
Cinv Car BEV LR	3.00E3	8.00E3	5.50E3	1.80E-04	8.10E-05	1.80E-04
Cinv Car BEV MR	6.60E4	2.00E5	1.30E5	2.70E-14	5.10E-14	-3.10E-15
Cinv Car FC	7.20E5	2.20E6	1.50E6	2.00E-04	7.50E-05	2.00E-04
Cinv Dec Solar	3.80E6	1.20E7	7.70E6	4.30E-05	1.60E-05	4.30E-05
Cinv DHN Geo.	8.10E7	2.40E8	1.60E8	2.80E-01	2.00E5	-2.80E-01
Cinv Hydro Dam	2.40E9	7.20E9	4.80E9	1.20E-03	4.70E-04	1.20E-03
Cinv Hydro River	2.70E10	8.10E10	5.40E10	4.30E-04	1.80E-04	4.30E-04
Cinv PV	5.00E10	1.50E11	1.00E11	2.00E-03	6.60E-04	2.00E-03
Cinv Wind	7.40E11	2.20E12	1.50E12	8.10E-04	2.70E-04	8.10E-04
Cmaint Geo.	2.30E12	7.00E12	4.70E12	1.20E-04	4.00E-05	1.20E-04
Cop Uranium	2.10E-03	6.20E-03	4.10E-03	1.10E-03	5.10E-04	1.10E-03
Demand Elec. HH	6.80E15	2.00E16	1.40E16	9.30E-01	6.60E12	-9.30E-01
Demand Elec. SE	7.90E16	2.40E17	1.60E17	2.80E-01	2.00E13	2.80E-01
Demand HLTSH HH	6.90E18	2.10E19	1.40E19	9.30E-01	6.60E14	-9.30E-01
Demand HLTSH IN	2.10E18	6.40E18	4.30E18	2.80E-01	2.00E15	-2.80E-01
Demand HLTSH SE	5.90E20	1.80E21	1.20E21	5.70E-01	2.80E16	5.70E-01
Demand Mob. Freight	2.00E21	6.00E21	4.00E21	9.20E-04	4.10E-04	9.20E-04
Demand Mob. Pass LD	2.00E22	6.10E22	4.00E22	2.80E-01	2.00E18	-2.80E-01
Demand Mob. Pass SD	5.00E23	1.50E24	1.00E24	2.80E-01	2.00E19	2.80E-01
fmax PV	1.10E22	2.00E22	1.50E22	1.20E20	6.80E20	1.20E20
fmax Wind Offshore	7.40E22	1.40E23	1.10E23	9.30E-01	6.60E21	9.30E-01
fmax Wind Onshore	7.50E23	1.40E24	1.10E24	3.20E-05	3.70E-05	-2.30E-05

5.8 Uncertainty analysis

The Monte-Carlo analysis was run for 5000 iterations for the reference case of France and Germany, allowing to characterize the energy system variations by representing the respective KPI variations visible in Figures 5.23 and 5.24. The variations are represented by applying quartile box-plots and density functions.
Several KPIs remain constant, independent of the input variations. While in France the renewable primary energy remains constant, variations for onshore wind are recognizable. The high share in nuclear power constrains France's energy system to be independent on input parameter variations within the defined deviations.

The vehicle parameter estimations are constant for the public and low range passenger mobility, relying on EV. Differences between the countries is visible for the long range mobility, where FCV and BEV are weighing each other up. In France, the densities are completely inverted, showing the compensation of each vehicle to another, while BEV are the preferred HD technology. Singular parameter combinations ($< 5\%$) lead to the apparition of FCV, without completely erasing mid-range BEV. Germany's model takes FCV in 9% of the cases, completely replacing the mid-range BEV. Latter vehicles are subject to binary apparition of same weight, such as MR BEV take either a share of 60% or no share at all for half of the scenarios. The representation of selecting either one or the other share per technology is characteristic of the linear optimization. While the primary energy consumption and the objective functions follow centered distributions, mobility technologies are not subjected to certain amount of constraints and other parameters, leading to more chaotic solutions. The chaotic character of the HD mobility in Germany leads to high variations in the energy consumption of mobility. Two densities are recognizable, in the Figure 5.24 *Energy Consumption*, reflecting the binary character of the HD vehicle selection.

The differences in the countries is also visible for the heating technologies selection. While the boilers use in France is fed with renewable biomass, heat pumps absorb the variations in heating demand. Germany is limited in electricity, forcing the system to install combined heat and power systems to generate the missing electricity.

The objective functions of Germany and France are varying with symmetric distributions around the reference value. The difference in variation can be explained by the primary energy consumption. While Germany's energy system uses the complete renewable energy potential, the electricity and heat generating system are almost fixed. Therefore price variations on latter technologies affect directly the total cost estimation, which is visible by the deviation of the total cost objective function (6.4% in the 75% interval & 18.5% in the 95% interval). France installed a nuclear electricity production baseline, which is complemented by renewable resources without reaching the respective potential. Price variations on the costs of these resources lead to different installation levels of onshore wind, which leads to lower deviations in the cost objective function distribution (3.7% in the 75% interval & 9.2% in the 95% interval).

The effect is amplified for the emissions objective function. As France can recur to renewbale resources, Germany uses NG as buffer to complement the renewable resources. Being a major source of CO_2, the total GWP is directly affected by the NG consumption, leading to total GWP variations of 9.8% on the 75% interval and 23% for the 95% one.

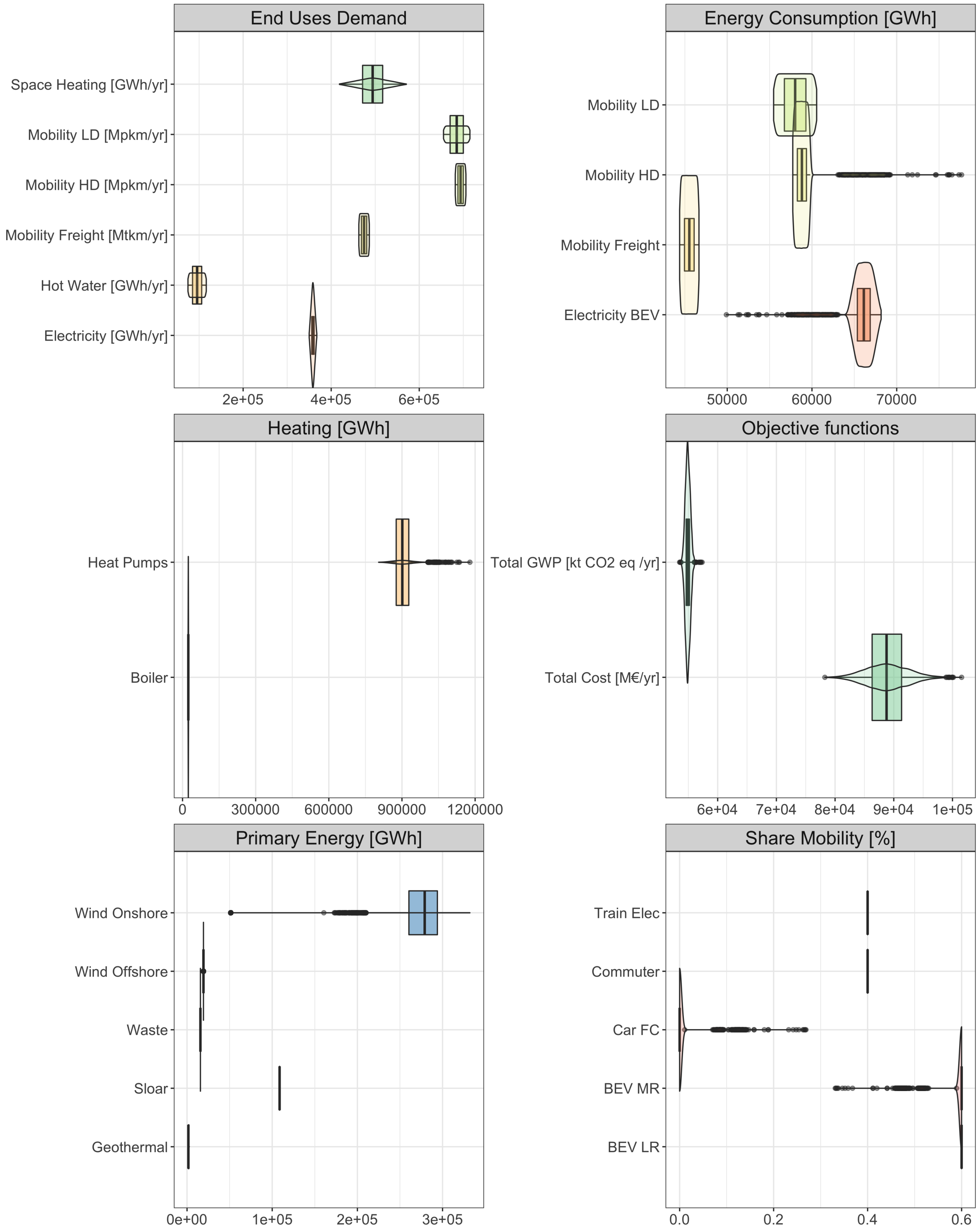

Figure 5.23: KPI variations resulting from Monte-Carlo method represented in quartile box-plots and violin-density distributions for reference scenario France 2050.

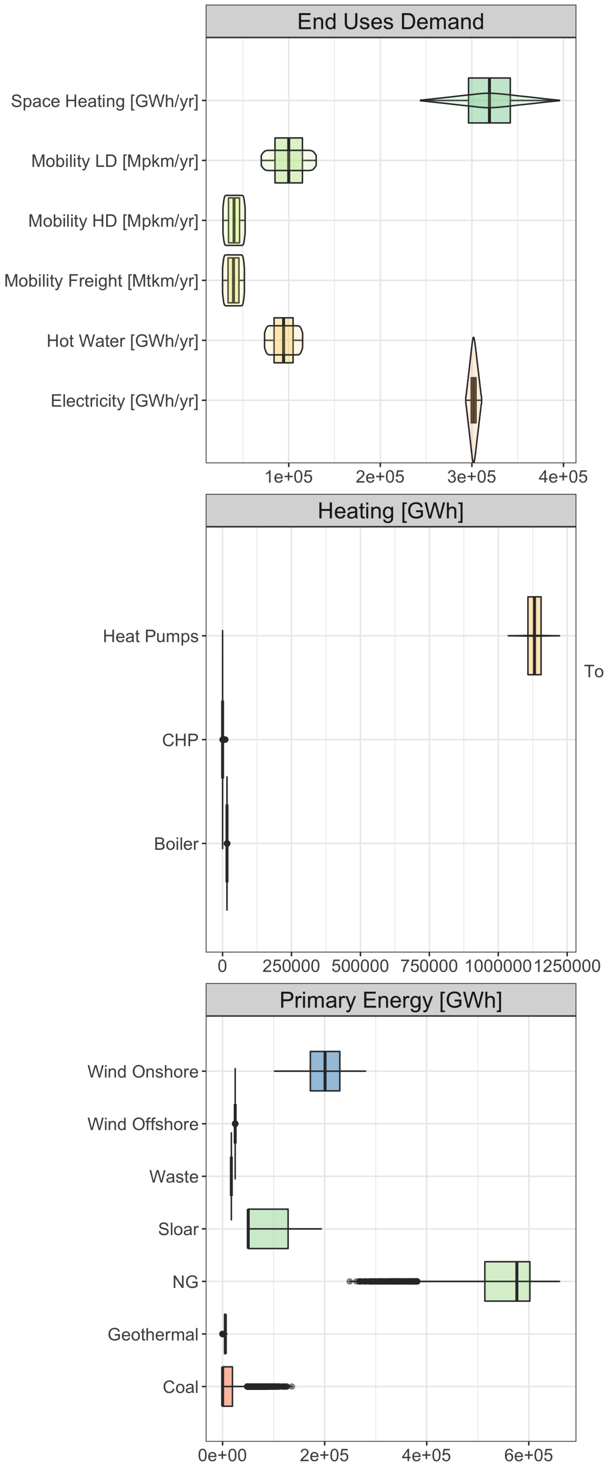

Figure 5.24: KPI variations resulting from Monte-Carlo method represented in quartile box-plots and violin-density distributions for reference scenario Germany 2050.

Chapter 6

Conclusion

The answers to the research questions of this thesis can be grouped in three parts, the impact of mobility within a global energy system, the specific cases of France and Germany, and the use of models with different time resolutions and assessment tools.

6.1 Mobility and energy systems

Each type of vehicle is characterized by a different type of resource, energy use and environmental impact, which results in different trends and impacts on the energy system.

Electric vehicles *BEV* are the most optimal vehicle technologies for both countries, but a large-scale deployment results in a greater electricity demand, which cannot always be satisfied with the current power mix. A strong expansion of solar and wind power is required in all cases, with possibly the needs for electricity imports. This enters in competition with the electrification of the heating sector, where heat pumps are being promoted.
The influence of smart charging systems and the V2G possibility depends strongly on the proportion of vehicles on the road and allows the temporary storage of electricity from renewable sources. These systems can help in levelling down down the power peaks, especially those induced by needs for short-distance mobility.

Synthetic fuels and biofuels While increasing the share in *synthetic fuels* (diesel and gasoline), the cost and the emissions increase. In fact, the limiting parameter is the availability of CO_2 to synthesize diesel or gasoline. Hydrogen on the other side can be generated from various sources, either from natural gas through steam methane reforming, or from water and renewable electricity with electrolysis. On the other hand, the amount of carbon required in hydrocarbon-based fuels is limited - it is more economical to recover it from biomass, then from carbon capture on power plants and industrial factories. At high shares of synthetic fuels without fossil fuel import, it becomes necessary to integrate direct air carbon capture technologies, which are still under development.

The production of *ethanol and other biofuels* is a possibility to continue with the existing vehicle fleet and use ICE. The production of biofuels and the use of ICE is by far less efficient (ecologically and economically) than alternative propulsion systems. Large-scale deployment is also limited because of the lack of carbon sources besides biomass and the power-/cement industries, which forces the use of unconventional technologies such as direct air capture. The advantage of these fuels is that the mobility energy vector is independent of the electrical renewable energies and therefore electricity can be used in heat pumps, decarbonizing the residential and industrial sectors.

Fuel cell vehicles Despite the initial high investment and maintenance costs, *Hydrogen FCV* are in competition with BEVs in term of economical optimization. By increasing the FCV share, the smaller the electricity demand for BEV gets and the more Hydrogen is generated from electrolysis. At low FCV penetration, the share of BEV is high, forcing the system to use fossil fuels for heating, inducing the trade-off between electric hydrogen synthesizing (electrolysis) and steam methane reforming.

6.2 Case studies

With France and Germany, two of the major energy consumers in Europe were modelled. The differences in energy strategy, renewable energy potential and transport habits allow to analyse the influence of different vehicle technologies.

France Nuclear power is the the most important factor within France's energy strategy, regarding the impact on the energy system. The constant availability of electricity allows the system to deal mainly with purely electrical technologies. For heating technologies, it allows a small margin of manoeuvre on the economically more interesting NG boilers, although some heat pumps and direct electrical heating must be covered in order to minimize the export of electricity. Moreover, the large amount of nuclear electricity does not allow the system to exploit the full renewable energy potential, which has advantages in terms of grid sizing. Due to a smaller share of renewable energy, the grid is less exposed to the intermittent nature of sun, wind and water cratering, which in turn is less interesting for V2G.

Germany The energy strategy of Germany aims to reduce fossil fuels as much as possible by 2050 and expand renewable energy. This strategy exploits the economic renewable potential, which is filled up with NG. If the potential is expanded to the technically possible, Germany can be operated in a completely renewable way. The large share of renewable energy requires the system to have storage facilities to bridge the voltage peaks and sinks. On the one hand V2G becomes interesting, but also P2G which allows to store hydrogen. This hydrogen is either used directly in FCV or can be converted back into electricity. Germany favours BEV for private mobility, but uses hydrogen powered technologies for freight transport.

6.3 Methodological aspects

Models with hourly and monthly resolution The comparison of the two types of models illustrates difficulties in selecting, applying and improving each model. On the one hand, a model based on typical days is more computationally-intensive, solving the current problem in the order of minutes to hour, depending on the scenarios and technologies considered in the problem (storage and carbon capture). It also relies on the prediction of demand profiles (electricity, heating and mobility) on an hourly basis, which may not be suitable on a 2050 horizon.

The strong impact of charging strategy methods (power steering over night and V2G) reflects these limitations, as the results are particularly sensitive to these assumptions. On the other hand, it better simulates the interactions between various sectors and demands, leading to more sound estimations of costs, global warming potentials and unit sizes.

A model with a monthly resolution can be solved in the order of seconds and reveals to be more stable and adaptable to a wider range of constraints. However, it seems to underestimate costs and environmental impacts of energy systems with high shares of renewables, as the backup technologies, electricity imports and infrastructure may be undersized. This issue may be alleviated by generating and including the equivalent of "extreme" days in the monthly models, as done when sizing building energy systems. However, this is out of scope of the present work and needs to be addressed at a further point.

Sensitivity and uncertainty analysis The classification of the scanned parameters allowed the identification of the parameters with the greatest influence on the final result. The Morris screening of the latter parameters underlined the linear character of the model, as well as the type of influence of the most important parameters on the objective function. However, for large models with high numbers of parameters and different orders of magnitude, the Morris screening may face computational issues depending on the number of levels and repetitions. This qualitative method of global sensitivity represents a good trade-off between the outcome quality and computational time, and may be completed by Sobol-based analyses or based on standardized regression coefficients.

Fluctuations in fuel prices can be neglected in comparison with the demand for heating, electricity and mobility. The potential of renewable energies (wind and solar), as well as the investment costs of the latter have a similar influence on the objective function as the EUD of the industry and service sectors.

The estimation of the different parameters has a great influence on the results. The estimation of the parameters has the greatest influence on the HD private mobility mix, where a chaotic pattern can be seen. Depending on the parameter constellation, the whole system in Germany can change from BEV to FCV, which also has an impact on primary energy consumption and thus on the technologies of the different sectors.

6.4 Programming contributions

The present project was conducted over a frame of 4 months, and helped in developing/implementing different features

Modelling The different features added in the EnergyScope model are:

- the modelling of the mobility demands, technologies and associated equations were developed in joint work and added to the two versions currently used at the IPESE group, namely the monthly and typical day versions;
- the carbon flow feature developed by two researchers in this group was also implemented, which allows for a tracking of the CO_2 flows at an hourly level;
- the time dependence of the carbon content and cost of the imported electricity were also implemented in the monthly model - the impact was tested but not studied in further details, as predictions of these features in 2050 is particularly tricky;
- storage units of diesel, gasoline, ethanol and methanol were added to the current long-term storage technologies, in addition to the hydrogen, natural gas and carbon dioxide ones - the modelling approach was similar - the impact of these units was tested but is not presented in further details in this thesis, as they are mostly relevant if the cost variations of the associated resources are included.

r-EnergyScope The creation of a singular tool controlling the whole results and scenarios generation has been created with r-EnergyScope (rES). The different features are:

- the creation of demand input parameters based on historical data and socio-economic forecasts, which allowed to estimate the EUD of the different OECD member state for each year until 2060;
- the standard simulation has been adapted for each model type (hourly or typical day), allowing to store the results and input parameters systematically, allowing potential future applications in machine learning;
- Pareto curve parametrization have been added, allowing to create the Pareto-front within the extreme optima, while storing the input parameters and results;
- the creation of sensitivity analysis by Morris screening allowed to define the relative uncertainty of the different input parameters;

- the Monte Carlo methodology allowed to define the uncertainty analysis with the preliminary identified uncertain parameters, while values of the KPI for each iteration are stored and represented in boxplot or violin distributions. Additional density functions representation and other analysis can be based on the results;
- the postcalculation uses the stored results of the Pareto and standard simulation runs, to create result analysis visualisation, which can be used as passive figures or interactive web-compatible illustrations of the energy system, such as Sankey diagrams, parallel coordinates, KPI comparisons, Pareto plots, power flow figures etc.

6.5 Final statement

According to the results of this study, electric mobility is the key to the future. But as the past has shown, the optimal solution is not always the chosen path: rational considerations are often trumped by emotional decisions. However, the urge to find the best solution for the individual is strived for, which does not necessarily correspond to the optimum for the system. The human being optimizes his environment in such a way that it is as comfortable as possible. In order to counteract this behaviour and to correspond as far as possible to the optimal solution for the system, the system-controlling bodies must exert external influence. One possibility is to help with the financial aspect by supporting subsidies for the optimal solutions for the system and by levying taxes on harmful technologies.

The status symbol "car" is associated with great emotions that satisfy the desire to go further, higher, stronger and faster. The aim is to attract attention, with a bubbling internal combustion engine or the screaming racing cars in motor sports giving goose bumps. But it is precisely in this sector that the paradigm shift has been pushed forward by continuously adapting the racing series to ecology. The role model and reference function contributes to changing the reference image and thus to pushing the change forward.

In order to drive the energy revolution, education must be provided so that people associate climate change with emotions and are aware of the risks and opportunities of energy transition. First positive results are visible, with the green parties gaining more and more weight and people being energy-sensitive and thus driving forward the energy transition.

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Appendix A

r-Energyscope

With increasing complexity of ES, data management of the results and inputs becomes more important. In order to systematically be able to store the results, create figures and interpretations and systematic parameter & variables storage for further implementations, as for example artificial intelligence, a repository called rES has been created. rES, regroups functions for precomputing parameters, running different models with systematic parameters, sets & variables storage and postprocessing functions.
rES is organised in a folder structure visible in Figure A.1, with the corresponding files (Table A.1). Within the repository, the controlling r-script `rES.R` is located. This script loads the necessary libraries, defines the paths and controls the whole procedure. `rES.R` allows the user to select which AMPL data and model files are loaded.
The repository is organised in three folders *Precalculation*, *Running* and *Postcalculation*. Each folder can be run independently, allowing to be used for independent purposes, as clustering only for example.

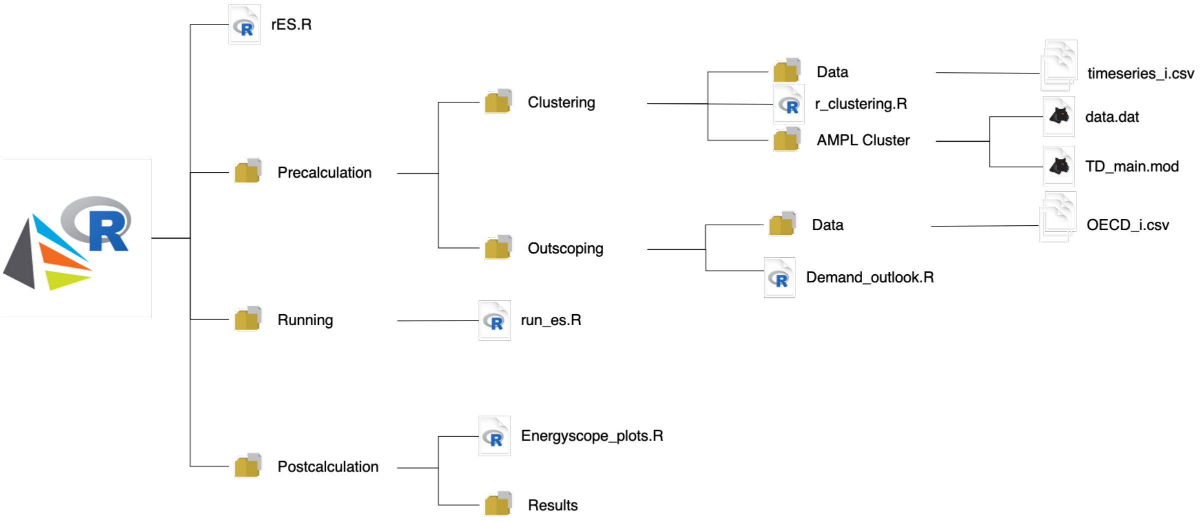

Figure A.1: Folder and files structure rES

Table A.1: Files description of Figure A.1

Folder	Filename	Description
rES	rES.R	Controlling script with all definitions
Clustering	r_clustering.R	Clustering function reading of timeseries, normalizing, clustering and writing ES input file
Clustering/Data	timeseries_i.csv	Clustering timeseries inputs
AMPL Cluster	data.dat	Clustering input gernerated from r_clustering.R and based on timeseries
	TD_main.mod	Clustering method written in AMPL
Outscoping	Demand_outlook.R	EUD parameters outlook calculation
Outscoping/Data	OECD_i.csv	Economic outlook OECD 1960-2060
Running	run_ES.R	Energyscope running with parameters, sets and variables extraction and storage
Postcalculation	ES_plots.R	Postcomputation based on sets, parameters & variables extracted from running
Results	paramsi.rds	Stored parameters run i
	setsi.rds	Stored sets run i
	varsi.rds	Stored variables run i

Precalculation methods are features and functions, running independently of AMPL. The theoretical background has been given in sections 4.2.2 and 3.4.

Different functions have been created to run ES according specific needs. `runESmon` and `runESTD` allow to run one case study and to store latter results. `ParetoTD` and `ParetoMonthly` run the model with total cost optimization, while the environmental aspect is constraint, allowing to create n results between the maximum and minimum GWP. `Morris` takes a predefined set of parameters with maximum and minumum values and feeds them to the model, while varying each parameter independently within the defined value at p steps. This allows to determine the relative sensitivity of the different model inpt parameters as explained in Sectionm 3.5.1. The same input is given for the `Monte-Carlo` function, which creates a space based on the deviation and the distribution of the input parameters by applying a Sobol dimension. This allows to determine the analyse the impact of the uncertainty of the input parameters as shown in Section 3.5.2.

For each function, the results of sets, parameters and variables are stored within `.rds` dataframes, which can be used for postprocessing. All figures within the sections 3.2 and 5 have been created based on the stored `.rds` dataframes. The systematic storage of all results, constraints, parameters and sets, allows to proceed to additional postcalculation without having to run the simulations again. The systematic storage furthermore is a first step towards application in machine learning.

rES is available on `https://gitlab.epfl.ch/ipese/energyscope/packages/renergyscope`

Appendix B

France EnergyScope data

B.1 Final Energy Consumption

B.1.1 Final energy consumption (FEC) per sector

The final energy consumption as presented in the official French statistics is usually classified by sectors (agriculture, transportation, industrial, service and residential) and, as of 2017, the transportation sector is the most-energy intensive one (Table B.1).

Table B.1: Final energy consumption in France (2017) (ref: Chiffres 2019)

	[Mtep]	[TWh]
Households	40.5	471
Services	24.2	281
Industry	26.5	308
Transportation	46.1	536
Agriculture	4.4	51

In addition, natural gas and crude oil are imported and treated for the production of non-energy products such as plastics. The final consumption of these resources amounted to 165 TWh in 2017, which was about 10 times less than the final energy consumption.

B.1.2 Final energy consumption (FEC) per end-use demand (EUD)

The final energy consumption in the residential and tertiary sectors as presented in the official French statistics is sorted by use (space heating, hot water production, cooking, specific electricity demand, ventilation and air conditioning) and sub-sorted by energy resource (electricity, natural gas, domestic fuel oil, liquefied petroleum gas, district heating, coal, biomass and heat pumps). Unlike other energy planning models, the EnergyScope model deals with end-use energy demands (for example, the number of passenger-kilometers and the space heating need instead of the gasoline and oil consumption) instead of final energy needs.

Heating

In the EnergyScope modelling framework, the heating demand is divided into two end-uses categories depending on its temperature level (low and high), and the low-temperature heating is itself divided into the space heating and hot water needs. This classification is different from the one employed in the French statistics, and the following assumptions are taken for simplification when validating the ES model for the year 2017:
General assumptions:

- the final energy consumption and the end-use energy demand are equal (conservative approach) when it comes to the use of light oil, natural gas, coal and electricity for space heating and hot water production purposes;
- the final energy consumption under the denomination "other uses" is split between these end-use demands: specific electricity for electricity, and domestic hot water for the fuel consumption, considering the FEC and EUD equal;
- the heating demand satisfied by use of a heat pump is calculated assuming a COP of 3, as in the French statistics;
- heat pumps are used only for low-temperature applications, and not for high-temperature ones - this is judged reasonable for the year 2017, as heat pumps with a temperature range above 140 °C are still at laboratory scale, and those between 100 °C and 140 °C at a prototype status (`www.sciencedirect.com/science/article/pii/S0360544218305759`);
- the cooling demand is not considered in the heating calculations, but in the electricity ones;
- the residential, tertiary and agricultural sectors only have a heating demand at low temperature, whereas the industry sector has both;

Residential and tertiary sectors:

- the domestic hot water and cooking needs, as presented in the French statistics, are aggregated in a single category (Table B.2) in the EnergyScope model - this is judged reasonable, as, unlike space heating, the cooking needs present a weak correlation with the external temperature and other climate conditions;

- The definition of the tertiary sector varies with the statistics and sources. For example, in the Chiffres cles 2019, which presents the global final energy consumption at a sectoral level, the tertiary sector includes, among others, the water management and wastewater treatment facilities. In the detailed analysis of the tertiary sector presented by the same institute, the latter are excluded from the analysis, and the final energy consumption amounts to 250 TWh, to be compared to the 281 TWh of the *Bilan de l'Energie*;
- as no information was available on the exact categories lumped within the tertiary sector in the *Bilan de l'Energie*, all the end-use demands (low-temperature heating and electricity) were multiplied by a correcting factor of 1.12 to match the figures available in the two sources.

Agricultural sector:

- no electricity is used for heating and is needed for specific appliances in livestock buildings;
- the remaining energy demand, neither used for mobility nor for specific electric appliances, and mostly satisfied with fossil fuels, is seen as low-temperature heating, split at 80%/20% between space heating and hot water.

Industry sector:

- the space heating demand represents roughly 6 % of the fuel final consumption (coke, oil, natural gas) on an energy basis (ref: Programmation Pluriannuelle de l'Energie 2013 et ADEME - Chiffres cles de l'energie);
- no precise data was found for the hot water consumption in the industry, and it was assumed to be 25 % of the space heating demand in the same sector, as for the residential and tertiary sectors;
- electricity used for heating purposes represents about 20 % of the total electricity consumption - it is allocated to the high-temperature heating demand, as it is mostly for electric arc furnaces (ref: Programmation Pluriannuelle de l'Energie 2013);
- the high-temperature heating from fuels is calculated knowing the total fuel consumption, the share to low-temperature heating (space heating and hot water consumption) and the fraction used for non-energy purposes;
- process heating and hot water consumption are considered constant over the year, while the space heating demand is shared over the year.

The final energy consumption, as given by the French statistics, is presented in details in Appendices (Table B.25 and Table B.26). A summary is given in Table B.3 and the corresponding end-use demands are given in Table B.4.

Table B.2: Classification of end-use heating and cooling demands - correspondence between the French statistics and the EnergyScope framework

French Statistics	EnergyScope
Space heating	Space heating
Domestic hot water	Domestic hot water
Cooking	Domestic hot water
Specific electricity	Specific electricity
Air conditioning	Specific electricity
Other uses (electricity)	Specific electricity
Other uses (fuels)	Domestic hot water

Table B.3: Final energy consumption for heating in France, expressed in TWh (2017)

FEC/Sector	Residential	Tertiary	Industry	Transportation	Agriculture
Fuels	299.1	126.1	189.9	0	10.7
District heating	17.8	10.5	0.0	0	0
Ambient heat	9.8	6.7	0.0	0	0
Electricity (HP)	4.9	3.4	0.0	0	0
Electricity (direct heating)	64.3	30.1	23.7	0	0

Table B.4: End-use heating demands in France, expressed in TWh (2017)

EUD/Sector	Residential	Tertiary	Industry	Transportation	Agriculture
Space heating	320.2	135.3	9.3	0.0	8.6
Hot water	75.6	41.6	1.4	0.0	2.1
High-temperature heating	0.0	0.0	203.5	0.0	0.0

Electricity

The electricity end-use demand (EUD) (Table B.5) is strongly different from the electricity final consumption (FEC). It does not include the heating demand by sector satisfied with electric devices or the electric demand with mobility, and considers specific applications such as lightning and IT appliances, as well as refrigeration and air conditioning systems. The distinction between lighting and non-lighting uses was not possible due to the lack of data.

Table B.5: End-use electricity demands in France, expressed in TWh (2017)

EUD/Sector	Residential	Tertiary	Industry	Transportation	Agriculture
Electricity	74.8	104.1	94.9	0.0	9.2

Mobility

The mobility end-used demand (EUD) is expressed in Bpkm (billion passenger-kilometers) for passenger transport and Mtkm (billion tons-kilometers) for freight transport.

Passenger mobility Unlike previous versions of EnergyScope (monthly and typical days), the model used in the frame of the PSA project distinguishes local (travels under 100 km (alternatively 80 km in the Enquête nationale)) and long-distance (travels above 100 km) mobility for passenger transportation (Table B.6).
General assumptions:

- the residential and tertiary sectors do not present any mobility demand;
- the mobility demand satisfied by air transport is considered apart, with a specific end-use demand expressed in TWh equivalent of jet-fuel.

Agricultural sector:

- the mobility demand in the agricultural sector is not part of the transport end-use demand, which is in accordance with the French statistics;
- natural gas, gasoline, diesel and other fossil fuel-based products are consumed in tractors and other vehicles - their shares of the final energy consumption amount to 53 % and 8 % in 2011, and the same values are taken for 2017 [52];
- the agricultural sector only has a local mobility demand;
- the final energy consumption is converted into its mobility end-use equivalent, considering a conversion factor of 40 l/100 km for tractors and of 10 l/100 km for conventional vehicles [53].

Transportation sector:

- the mobility demand is taken from the French statistics of the INSEE [54], excluding airline transport;
- the split between short- and long-distance mobility in terms of passenger-kilometers is taken to 60 %-40 % [55], based on the ENTD 2008, which will be actualised and made available in 2020;

Freight mobility The freight mobility end-use demand is not split into its local and long-distance parts, and the value is directly taken from the INSEE statistics [56] for the year 2017 (Table C.7). There is supposedly no demand associated with the other sectors.

Table B.6: End-use passenger mobility demands in France, expressed in Bpkm (2017)

EUD/Sector	Residential	Tertiary	Industry	Transportation	Agriculture
Local	0	0	0	556	10.1
Long-distance	0	0	0	370	0

Table B.7: End-use freight mobility demands in France, expressed in tpkm (2017)

EUD/Sector	Residential	Tertiary	Industry	Transportation	Agriculture
Freight	0	0	0	360	0

Air transport Only air transport within the country of interest is taken into account in the calculations of the jet fuel end-use demand. The corresponding value is converted into the equivalent energy end-use demand assuming the fuel consumption of a Boeing 747-400 [57], an occupancy rate of 80 % and a heating value of jetfuel, which is the most common airplane fuel, of 10.4 kWh/l (Table B.8).

Table B.8: End-use airplane fuel demand in France, expressed in TWh (2017)

EUD/Sector	Residential	Tertiary	Industry	Transportation	Agriculture
Airplane fuel	0	0	0	6.2	0

Non-energy uses

Non-energy uses in France consist of oil and natural gas-derived products - a finer decomposition into the various types of plastics, paper and steel was not possible due to the lack of data, and they are allocated to the industry sector (Table B.9).

Table B.9: Non-energy end-use demand in France, expressed in TWh (2017)

EUD/Sector	Residential	Tertiary	Industry	Transportation	Agriculture
Non-energy	0	0	0	165	0

B.2 Electricity production

The French energy system consists of conventional thermal power plants (coal, natural gas, oil), nuclear facilities and renewable energies. The contributions of geothermal and wave power plants for centralised power production are neglected. Electricity generation in France is ensured mostly by nuclear and hydroelectric power plants (Table B.10) - the trend in the last decade (2010-2020) is a reduction of the oil and coal facilities and an increase of the renewable ones (`bilan-electrique-2019.rte-france.com/hydraulique/#1`).

Table B.10: Installed power plants, electricity production and corresponding share in France (2017)

	Oil	Coal	Gas	Hydro	Nuclear	Solar	Wind	Biomass
Capacity (GW)	4.10	3.00	11.93	25.52	63.13	7.65	13.55	1.95
Generation (TWh)	3	9.8	41.1	53.5	379.1	9.2	24	9.5
Production share (%)	0.57%	1.85%	7.77%	10.11%	71.64%	1.74%	4.54%	1.80%

The average capacity factors of wind and solar power plants on a typical day basis are derived from the measures of the average monthly capacity factors over the year 2017 (Table B.11). They are assumed to be 90 % for conventional thermal power plants (fossil and biomass) and the power generation from nuclear facilities is assumed constant over the year with an equivalent running capacity of 45 GW.

Table B.11: Average monthly capacity factors c_p of intermittent renewable energies (expressed in %)

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Wind	23.2	31.5	29.5	16.8	16.4	16.6	18.4	13.2	17.8	21.5	24.4	33.6
Solar	7.1	9.3	13.7	21	21	22.3	20.4	19.7	15.7	13.1	8.4	4.8

The estimations of wind (Table B.12) and solar potentials vary widely depending on the study and restrictions (for example, share of land available for onshore wind or share of roofs available for PV).

Table B.12: Wind potential in France, in terms of installed capacity and power production

Onshore	GW	TWh
Low	107	165
Medium	298	588
High	646	1670
Offshore	GW	TWh
Low	0	0
Medium	0	0
High	331	1211

For hydropower, the capacity factors vary widely depending on the year and type of plant (run-of-river or lake) [58]. For simplicity, hydroelectric power plants are grouped into two categories (hydro dam and hydroriver), and pondage (peaking), lake and pumped hydro stations are grouped into the first category when the capacity factors are estimated.

Table B.13: Average monthly capacity factors c_p of hydropower (expressed in %)

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Hydro dam	21.1	27.6	34.8	24.9	32.4	29.2	21.5	18.8	16.5	13.9	20.6	29.0
Hydro river	33.6	50.0	64.6	44.3	62.2	57.6	41.9	37.8	33.0	24.4	37.4	54.3

Similarly, the estimations of the hydroelectricity potential depend on whether technical and economic considerations are taken into account. According to the WEC, the technically exploitable potential is about 100 TWh per year, while the economically exploitable one is about 70 TWh (ref: Conseil mondial de l'énergie). A further study estimates much lower potentials, of only 3.2 GW in total and 12 TWh/year (Table B.14).

Table B.14: Hydroelectricity potential in France, in terms of installed capacity and power production

Onshore	GW	TWh
New sites	2.9	10.3
Renovation	0.5	1.7

B.3 Heating and cogeneration

B.3.1 Decentralized low-temperature heat

Detailed data on the use of fuels, ambient heat and electricity for heating purposes (space heating, hot water production and cooking) are available for the residential and tertiary sectors, but are lacking for the industrial and agricultural cases. Information on the electricity generation technologies was also missing, so the yearly shares of decentralized low-temperature heating were calculated using weighted averages of the residential and tertiary sectors (Table B.15).

The low-temperature heating demands - decentralized - were estimated to 512 TWh in 2017. This number is far greater than the cumulative LT heat demand of the industrial and agricultural sectors, of roughly 21 TWh, and the assumption is therefore deemed reasonable. The use of heat from cogeneration units for heating without a district heating medium is neglected. The assumption is reasonable, as it represents less than 1% in other European countries such as Switzerland.

Table B.15: Yearly shares - estimated - of decentralized low-temperature heat for the French energy system in 2017

	TWh	Share
Renewables (excl. biomass)	2.9	0.6%
Boiler Biomass	87.5	17.1%
Boiler Oil	83.1	16.2%
Boiler NG	227.7	44.5%
Heat pump	23.7	4.6%
Direct electricity	86.7	16.9%

B.3.2 Centralized low-temperature heat

Detailed data on the fuel share for district heating was available from the Chiffres de l'Energie and the surveys of district heating and cooling. For simplicity, the different types of fuel oil were aggregated as a generic oil fuel, and biomass, biogas and industrial heat were aggregated under the biomass denomination. Renewables used for heating other than geothermal, biomass, waste and ambient heat were considered as solar thermal (Table B.16).

Table B.16: Yearly shares - estimated - of centralized low-temperature heat for the French energy system in 2017 [5]

	TWh	Share
Boiler Coal	1.35	4.4%
Boiler Oil	0.29	1.0%
Boiler NG	11.3	37.1%
CHP NG	0.21	0.7%
Boiler Biomass	6.3	20.8%
Boiler Waste	8.19	27.0%
Geothermal	1.47	4.8%
CHP Biomass	0.97	3.2%
Heat pump	0.14	0.5%
Solar thermal	0.15	0.5%
Direct Elec	0.003	0.0%

B.3.3 Industrial high-temperature heat

As for decentralized heat, data on industrial heat was not available in details - the contribution of each heating technology was therefore derived (Table B.17) based on the following assumptions:

- the shares of the low-temperature decentralized heating technologies are equal to the shares for the residential and tertiary sectors (Table B.15);
- the electricity use for low-temperature heating is negligible compared to the electricity used for direct high-temperature heating in arc furnaces;
- commercial heat refers to heat produced by cogeneration in natural gas combined heat and power plants, which are far more numerous in France than biomass CHPs;

Table B.17: Yearly shares - estimated - of industrial high-temperature heat for the French energy system in 2017

	TWh	Share
Boiler Coal	11.8	5.8%
Boiler Oil	28.5	14.1%
Boiler NG	109.1	53.9%
CHP NG	17.0	8.4%
Renewables	12.5	6.2%
Direct elec	23.6	11.7%

B.4 Mobility

B.4.1 Passenger mobility

Passenger mobility amounts to nearly 1 billion passenger-kilometers in the last year, most being ensured by private transportation. Excluding air transport, the shares between public and private transport for passenger mobility are roughly 80%-20% (Table B.18).

Table B.18: Uses and shares of passenger mobility technologies in France (2017) (ref: SDES, CCTN 2018)

	Absolute (Bpkm)	Relative (%)
Private cars	757.3	82%
Public transport (excl. airplaines)	168.7	18%

Private passenger mobility

The only passenger mobility technologies with a non-negligible penetration share are diesel and gasoline cars (Table B.19), the first one representing nearly two-thirds of the total fleet [6]. Low-duty vehicles are mostly used in the agricultural sector - as there is no distinction, in EnergyScope, between the mobility shares for different types of passenger mobility, the penetration of each type of vehicle is calculated considering both sub-categories together.

Table B.19: Types of cars in France (2017) (ref: SDES, CCTN 2018)

Number (kcars)	Gasoline	Diesel
Private	12,665	19,855
Low-duty	265	5886
Total	12,930	25,741
Percentage	Gasoline	Diesel
Private	38.9%	61.1%
Low-duty	4.3%	95.7%
Total	33.4%	66.5%

The total number of vehicles given by the SDES is slightly lower (32.5k) than the one given by the ACEA (32.7k), which may come from the accounting of electric and other alternative cars. The car density for France is about 499 cars per 1000 people in 2017 [8].
However, the share of a given type of vehicles in use may be different than the corresponding one in the total fleet car, and the ACEA data is used as reference. The shares of vehicles by use are assumed similar to those when calculated the shares in passenger-cars [8].

Table B.20: Shares of vehicle in use, by fuel type, in France (2017)

	Gasoline	Diesel	Hybrid	Battery	Plug-in	LPG	Others
France	40.1%	59.1%	0.0%	0.4%	0.0%	0.4%	0.0%

The differences of private vehicle shares for local- and long-distance mobility are neglected in the French case, as the penetration of electric vehicles is negligible.

Public passenger mobility

In general Public passenger mobility, including or excluding the air transport, is dominated by rail transport (trains, subways and regional trains).

Table B.21: Uses and shares of public passenger mobility technologies in France (2017) (ref: SDES, CCTN 2018)

	Absolute (Bpkm)	Relative (%)
Buses, coaches and tramways	58.22	34.5%
Trains (urban and national)	110.47	65.5%

Local mobility The distinction between local and long-distance mobility, for public transport, can be approximated as the split between urban and non-urban mobility. Local and public mobility represents roughly 45 Bpkm, which is about 24% (incl. air transport)/26% (excl. air transport) of the total public mobility. Urban and public mobility technologies in France include conventional trains, commuter trains, metros, tramways, buses and coaches (Table B.22).

Table B.22: Uses and shares of local and public passenger mobility technologies in France (2017) (ref: SDES, CCTN 2018)

	Absolute (Bpkm)	Relative (%)
Trains	19.5	44.2%
Subways	10.4	23.5%
Tramways and Buses	14.3	32.3%

Long-distance mobility As no long-distance subways and tramways exist in France for travels longer than 80-100 km, only trains and coaches are considered (Table B.23).

Table B.23: Uses and shares of long-distance and public passenger mobility technologies in France (2017) (ref: SDES, CCTN 2018)

	Absolute (Bpkm)	Relative (%)
Trains	80.6	64.7%
Subways	0	0.0%
Tramways and Buses	44.0	35.3%

Neither airplane nor maritime transport contributions are considered in the mobility demands and technologies.

B.4.2 Freight mobility

Freight mobility amounts to more than 350 billion tons-kilometers in the last year, most being ensured by road transportation. Freight mobility with air transport is negligible and generally not considered in the French statistics. The shares between road and non-road transport are roughly 86%-14% (Table B.24).

B.4.3 Hourly Profiles / Time series

The passenger mobility profiles on hourly resolution can be based on the the traffic counting data by *Data Paris* [25]. The data is the hourly measurement of traffic on 3250 counting stations summing up to 13.01 billions vehicles counted in 2018. The measurement stations

Table B.24: Uses and shares of freight mobility technologies in France (2017) (ref: SDES, CCTN 2018)

	Absolute (Btkm)	Relative (%)
Rail	33.4	9.3%
Road	307.7	85.7%
Maritime	6.7	1.9%
Pipelines	11.2	3.1%

are spread through the city of Paris, corresponding to urban mobility (Short Distance).
No hourly open-data is available for rural and highway mobility (short-distance) in France. Therefore the long distance profiles are taken from measurements of Germany in Appendix C.

- The measurements correspond to the total traffic on the roads, being passenger and freight traffic combined.
- Following the hypothesis of Limpens [1], the freight traffic is constant over time.
- The normalized profiles of the measurements are independent of the freight and correspond to the passenger mobility.
- Long Distance Mobility can be modelled with the data of the highways and highroads
- Mobility profiles are similar for France and Germany.

With those assumptions, the time series are summarised by taking the hourly sum of all measurement sites to create one single profile for each day. Latter profiles are normalized in order to get the annual time series of Passenger Mobility. The time series are clustered with other time series (electricity demand, heating demand, hydro production, solar production and wind production) to get typical days profiles, which are integrated in Energyscope.

B.5 Storage technologies

Pumped hydrostorage is the only electricity storage technology deployed at large cale in France, and there are at present only seven sites, for a total installed capacity of about 7 GW. Based on the data given by INERIS [59] on the turbine powers and time constants, the total energy that can be stored is about 15 TWh.

B.5.1 Residential sector - final energy consumption by use and energy carrier (2017)

The final energy consumption in the residential sector is sorted by uses and energy carriers - heating, cooking, domestic hot water, specific electrical appliances and air conditioning (Table B.25).

Table B.25: Final energy consumption in the residential sector

HEATING		COOKING	
Electricity	34.6	Electricity	11.1
of which heat pump	*4.9*	Natural Gas	8.9
Natural Gas	126.2	**Liquefied petroleum gas**	5.0
Domestic fuel oil	42.6	Total*	**24.1**
Liquefied petroleum gas	3.3		
District heating	13.9	SPECIFIC	
Coal, other	2.6	Electricity	73.9
Wood	87.1		
Heat pump	9.8	AIR CONDITIONING	
Total*	**307.6**	Electricity**	0.8
DOMESTIC HOT WATER (ECS)		ALL PURPOSES	
Electricity	23.4	*Electricity*	143.9
Natural Gas	16.1	of which heat pump	*4.9*
Domestic fuel oil	5.8	Natural Gas	151.2
Liquefied petroleum gas	0.8	Domestic fuel oil	48.4
District heating	3.8	Liquefied petroleum gas	9.0
Coal, other	0.2	District heating	17.8
Wood	0.4	Coal, other	2.8
Total*	**49.0**	Wood	87.5
		Heat pump	9.8
		Total*	**455.4**

B.5.2 Tertiary sector - final energy consumption by use and energy carrier (2017)

The final energy consumption in the tertiary sector is sorted by uses and energy carriers - heating, cooking, domestic hot water, specific electrical appliances and air conditioning (Table B.26).

Table B.26: Energy demands in the tertiary sector

HEATING		SPECIFIC	
Electricity	18.3	Electricity	69.9
of which heat pump	*3.0*		
Natural Gas	59.6	AIR CONDITIONING	
Domestic fuel oil	19.4	Electricity	20.6
Liquefied petroleum gas	1.4	of which heat pump	*2.7*
District heating	7.8		
Renewable Energy	1.3	Other USES	
Heat pump	*6.0*	Electricity	2.1
Total	**107.8**	Natural Gas	3.0
		Domestic fuel oil	4.4
DOMESTIC HOT WATER (ECS)		Liquefied petroleum gas	1.0
Electricity	7.1	Renewable Energy	0.2
Natural Gas	11.1	Total	**10.4**
Domestic fuel oil	3.1		
Liquefied petroleum gas	0.4	ALL PURPOSES	
District heating	1.5	Electricity	122.3
Renewable Energy	0.1	of which heat pump	*5.7*
Total	**22.3**	Natural Gas	79.5
		Domestic fuel oil	26.9
COOKING		Liquefied petroleum gas	4.1
Electricity	4.4	District heating	9.3
Natural Gas	5.7	Renewable Energy	1.7
Domestic fuel oil	0.1	Heat pump	*6.0*
Liquefied petroleum gas	1.3	Total	**241.9**
Renewable Energy	0.1		
Total	**11.0**		

B.5.3 Electricity generation - hydroelectricity (2017)

The total installed capacity is about 25.5 GW and can be divided as 16% écluse, 26% fil de l'eau, 40% lake and 18% pumped hydropower.

B.5.4 Mobility sector - details

Public and private passenger mobility technologies in France can be grouped into road, rail and airplane transport (Table B.28).

Table B.27: Power production per type of hydropower plant

	Ecluse	Run-of-river	Lake	Pumped hydro
Jan.	709	1655	2269	592
Feb.	762	2227	1062	505
Mar.	1106	3187	1372	590
Apr.	720	2117	801	545
May	874	3067	1180	607
Jun.	645	2748	1128	576
Jul.	454	2066	868	505
Aug.	306	1865	858	472
Sep.	291	1574	851	374
Oct.	254	1205	783	488
Nov.	435	1785	1138	579
Dec.	810	2680	1258	587

Table B.28: Uses of public and private passenger mobility technologies in France, 2017, expressed in Bpkm, [6]

Mode de transport	**2017**
Voitures particulières (1)	757.3
Autobus, autocars et tramways (2)	58.2
Transports ferrés (3)	110.5
Transport ferroviaire	100.1
TGV	59.6
Trains interurbains	7.2
Trains sous convention avec les conseils régionaux	13.7
Réseau d'Île-de-France (trains et RER)	19.5
RATP (4)	7.8
Métros hors Île-de-France	2.6
Transports aériens (5)	15.4
Total	**941.4**

Appendix C

Germany EnergyScope data

C.1 Final Energy Consumption

C.1.1 Final energy consumption (FEC) per sector

The final energy consumption, as presented in the official German statistics, is usually classified by sectors (transportation, industrial, service and residential) and, as of 2017, the transportation sector is the most-energy intensive one (Table C.1), slightly ahead of the industrial one. The demands of the agricultural sector are not presented separately as in the French statistics.

Table C.1: Final energy consumption in Germany (2017) (ref: Energiebilanzen)

	[PJ]	[TWh]
Households	2430	675
Services	1443	401
Industry	2700	750
Transportation	2755	765

In addition, natural gas and crude oil are imported and treated for the production of non-energy products such as plastics. The final consumption of these resources amounted to 165 TWh in 2017, which was about 10 times less than the final energy consumption.

C.1.2 Final energy consumption (FEC) per end-use demand (EUD)

The final energy consumption in the residential and tertiary sectors as presented in the official French statistics is sorted by use (space heating, hot water production, cooking, specific electricity demand, ventilation and air conditioning) and sub-sorted by energy resource (electricity, natural gas, domestic fuel oil, liquefied petroleum gas, district heating, coal, biomass and heat pumps). Unlike other energy planning models, the EnergyScope model deals with end-use energy demands (for example, the number of passenger-kilometers and the space heating need instead of the gasoline and oil consumption) instead of final energy needs.

Heating

In the EnergyScope modelling framework, the heating demand is divided into two end-uses categories depending on its temperature level (low and high), and the low-temperature heating is itself divided into the space heating and hot water needs. A similar classification is used in the German statistics, and the following assumptions were taken:

- the cooling demand is not considered in the heating calculations, but in the electricity ones;
- the residential, tertiary and agricultural sectors only have a heating demand at low temperature, whereas the industry sector has both;

Table C.2: Classification of end-use heating and cooling demands - correspondence between the German statistics and the EnergyScope framework

German Statistics	EnergyScope
Space heating (Raumwärme)	Space heating
Domestic hot water (Warmwasser)	Domestic hot water
Other process heat (Sonstige Prozesswärme)	High-temperature heat
Cooling (Kilmakälte)	Specific electricity
Other cooling needs (Sonstige Prozesskälte)	Specific electricity
Mechanical energy (Mechanische Energie)	Specific electricity
Information technology (Informations- und Kommunikationstechnik)	Specific electricity
Lightning (Beleuchtung)	Specific electricity

The final energy consumption, as given by the French statistics, is presented in details in Appendices (Table C.24 and Table C.26). A summary is given in Table C.3 and the corresponding end-use demands are given in Table C.4.

Electricity

The electricity end-use demand (EUD) (Table C.5) is strongly different from the electricity final consumption (FEC). It does not include the heating demand by sector satisfied with electric devices or the electric demand with mobility, and considers specific applications such as lightning and IT appliances, as well as refrigeration and air conditioning systems. The end-use electricity demand was taken equal to the final electricity consumption associated

Table C.3: Final energy consumption for heating in France, expressed in TWh (2017)

FEC/Sector	Residential	Tertiary	Industry	Transportation	Agriculture
Fuels	299.1	126.1	189.9	0	10.7
District heating	17.8	10.5	0.0	0	0
Ambient heat	9.8	6.7	0.0	0	0
Electricity (HP)	4.9	3.4	0.0	0	0
Electricity (direct heating)	64.3	30.1	23.7	0	0

Table C.4: End-use heating demands in Germany, expressed in TWh (2017)

EUD/Sector	Residential	Tertiary	Industry	Transportation
Space heating	465.075	193.20	42.75	0
Hot water	103.275	18.84	4.5	0
Process heating	39.825	28.06	504.75	0

with refrigeration, assuming a cooling COP of 2 (by analogy with the French statistics where a heating COP of 3 was assumed).

Table C.5: End-use electricity demands in Germany, expressed in TWh (2017)

EUD/Sector	Residential	Tertiary	Industry	Transportation
Electricity	52.0	152.5	190.5	0.0

Mobility

The mobility end-used demand (EUD) is expressed in Bpkm (billion passenger-kilometers) for passenger transport and Mtkm (billion tons-kilometers) for freight transport.

Passenger mobility Unlike previous versions of EnergyScope (monthly and typical days), the model used in the frame of the PSA project distinguishes local (travels under 100 km (alternatively 80 km in the Enquête nationale)) and long-distance (travels above 100 km) mobility for passenger transportation (Table C.6).
General assumptions:

- the residential and tertiary sectors do not present any mobility demand;
- the mobility demand is taken from the German statistics (Bundesministerium für Verkehr, Bau und Stadtentwicklung, DIW (Deutsches Institut für Wirtschaftsforschung)), excluding airline transport for consistency with the other EnergyScope case studies, and is about 1111 Bpkm for 2017;

- the split between short- and long-distance mobility in terms of passenger-kilometers is usually around 55 %-45 % [60];

  The presented ratio is supposedly given with regards to the mileages, but is supposed reasonable in terms of passenger-kilometers demand, as it is similar to the ratio in France (60 %-40 %).

- as airline transport in EnergyScope is modelled separately from the other types of mobility, the share between long-distance and local mobility is adjusted to 24 %-76 % based on the study on long-distance mobility from the Institute for Mobility Research (LANGSTRECKENMOBILITÄT – AKTUELLE TRENDS UND PERSPEKTIVEN) conducted for the year 2011.

Table C.6: End-use passenger mobility demands in Germany, expressed in Bpkm (2017)

EUD/Sector	Residential	Tertiary	Industry	Transportation
Local	0	0	0	843
Long-distance	0	0	0	267

Freight mobility The freight mobility end-use demand is not split into its local and long-distance parts, and the value is directly taken from the German statistics [9] for the year 2017 (Table C.7). There is supposedly no demand associated with the other sectors.

Table C.7: End-use freight mobility demands in Germany, expressed in tpkm (2017)

EUD/Sector	Residential	Tertiary	Industry	Transportation	Agriculture
Freight	0	0	0	691	0

Air transport The air transport demand is about 67.5 Mpkm in 2017 (Bundesministerium für Verkehr, Bau und Stadtentwicklung, DIW (Deutsches Institut für Wirtschaftsforschung)) and the equivalent fuel demand, according to the official statistics (ref: BWE-Energieeffizienz-in-Zahlen) is 426 PJ or 118 TWh. This value includes international air transport and may be modified further.

Table C.8: End-use airplane fuel demand in Germany, expressed in TWh (2017)

EUD/Sector	Residential	Tertiary	Industry	Transportation	Agriculture
Airplane fuel	0	0	0	118	0

Non-energy uses

Non-energy uses in Germany consist of oil and natural gas-derived products - a finer decomposition into the various types of plastics, paper and steel was not possible due to the lack of data and they are allocated to the industry sector (Table C.9).

Table C.9: Non-energy end-use demand in Germany, expressed in TWh (2017)

EUD/Sector	Residential	Tertiary	Industry	Transportation
Non-energy	0	0	275	0

C.2 Electricity production

The German energy system consists of conventional thermal power plants (coal, natural gas, oil), nuclear facilities and renewable energies. The contributions of geothermal and wave power plants for centralised power production are neglected. Electricity generation in Germany is ensured mostly by coal power plants (Table C.10) - the trend in the last decade (2010-2020) is a reduction of the share of the nuclear facilities and an increase of the renewable ones such as wind and solar [61]. The total hydropower capacity amounts to about 11.3 GW, of which 4.8 GW correspond to run-of-river plants and 6.8 GW of pumped hydrostorage [62].

Table C.10: Installed power plants, electricity production and corresponding share in Germany (2017) [7]

	Oil	Coal	Gas	Hydro	Nuclear	Solar	Wind	Biomass
Capacity (GW)	4.4	44.9	29.8	11.3	10.8	42.3	55.6	7.8
Generation (TWh)	0	216	49	20.1	72.2	39.4	105.7	44.7
Production share (%)	0%	39.1%	8.9%	3.7%	13.1%	7.2%	19.1%	8.1%

The average capacity factors of wind and solar [63] power plants on a typical day basis are derived from the measures of the average monthly capacity factors over the year 2017 (Table C.11). Power generation from nuclear facilities is assumed constant over the year with an equivalent running capacity of 8.2 GW.

The estimations of wind (Table C.12) and solar potentials vary widely depending on the study and restrictions (for example, share of land available for onshore wind or share of roofs available for PV).

For hydropower, the capacity factors vary widely depending on the year and type of plant (run-of-river or lake) [64]. Detailed data on the average monthly capacity factors of run-of-river power plants were not available for all, so those were extrapolated based on the data for the Iffezheim, Laufenburg and Rheinfelden facilities. The latter are the largest run-of-river

Table C.11: Average monthly capacity factors c_p of intermittent renewable energies (expressed in %)

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
PV	2.4	5.3	10.2	12.5	16.2	17.7	15.6	14.6	10.2	6.7	2.6	1.6
Wind Onshore	17.4	23.7	20.9	18.3	11.8	16.1	12.1	11.8	14.4	27.3	23.5	34.0
Wind Offshore	29.8	52.3	37.3	35.9	29.8	32.1	22.9	27.3	25.7	54.9	42.4	50.9

Table C.12: Wind potential in Germany, in terms of installed capacity and power production

Onshore	GW	TWh
Low	116	236
Medium	154	300
High	192	378
Offshore	GW	TWh
Low	0	0
Medium	0	0
High	106	404

facilities in Germany but represent only about 10 % of the total installed capacity of such plants.

Table C.13: Average monthly capacity factors c_p of hydropower (expressed in %)

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Hydro river	27	41	57	44	63	60	53	55	59	46	49	55

Similarly, the estimations of the hydroelectricity potential depend on whether technical and economic considerations are taken into account. According to the various sources cited by Bodis et al. [65], the technically exploitable potential is about 25-36 TWh per year, while the economically exploitable one is about 11-20 TWh (ref: Conseil mondial de l'énergie). (Table C.14).

Table C.14: Hydroelectricity potential in Germany, in terms of installed capacity and power production

Hydroelectric	GW	TWh
Economical	-	11, 20, 20
Technical	-	36, 24.7, 25

C.3 Heating and cogeneration

C.3.1 Decentralized low-temperature heat

Detailed data on the use of fuels, ambient heat and electricity for heating purposes (space heating and hot water production) are available for the residential and tertiary sectors, but are lacking for the industrial and agricultural cases. The yearly shares of decentralized low-temperature heating were calculated using weighted averages of the residential, tertiary and industrial sectors (Table C.15). Assumptions on the allocation of low- and high-temperature heat and of the associated fuels are presented in the dedicated subsection, and the ones specific to low-temperature heat are given as follows:

- solar thermal and geothermal heat are used only in the residential sector for low-temperature heating (usually space heating) and the corresponding figures are derived from the balances on primary energy of the German statistics;
- the category "other renewables" are assumed to be biomass, while "others" are considered to be non-renewable waste, as the use of heat from nuclear power plants is negligible to nonexistent in the last years;
- the heat pump contribution is defined as the sum of the ambient heat, which value is given in the German statistics, and the electricity required to drive the cycle, assuming a heating COP of 3;
- the ratios between the heat supplies from coal, natural gas, oil, biomass and waste are the same for low-temperature applications and for all the entire heat demand of the industrial sector (for example, 2.1 times more gas is consumed in the industrial sector than coal and the same ratio is taken when it comes to the low-temperature heat supply of the same sector);
- direct electrical heating is calculated as the difference between the total low-temperature heat demand and the sum of the other energy sources.

The low-temperature heating demands - decentralized - were estimated to 1235 TWh in 2017. This number is far greater than the cumulative LT heat demand of the industrial and agricultural sectors, of roughly 21 TWh, and the assumption is therefore deemed reasonable. The use of heat from cogeneration units for heating without a district heating medium is neglected. The assumption is reasonable, as it represents less than 1% in other European countries such as Switzerland.

C.3.2 Centralized low-temperature heat

Detailed data on the fuel share for district heating production was available, although it was not specified whether the processed fossil fuels were converted in heat-only boilers or in

Table C.15: Yearly shares - estimated - of decentralized low-temperature heat for the German energy system in 2017

	TWh	Share
Boiler Coal	19.1	1.5%
Boiler Oil	224.9	18.2%
Boiler NG	421.4	34.1%
Boiler Biomass	92.1	7.5%
Boiler Waste	2.1	0.2%
Geothermal	3.1	0.2%
CHP Biomass	6.1	0.5%
Heat pump	156.8	12.7%
Solar thermal	274.4	22.2%
Direct Elec.	34.9	2.8%

cogeneration units. As of 2011, heat-only boilers represented less than 10% of the total heat supply (of which 7% are with natural gas [66], and it is assumed, for 2017, that all district heat comes from cogeneration units (Table C.16). Contributions from industrial heat, solar thermal, geothermal and heat pumps are neglected.

Table C.16: Yearly shares - estimated - of centralized low-temperature heat for the German energy system in 2017

	TWh	Share
CHP Coal	37.2	25.7%
CHP Oil	1.7	1.1%
CHP Gas	60.6	41.8%
CHP Biomass	27.5	19%
CHP Waste	18.1	12.5%

C.3.3 Industrial high-temperature heat

The following issues were faced when analysing the production of high-temperature heat:

- data on the types and shares of technologies for heat generation were not available in details;
- according to the German statistics of 2017, the heat supply from district heating (50 TWh) exceeds the heat demand at low temperature for space heating (43 TWh) and hot water production (4.5 TWh);

This implies that a fraction of district heating is used for process heating, which could either be at low- or high-temperature, depending on the type of industry.

The shares of each heating technology were therefore derived (Table C.17) based on the following assumptions:

- all process heat is needed at high temperatures;
- the electricity use for low-temperature heating is negligible compared to the electricity used for direct high-temperature heating in arc furnaces;
- all district heat is used to cover the demands of process heating, which is relevant if one considers steam extraction for CHP plants at medium- to high-pressures and neglects the use of district heating for space heating as for households;
- geothermal and solar energy are not used for neither low- nor high-temperature heating - the first assumption is reasonable as there is no deep geothermal plant in Germany as in Iceland and the second one builds on the hypothesis that all solar heat is mostly for decentralised low-temperature heat in households;
- the share of high-temperature heat pumps is negligible, and the heat provided by "renewable" and "other" sources is allocated to biomass and waste boilers.

Table C.17: Yearly shares - estimated - of industrial high-temperature heat for the German energy system in 2017

	TWh	Share
Boiler Coal	111.91	22.2%
Boiler Oil	24.27	4.8%
Boiler Gas	235.28	46.6%
Electricity	34.50	6.8%
Boiler Biomass	29.66	5.9%
Boiler Waste	18.88	3.7%
CHP Coal	12.90	2.6%
CHP Oil	0.58	0.1%
CHP Gas	20.99	4.2%
CHP Biomass	9.53	1.9%
CHP Waste	6.26	1.2%

C.4 Mobility

C.4.1 Passenger mobility

Passenger mobility amounts to more than 1 billion passenger-kilometers in the last years, most being ensured by private transportation. Excluding air transport, the shares between public and private transport for passenger mobility are roughly 80%-20% (Table C.18), as in France.

Table C.18: Uses and shares of passenger mobility technologies in Germany (2017) (ref: Bundesministerium für Verkehr, Bau und Stadtentwicklung, DIW (Deutsches Institut für Wirtschaftsforschung))

	Absolute (Bpkm)	Relative (%)
Private cars	868	78%
Public transport (excl. airplanes)	243	22%

Private passenger mobility

The only passenger mobility technologies with a non-negligible penetration share are diesel and gasoline cars, the second one representing nearly two-thirds of the total fleet. The total number of passenger cars, as given by the ACEA, is roughly 46 million cars, which gives a car density for Germany of about 550 cars per 1000 people in 2017 [8]. The shares of vehicles by use are assumed similar to those when calculated the shares in passenger-cars.

Table C.19: Shares of vehicle in use, by fuel type, in Germany (2017) [8]

	Gasoline	Diesel	Hybrid	Battery	Plug-in	LPG	Others
Germany	65.9%	32.2%	0.6%	0.2%	0.1%	1.0%	0.0%

The differences of private vehicle shares for local- and long-distance mobility are neglected in the German case, as the penetration of electric vehicles is negligible.

Public passenger mobility

In general Public passenger mobility, including or excluding the air transport, is dominated by rail transport (trains, subways and regional trains).

Local mobility Based on the trends drawn for 2011 in the study on long-distance mobility, local and public mobility represents roughly 94 Bpkm (excl. air transport), which is about

Table C.20: Uses and shares of public passenger mobility technologies in Germany (2017) (ref: Bundesministerium für Verkehr, Bau und Stadtentwicklung, DIW (Deutsches Institut für Wirtschaftsforschung)

	Absolute (Bpkm)	Relative (%)
Buses, coaches and tramways	79.7	45.5%
Trains (urban and national)	95.5	54.5%

39% (incl. air transport)/53% (excl. air transport) of the total public mobility. Urban and public mobility technologies in Germany include conventional trains, commuter trains, metros, tramways, buses and coaches (Table C.21).

Table C.21: Uses and shares of local and public passenger mobility technologies in Germany (2017) (ref: Bundesministerium für Verkehr, Bau und Stadtentwicklung, DIW (Deutsches Institut für Wirtschaftsforschung)

	Absolute (Bpkm)	Relative (%)
Rail	38	41%
Bus	56	59%

Long-distance mobility As no long-distance subways and tramways exist in Germany for travels longer than 100 km, only trains and coaches are considered (Table C.22).

Table C.22: Uses and shares of long-distance and public passenger mobility technologies in Germany (2017) (ref: INFRAS / NIT)

	Absolute (Bpkm)	Relative (%)
Trains	57.3	70.5%
Subways & Tramways	0	0.0%
Buses	24.0	29.5%

Neither airplane nor maritime transport contributions are considered in the mobility demands and technologies.

C.4.2 Freight mobility

Freight mobility amounts to nearly 500 billion tons-kilometers in the last year, most being ensured by road transportation. Freight mobility with air transport is negligible and generally not considered in the French statistics. The shares between road and non-road transport are roughly 63%-37% (Table C.23).

Table C.23: Uses and shares of freight mobility technologies in Germany (2017) [9]

	Absolute (Btkm)	Relative (%)
Rail	111.9	22.4%
Road	313.1	62.8%
Maritime	55.5	11.1%
Pipelines	18.2	3.6%

C.4.3 Hourly Profiles / Time series

The passenger mobility profiles on hourly resolution can be based on the the traffic counting data by the bast (Bundesanstalt für Strassenwesen) [26]. The data is the hourly measurement of traffic on 846 highway and 667 highroad counting stations summing up to 221.51 billions vehicles counted in 2018, corresponding to long distance mobility.
No hourly open-data is available for city traffic (short-distance) in Germany and the urban traffic measurement profile is taken from France, visible in Appendix B.

- The measurements correspond to the total traffic on the roads, being passenger and freight traffic combined.
- Following the hypothesis of Limpens [1], the freight traffic is constant over time.
- The normalized profiles of the measurements are independent of the freight and correspond to the passenger mobility.
- Long distance mobility can be modelled with the data of the highways and highroads.
- Short distance mobility profile for short distance is similar to the France short distance.

With those assumptions, the time series are summarised by taking the hourly sum of all measurement sites to create one single profile for each day. Latter profiles are normalized in order to get the annual time series of Passenger Mobility. The time series are clustered with other time series (electricity demand, heating demand, hydro production, solar production and wind production) to get typical days profiles, which are integrated in Energyscope.

C.5 Storage technologies

Germany has a pumped hydrostorage capacity nearly constant over time, of about 5.5 GW, as no new sites have been built [67]. Few large-scale battery systems have been installed in the last decade, with a capacity of 117 MW as of 2017 [68]. In addition, Germany is a pioneer in compressed air energy storage, as demonstrated with the successful operation of the Huntorf plant [69], which has a capacity of 290 MW.

C.5.1 Residential sector - final energy consumption by use and energy carrier (2017)

The final energy consumption in the residential sector is sorted by energy carriers (Table C.24) and by final use, such as heating, cooking, domestic hot water, specific electrical appliances and air conditioning (Table C.25).

Table C.24: Final energy consumption in the residential sector in Germany (2017)

		%	PJ	TWh
Steinkohle	Hard coal	0.003	7.29	2.03
Braunkohle	Lignite	0.006	14.58	4.05
Mineralölprodukte	Petroleum Products	0.202	490.86	136.35
Gase	Gases	0.395	959.85	266.63
Strom	Electricity	0.191	464.13	128.93
Fernwärme	District heating	0.075	182.25	50.63
Erneuerbare Wärme	Renewable heat	0.128	311.04	86.40
Sonstige Energieträger	Other energy sources	0	0.00	0.00

Table C.25: Final energy consumption in the residential sector in Germany (2017)

		%	PJ	TWh
Raumwärme	Space heating	0.689	1674.27	465.08
Warmwasser	Hot water	0.153	371.79	103.28
Sonstige Prozesswärme	Other process heat	0.059	143.37	39.83
Klimakälte	Air-conditioning	0.002	4.86	1.35
Sonstige Prozesskälte	Other process refrigeration	0.042	102.06	28.35
Mechanische Energie	Mechanical energy	0.008	19.44	5.40
Informations- und Kommunikationstechnik	Information technology	0.032	77.76	21.60
Beleuchtung	Lighting	0.015	36.45	10.13

C.5.2 Tertiary sector - final energy consumption by use and energy carrier (2017)

The final energy consumption in the tertiary sector is sorted by energy carriers (Table C.26) and uses (Table C.27) - heating, cooking, domestic hot water, specific electrical appliances and air conditioning.

Table C.26: Final energy consumption in the tertiary sector in Germany (2017)

		%	PJ	TWh
Steinkohle	Hard coal	0.001	1.44	0.40
Braunkohle	Lignite	0	0.00	0.00
Mineralölprodukte	Petroleum Products	0.214	308.80	85.78
Gase	Gases	0.32	461.76	128.27
Strom	Electricity	0.367	529.58	147.11
Fernwärme	District heating	0.031	44.73	12.43
Erneuerbare Wärme	Renewable heat	0.067	96.68	26.86
Sonstige Energieträger	Other energy sources	0	0.00	0.00

Table C.27: Final energy consumption in the tertiary sector in Germany (2017)

		%	PJ	TWh
Raumwärme	Space heating	0.482	695.53	193.20
Warmwasser	Hot water	0.047	67.82	18.84
Sonstige Prozesswärme	Other process heat	0.07	101.01	28.06
Klimakälte	Air-conditioning	0.01	14.43	4.01
Sonstige Prozesskälte	Other process refrigeration	0.031	44.73	12.43
Mechanische Energie	Mechanical energy	0.179	258.30	71.75
Inf.- und Komm.technik	information technology	0.062	89.47	24.85
Beleuchtung	Lighting	0.119	171.72	47.70

C.5.3 Industry sector - final energy consumption by use and energy carrier (2017)

The final energy consumption in the industry sector is sorted by energy carriers (Table C.28) - heating, cooking, domestic hot water, specific electrical appliances and air conditioning, and uses (Table C.29).

Table C.28: Final energy consumption in the industry sector in Germany (2017)

		%	PJ	TWh
Steinkohle	Hard coal	0.138	372.6	103.5
Braunkohle	Lignite	0.028	75.6	21
Mineralölprodukte	Petroleum Products	0.036	97.2	27
Gase	Gases	0.349	942.3	261.75
Strom	Electricity	0.31	837	232.5
Fernwärme	District heating	0.067	180.9	50.25
Erneuerbare Wärme	Renewable heat	0.044	118.8	33
Sonstige Energieträger	Other energy sources	0.028	75.6	21

Table C.29: Final energy consumption in the industry sector in Germany (2017)

		%	PJ	TWh
Raumwärme	Space heating	0.057	153.9	42.75
Warmwasser	Hot water	0.006	16.2	4.5
Sonstige Prozesswärme	Other process heat	0.673	1817.1	504.75
Klimakälte	Air-conditioning	0.006	16.2	4.5
Sonstige Prozesskälte	Other process refrigeration	0.014	37.8	10.5
Mechanische Energie	Mechanical energy	0.22	594	165
Inf.- und Komm.technik	information technology	0.012	32.4	9
Beleuchtung	Lighting	0.012	32.4	9

Appendix D

Modelling

D.1 Parameters of Mobility Energyscope

Table D.1: Morris analysis input parameters and results preliminary run

Parameter	Units	Description
Batt_per_Car	GWh	Battery size per EVs car technology, modified to include non V2G vehicles that are electric
bio_ratio	-	Biomass fraction used minimum of potential
c_access_t	-	access of a car to an EV charging station (assumed to 90% at home time, 40% or less out of home time)
c_ecos_mob		Ecological subsidy bonus/tax (subsidy from the state)
c_inf_marg		infrastructure marginal cost associated with the increase of demand with a specific type of mobility technology
c_inv_limit_car	-	default value for investment cost of a car for getting subsidies
c_link	-	
capacity_mpkm_network		Capacity passenger mobility network
capacity_mtkm_network		Capacity freight mobility network
car_per_ppl	car/ppl	Share of motorisation

Parameter	Units	Description
d_pkm_car_avtg0	Mpkm	average demand-distance run by a car over a year
f_car_circ	-	fraction of the car park in circulation
f_ext	GW	Existing of technologies not to be paid further
fext_perc	-	existing share of a technology, of the total output of its sector over the entire year
gwp_limit	ktCO2-eq./year	
gwp_limit_car	ktCO2-eq/GWh	default value for GWP of a car (limit for ecological malus)
h_peak_start,end	h	hours of start and end of peak electricity
h_work_start,end	h	working hours
length_network	km	Lenght of mobility infrastructure network
mob_pass_local_time_series		factor sharing passenger transportation across Typical days
mob_pass_longd_time_series		factor sharing passenger transportation across Typical days
n_car,total	car	number of cars
n_ppl	ppl	Population of studied region
n_ppl0	ppl	population of studied region at reference year
Number_of_Cars_per_Type	cars	number of cars per type
Number_of_Stations	-	Number of Station per type
p_car_average	kW/car	Mean power of a car
p_car_average	kW	Mean total power of cars
Power_per_Car	GW	Specific power per type of car
Power_per_Station	GW	Power per Station type
re_share_elec	-	Share of renewable energy in electricity
re_share_primary	-	Share of renewable energy in primary energy
share_v2g	-	vehicles can be connected on the grid and be used as in/out to the grid
sng_min	-	SNG minimum
Stations_per_Car	stations/car	Stations per Car per type
sustmob_local_limit	-	Share of sustainable mobility local
sustmob_longd_limit	-	Share of sustainable mobility longd
trl_min,max	-	technology readiness level min/max

Parameter	Units	Description

Appendix E

Additional scenario data

E.1 Battery Electric vehicles

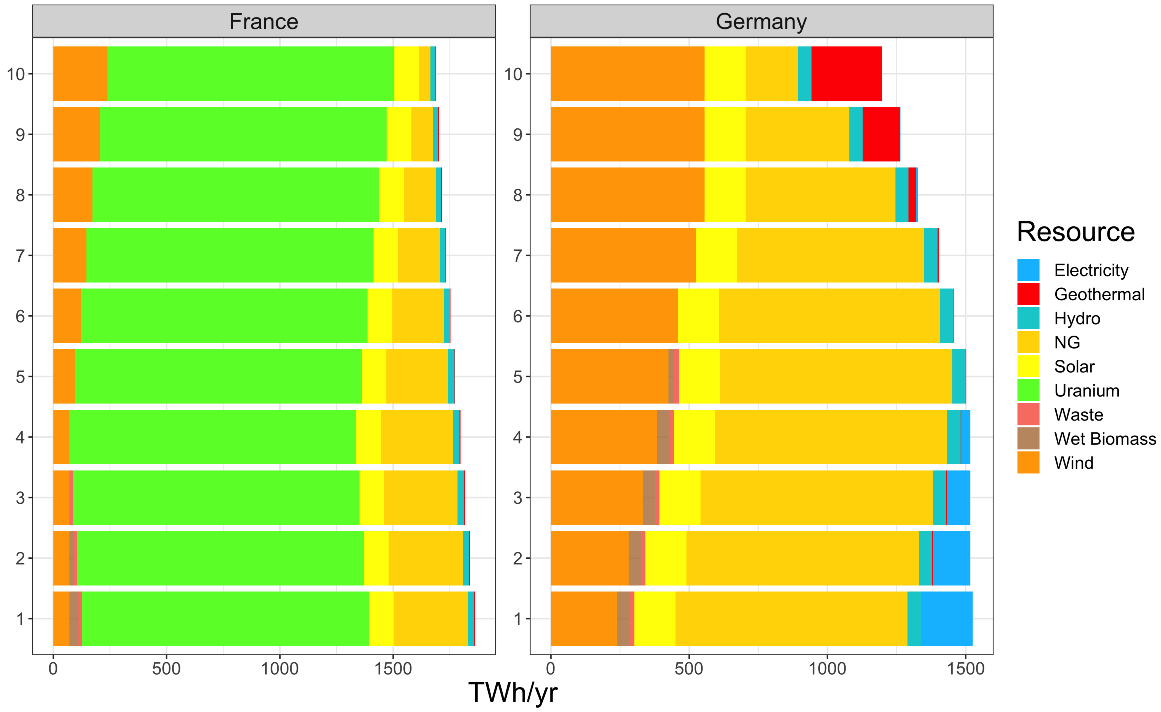

Figure E.1: Primary energy consumption Pareto points BEV scenario

E.2 Synthetic Fuel vehicles

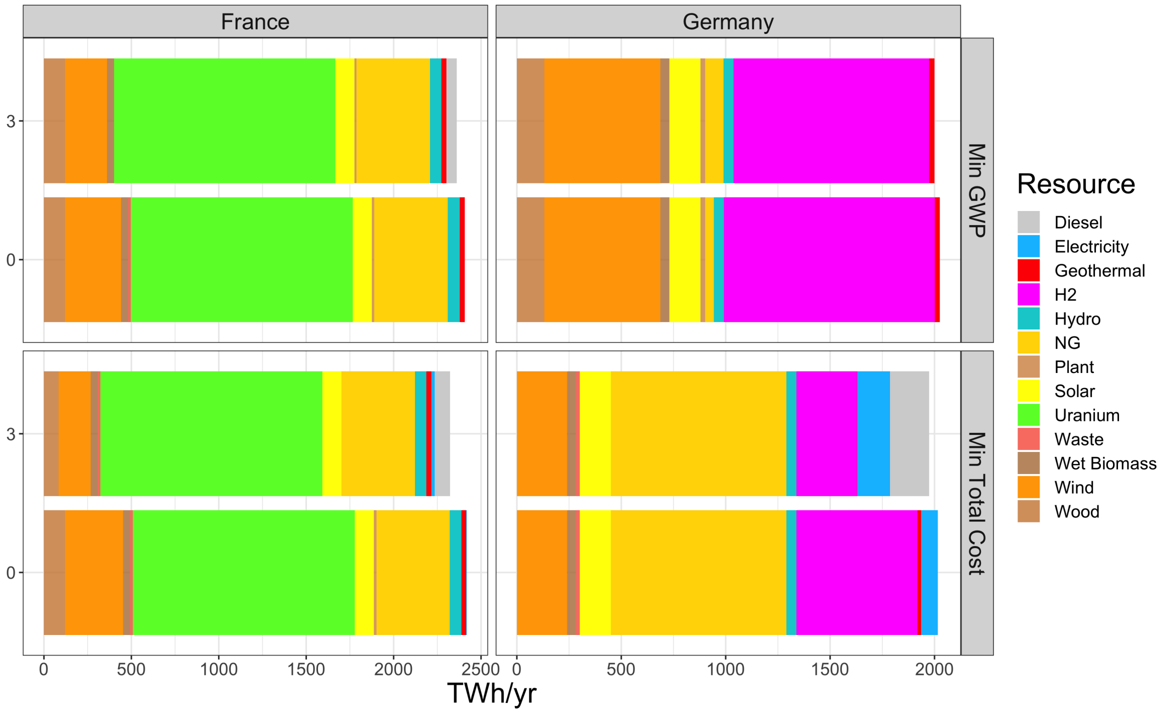

Figure E.2: Primary energy consumption extreme points synthetic fuels powered vehicles

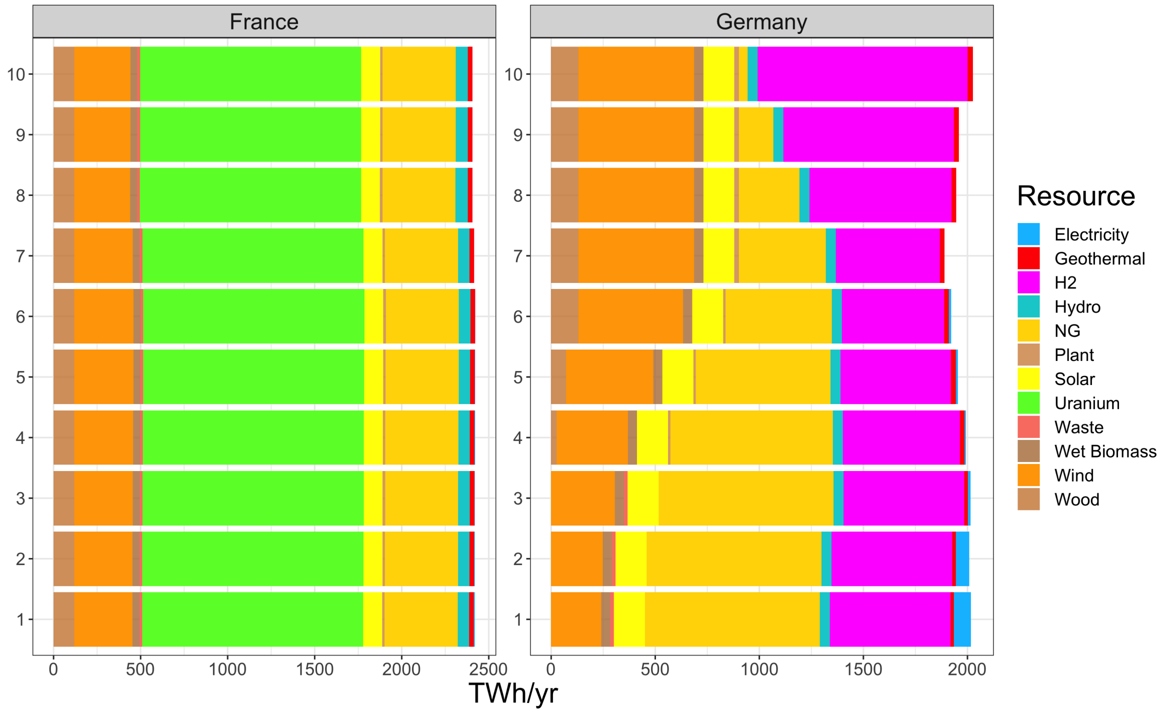

Figure E.3: Primary energy consumption Pareto points synthetic fuels scenario.

E.3 Fuel cell vehicles

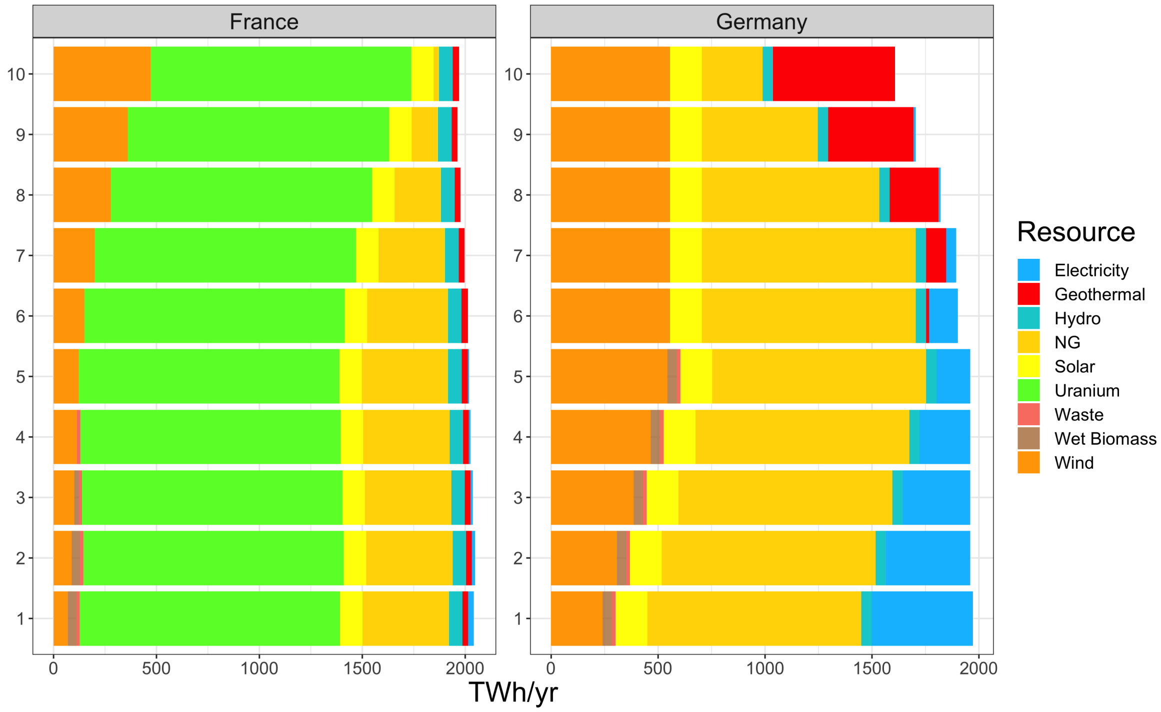

Figure E.4: Primary energy consumption Pareto points hydrogen scenario.

E.4 Ethanol driven vehicles

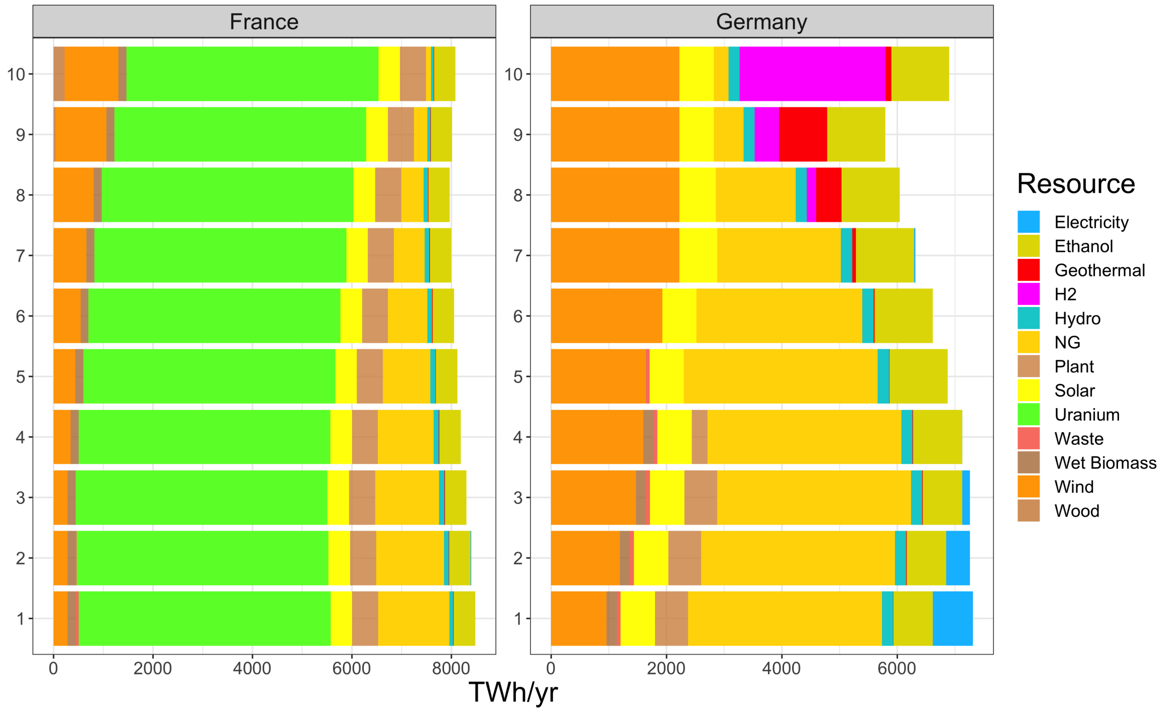

Figure E.5: Primary energy consumption Pareto points ethanol powered vehicles

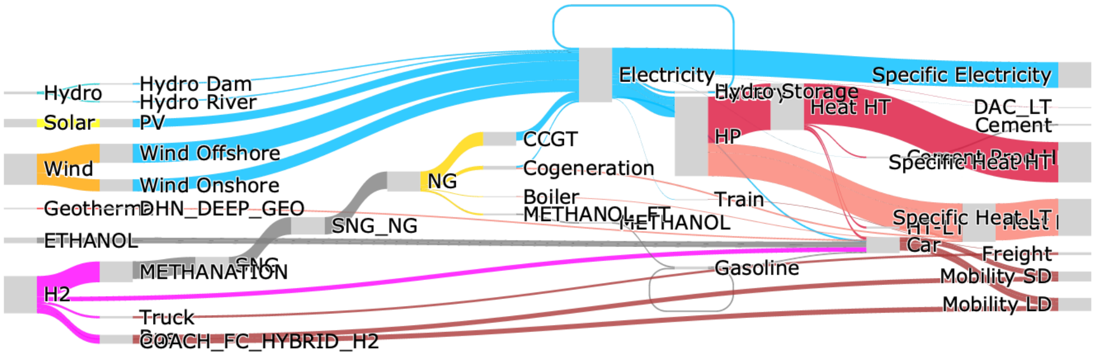

Figure E.6: Sankey diagram Germany 25% E85 shares GWP minimization

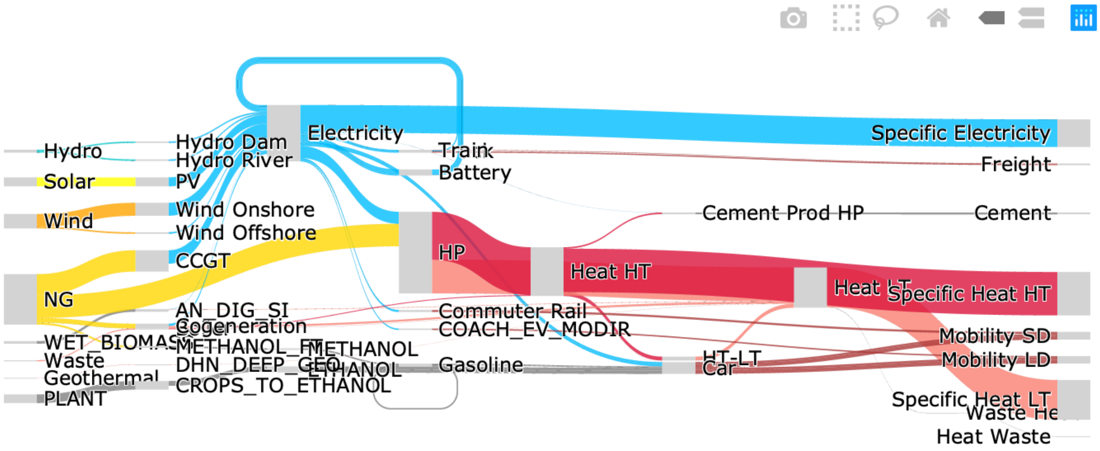

Figure E.7: Sankey diagram Germany 25% E85 shares economic minimization

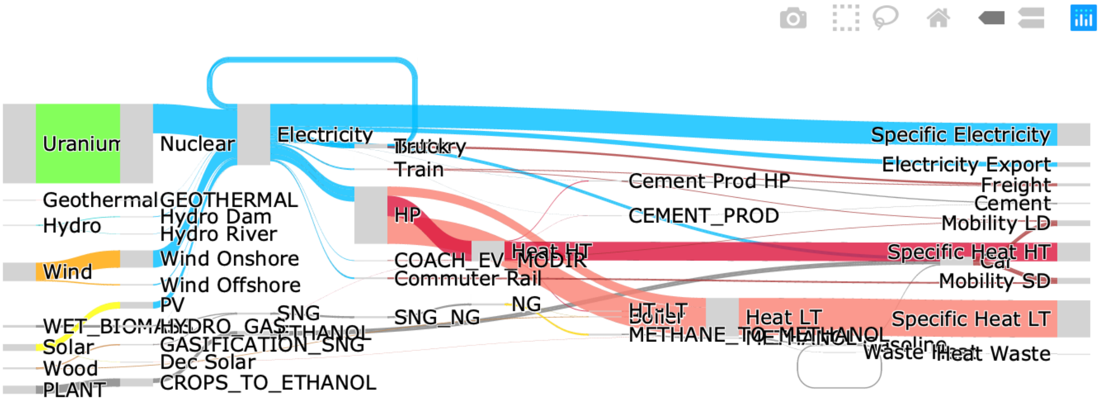

Figure E.8: Sankey diagram France 25% E85 shares GWP minimization

Appendix F

Morris illustrations

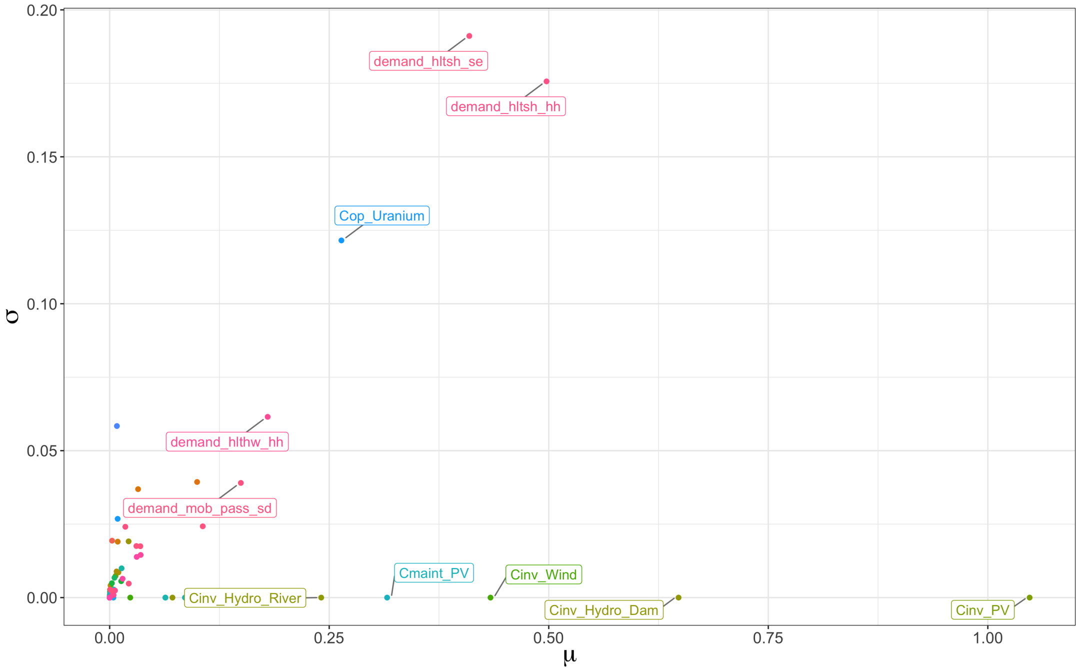

Figure F.1: Standardised Morris analysis results on parameters listed in Table F.1.

Table F.1: Morris analysis input parameters and results preliminary run

Parameter	Min	Max	Base	μ	σ	μ^*
Battery Capacity HR	3.6E-05	2.0E-04	1.2E-04	-1.9E-08	5.8E-08	1.4E-08
Battery Capacity LR	1.6E-05	4.0E-05	2.8E-05	-6.9E-09	1.0E-08	5.3E-09
Battery Capacity PHEV	7.6E-06	2.4E-05	1.6E-05	-2.7E-03	1.9E-02	2.7E-03
Cinv Bus CNG	4.0E6	8.0E6	6.0E6	0.0E4	3.3E-13	8.6E-14
Cinv Bus Diesel	4.0E7	8.0E7	6.0E7	-5.4E-06	1.2E-05	1.6E-06
Cinv Bus EV V1G	4.5E8	1.4E9	9.0E8	1.1E-12	2.5E-12	9.8E-13

Parameter	Min	Max	Base	μ	σ	μ^*
Cinv Bus EV V2G	4.5E9	1.4E10	9.0E9	0.0E7	2.1E-05	4.2E-06
Cinv Bus FC	5.0E10	1.5E11	1.0E11	9.1E-14	6.1E-13	1.6E-13
Cinv Bus Hy	4.0E11	8.0E11	6.0E11	-5.4E-06	1.2E-05	1.6E-06
Cinv Car A10	3.3E12	1.0E13	6.7E12	2.4E-13	1.7E-12	6.0E-13
Cinv Car A80	3.3E13	1.0E14	6.7E13	-5.2E-06	3.2E-02	4.6E-03
Cinv Car BEV LR V1G	3.0E14	8.0E14	5.5E14	2.5E13	9.8E12	2.5E13
Cinv Car BEV LR V2G	3.0E15	8.0E15	5.5E15	4.5E-14	1.4E-05	2.0E-06
Cinv Car BEV MR V1G	6.6E16	2.0E17	1.3E17	2.1E15	2.5E15	2.2E15
Cinv Car BEV MR V2G	6.6E17	2.0E18	1.3E18	4.8E-12	7.6E-12	2.1E-12
Cinv Car Diesel	3.2E18	9.7E18	6.5E18	4.5E-09	3.3E-08	5.8E-09
Cinv Car E10	3.3E19	1.0E20	6.7E19	-5.2E-06	1.1E-05	1.5E-06
Cinv Car E85	3.3E20	1.0E21	6.7E20	-1.8E-13	2.5E-12	1.2E-12
Cinv Car FC	7.2E21	2.2E22	1.5E22	1.1E20	1.4E20	6.7E19
Cinv Car Gasoline	3.3E22	1.0E23	6.7E22	4.2E-01	9.0E-01	1.3E-01
Cinv Car HEV	7.4E23	2.2E24	1.5E24	-6.7E-13	5.1E-12	2.2E-12
Cinv Car NG	2.6E24	7.9E24	5.3E24	7.6E22	7.6E22	6.1E22
Cinv Car PHEV V1G	7.4E25	2.2E26	1.5E26	6.4E-01	3.1E23	7.5E-01
Cinv Car PHEV V2G	7.4E26	2.2E27	1.5E27	-5.4E-05	1.2E-04	1.6E-05
Cinv Coach CNG	7.5E26	2.3E27	1.5E27	2.3E-13	5.1E-13	2.1E-13
Cinv Coach Diesel	7.5E27	2.3E28	1.5E28	-1.4E-14	6.9E-13	1.7E-13
Cinv Coach EV V1G	2.0E29	6.0E29	4.0E29	2.4E-02	1.4E-01	4.4E-02
Cinv Coach EV V2G	2.0E30	6.0E30	4.0E30	9.0E-02	2.5E-01	5.9E-02
Cinv Coach Fuel Cell	1.5E31	4.5E31	3.0E31	-5.7E-13	4.5E-08	6.4E-09
Cinv Coach Hy	7.5E31	2.3E32	1.5E32	2.7E-14	3.0E-13	1.0E-13
Cinv Dec Solar	3.8E33	1.2E34	7.7E33	9.0E31	3.6E-15	9.0E31
Cinv DHN Boiler Gas	3.2E33	9.4E33	6.3E33	1.9E-01	2.8E-01	2.5E-01
Cinv DHN Boiler Oil	2.9E34	8.8E34	5.9E34	3.1E-01	2.5E-01	2.9E-01
Cinv DHN Boiler Wood	6.2E35	1.9E36	1.2E36	5.8E-03	1.2E-01	2.5E-02
Cinv DHN Cogen Gas	6.7E37	2.0E38	1.3E38	1.2E-13	2.2E-12	5.8E-13
Cinv DHN Cogen Waste	1.6E39	4.7E39	3.1E39	5.6E-13	7.0E-12	1.6E-12
Cinv DHN Cogen Wood	1.6E40	4.7E40	3.1E40	1.1E-12	6.7E-12	1.9E-12
Cinv DHN Geothermal	8.1E40	2.4E41	1.6E41	1.5E-13	4.3E-12	1.1E-12
Cinv DHN HP	1.8E41	5.5E41	3.7E41	5.1E39	3.5E39	4.0E39
Cinv Freight Diesel	5.2E41	1.6E42	1.0E42	-5.4E-06	1.5E-05	2.5E-06
Cinv Geothermal	5.8E44	1.7E45	1.2E45	4.1E43	5.7E-14	4.1E43
Cinv Hydro Dam	2.4E45	7.2E45	4.8E45	1.6E45	6.9E-13	1.6E45
Cinv Hydro River	2.7E46	8.1E46	5.4E46	6.5E45	8.0E-13	6.5E45
Cinv IND Cogen Gas	7.5E46	2.3E47	1.5E47	0.0E44	2.0E-12	2.9E-13

Parameter	Min	Max	Base	μ	σ	μ^*
Cinv Ind Cogen Waste	1.6E48	4.7E48	3.1E48	0.0E45	5.5E-12	1.4E-12
Cinv IND Cogen Wood	5.7E48	1.7E49	1.2E49	2.1E-13	1.4E-12	3.8E-13
Cinv PV	5.0E49	1.5E50	1.0E50	5.2E49	2.3E-13	5.2E49
Cinv Train Elec	2.8E50	8.5E50	5.6E50	2.1E48	2.1E48	1.9E48
Cinv Train Freight	5.2E50	1.6E51	1.0E51	7.1E-02	4.0E-02	8.1E-02
Cinv Tramway	3.1E52	9.4E52	6.3E52	-5.7E-14	1.0E-05	1.5E-06
Cinv Truch FC	1.7E53	5.0E53	3.3E53	-3.0E-14	6.5E-06	1.3E-06
Cinv Truck	1.1E54	3.3E54	2.2E54	2.2E-13	3.6E-06	5.1E-07
Cinv Truck CNG	1.1E55	3.3E55	2.2E55	-6.0E-14	4.5E-13	1.3E-13
Cinv Truck CO2	1.5E56	4.4E56	3.0E56	-1.6E-13	9.0E-13	3.1E-13
Cinv Truck EV V1G	7.4E56	2.2E57	1.5E57	1.7E-01	2.2E-01	1.8E-01
Cinv Truck EV V2G	7.4E57	2.2E58	1.5E58	2.0E-01	2.0E-01	2.0E-01
Cinv Wind	7.4E59	2.2E60	1.5E60	3.2E59	4.0E-13	3.2E59
Cmaint BEV MR Bi	5.0E58	1.5E59	1.0E59	-7.2E-15	2.8E-14	8.7E-15
Cmaint BEV MR Mo	5.0E59	1.5E60	1.0E60	6.9E-03	2.5E-02	1.3E-02
Cmaint Bus CNG	1.9E61	5.6E61	3.7E61	0.0E60	7.1E-15	1.0E-15
Cmaint Bus Diesel	1.9E62	5.6E62	3.7E62	-3.0E-14	7.7E-14	1.7E-14
Cmaint Bus EV Bi	1.5E63	4.4E63	2.9E63	-3.6E-08	7.5E-07	1.8E-07
Cmaint Bus EV Mo	1.5E64	4.4E64	2.9E64	-1.3E-14	7.5E-14	3.0E-14
Cmaint Bus FC	1.5E65	4.4E65	2.9E65	1.3E-14	2.5E-14	5.5E-15
Cmaint Bus Hy	1.9E66	5.6E66	3.7E66	6.7E-15	1.2E-14	3.0E-15
Cmaint Car A10	1.2E67	3.6E67	2.4E67	-2.8E-14	7.9E-14	3.5E-14
Cmaint Car A80	1.2E68	3.6E68	2.4E68	3.9E-09	8.2E-09	1.2E-09
Cmaint Car BEV LR Bi	5.0E68	1.5E69	1.0E69	-1.8E-15	1.3E-14	4.6E-15
Cmaint Car Diesel	1.2E70	3.6E70	2.4E70	-2.4E-14	8.4E-14	3.9E-14
Cmaint Car E10	1.2E71	3.6E71	2.4E71	-1.6E-07	6.2E-07	1.5E-07
Cmaint Car E85	1.2E72	3.6E72	2.4E72	-1.6E-07	3.4E-06	5.7E-07
Cmaint Car FC	5.0E72	1.5E73	1.0E73	6.6E-03	1.2E-02	5.5E-03
Cmaint Car Gasoline	1.2E74	3.6E74	2.4E74	-1.1E-14	5.5E-14	1.8E-14
Cmaint Car HEV	1.7E75	5.1E75	3.4E75	-9.2E-15	9.8E-07	1.4E-07
Cmaint Car NG	1.2E76	3.6E76	2.4E76	6.2E-02	8.1E-02	6.6E-02
Cmaint Car PHEV Bi	1.7E77	5.1E77	3.4E77	1.1E-06	2.4E-06	3.4E-07
Cmaint Car PHEV Mo	1.7E78	5.1E78	3.4E78	1.7E-02	3.6E-02	7.1E-03
Cmaint Cat BEV LR Mo	5.0E78	1.5E79	1.0E79	6.7E-02	2.8E-02	6.6E-02
Cmaint Coach CNG	2.6E80	7.8E80	5.2E80	-2.8E-14	1.1E-06	2.2E-07
Cmaint Coach Diesel	2.6E81	7.8E81	5.2E81	-4.7E-15	7.1E-14	2.3E-14
Cmaint Coach EV Bi	2.1E82	6.2E82	4.1E82	-3.2E-07	7.2E-04	1.0E-04
Cmaint Coach EV Mo	2.1E83	6.2E83	4.1E83	3.6E-03	2.0E-02	5.8E-03

Parameter	Min	Max	Base	μ	σ	μ^*
Cmaint Coach FC	2.1E84	6.2E84	4.1E84	-2.7E-07	5.7E-07	8.0E-08
Cmaint Coach Hy	2.6E85	7.8E85	5.2E85	5.6E-14	1.2E-06	2.4E-07
Cmaint Dec Solar	4.3E85	1.3E86	8.6E85	1.8E-02	7.0E-18	1.8E-02
Cmaint DHN Boiler Gas	6.3E-01	1.9E86	1.3E86	1.3E-03	1.7E-03	1.5E-03
Cmaint DHN Boiler Oil	6.3E-01	1.9E87	1.3E87	1.7E-03	1.6E-03	1.8E-03
Cmaint DHN Boiuler Wood	1.2E88	3.7E88	2.5E88	-2.4E-15	1.1E-03	1.5E-04
Cmaint DHN Cogen Gas	2.0E90	6.0E90	4.0E90	7.2E-15	4.9E-14	1.7E-14
Cmaint DHN Cogen Waste	6.0E91	1.8E92	1.2E92	-1.7E-13	3.7E-13	1.4E-13
Cmaint DHN Cogen Wood	2.2E92	6.5E92	4.3E92	-1.6E-06	3.4E-06	4.8E-07
Cmaint DHN Geothermal	3.0E93	9.0E93	6.0E93	5.4E-15	2.2E-13	9.6E-14
Cmaint DHN HP	6.4E93	1.9E94	1.3E94	8.5E-02	6.4E-02	8.7E-02
Cmaint Geothermal	2.3E96	7.0E96	4.7E96	1.5E95	1.4E-14	1.5E95
Cmaint Hydro Dam	1.2E96	3.6E96	2.4E96	1.0E95	9.0E-16	1.0E95
Cmaint Hydro River	2.7E97	8.1E97	5.4E97	1.7E96	1.6E-15	1.7E96
Cmaint IND Cogen Gas	4.9E98	1.5E99	9.9E98	-1.4E-06	2.9E-06	4.1E-07
Cmaint IND Cogen Waste	6.0E99	1.8E100	1.2E100	-6.4E-14	3.4E-06	4.8E-07
Cmaint IND Cogen Wood	2.2E100	6.5E100	4.3E100	0.0E99	9.9E-14	2.5E-14
Cmaint PV	8.0E100	2.4E101	1.6E101	2.5E100	2.2E-15	2.5E100
Cmaint Train Elec	7.0E101	2.1E102	1.4E102	2.6E-02	1.3E-02	2.8E-02
Cmaint Train Freight	5.5E102	1.7E103	1.1E103	2.4E-02	1.5E-02	2.6E-02
Cmaint Train Freight Diesel	5.5E103	1.7E104	1.1E104	-1.7E-07	1.7E-06	3.4E-07
Cmaint Tramway	4.8E105	1.4E106	9.6E105	4.3E-14	1.6E-13	4.4E-14
Cmaint Truck	4.5E105	1.4E106	9.0E105	7.4E-08	1.3E-06	2.0E-07
Cmaint Truck CO2	4.5E106	1.4E107	9.0E106	-2.4E-14	1.5E-07	2.1E-08
Cmaint Truck EV Bi	3.5E107	1.1E108	7.0E107	5.8E-03	5.8E-03	6.4E-03
Cmaint Truck EV Mo	3.5E108	1.1E109	7.0E108	5.4E-03	5.7E-03	4.0E-03
Cmaint Truck FC	4.5E109	1.4E110	9.0E109	-2.4E-15	2.3E-14	9.3E-15
Cmaint Truck SNG	4.5E110	1.4E111	9.0E110	-7.0E-08	1.5E-07	2.1E-08
Cmaint Wind	1.1E112	3.4E112	2.3E112	1.3E111	9.0E-16	1.3E111
Cop Coal	1.5E-02	4.5E-02	3.0E-02	-2.5E-17	1.6E-16	4.6E-17
Cop Diesel	7.1E-02	2.2E-01	1.4E-01	-2.6E-17	2.9E-16	1.0E-16
Cop Electricity	4.5E-01	1.4E114	9.0E-01	-9.8E-16	2.1E-15	5.6E-16
Cop Ethanol	1.3E-01	3.9E-01	2.6E-01	-1.3E-10	2.8E-10	4.0E-11
Cop Gasoline	9.4E-02	2.8E-01	1.9E-01	-3.4E-17	7.3E-16	3.2E-16
Cop Jetfuels	9.5E-02	2.9E-01	1.9E-01	6.9E-17	2.6E-16	5.7E-17
Cop LFO	7.5E-02	2.3E-01	1.5E-01	-1.4E-17	4.3E-16	1.1E-16
Cop Methanol	3.6E-02	1.1E-01	7.2E-02	2.0E-17	2.1E-09	3.0E-10
Cop NG	1.8E-02	5.3E-02	3.5E-02	3.6E-04	4.7E-04	1.6E-04

Parameter	Min	Max	Base	μ	σ	μ^*
Cop Uranium	2.1E-03	6.2E-03	4.1E-03	5.3E-04	2.5E-04	5.4E-04
Cop Wood	4.7E-02	1.4E-01	9.3E-02	1.0E-16	1.3E-09	1.8E-10
Deand HLTHW SE	1.2E126	3.6E126	2.4E126	7.5E123	2.9E123	7.3E123
Demand Elec In	3.2E127	9.6E127	6.4E127	4.7E125	2.0E125	4.7E125
Demand Electricity HH	6.8E128	2.0E129	1.4E129	2.5E127	9.5E126	2.1E127
Demand Electricity SE	7.9E129	2.4E130	1.6E130	3.0E128	1.1E128	2.8E128
Demand HHT In	1.8E130	5.4E130	3.6E130	8.1E127	1.6E127	8.0E127
Demand HLTHW HH	3.5E132	1.0E133	6.9E132	6.8E131	2.1E131	6.2E131
Demand HLTHW IN	6.6E131	2.0E132	1.3E132	2.4E129	7.9E-01	2.2E129
Demand HLTSH HH	6.9E134	2.1E135	1.4E135	3.7E134	1.2E134	3.5E134
Demand HLTSH IN	2.1E134	6.4E134	4.3E134	3.3E132	5.1E132	3.8E132
Demand HLTSH SE	5.9E136	1.8E137	1.2E137	2.4E136	1.1E136	2.4E136
Demand Mobility Freight	2.0E137	6.0E137	4.0E137	4.7E135	9.5E134	4.3E135
Demand Mobility Pass LD	2.0E138	6.1E138	4.0E138	2.0E137	4.9E136	2.1E137
Demand Mobility Pass SD	5.0E139	1.5E140	1.0E140	7.8E138	2.0E138	7.5E138
GWP Bus CNG	5.8E140	1.7E141	1.2E141	-1.5E-13	3.3E-13	1.1E-13
GWP Bus Diesel	5.8E141	1.7E142	1.2E142	0.0E140	1.9E-06	2.7E-07
GWP Bus EV Bi	7.6E142	2.3E143	1.5E143	1.4E-14	1.7E-13	4.1E-14
GWP Bus EV Mo	7.6E143	2.3E144	1.5E144	-6.8E-14	2.5E-06	3.5E-07
GWP Bus FC	8.8E144	2.6E145	1.8E145	0.0E143	5.5E-13	2.0E-13
GWP Bus Hy	5.8E145	1.7E146	1.2E146	0.0E144	2.4E-13	8.5E-14
GWP Car A10	1.7E147	5.2E147	3.5E147	9.4E-14	1.0E146	1.4E145
GWP Car A80	1.7E148	5.2E148	3.5E148	-4.7E-13	1.1E-12	4.7E-13
GWP Car BEV LR Bi	1.9E149	5.8E149	3.9E149	1.4E-13	1.3E-12	5.7E-13
GWP Car BEV LR Mo	1.9E150	5.8E150	3.9E150	3.0E-06	6.3E-06	8.9E-07
GWP Car BEV MR Bi	6.6E151	2.0E152	1.3E152	-1.2E-13	2.8E-12	8.0E-13
GWP Car BEV MR Mo	6.6E152	2.0E153	1.3E153	-2.4E-13	1.7E-02	2.4E-03
GWP Car Diesel	1.7E153	5.2E153	3.5E153	-3.1E-13	7.7E-13	2.8E-13
GWP Car E10	1.7E154	5.2E154	3.5E154	-2.5E-13	1.7E-08	2.4E-09
GWP Car E85	1.7E155	5.2E155	3.5E155	-2.3E-05	4.9E-05	8.2E-06
GWP Car FC	3.9E156	1.2E157	7.9E156	5.0E-13	9.5E-13	3.0E-13
GWP Car Gasoline	1.7E157	5.1E157	3.4E157	1.5E-13	1.6E-11	2.6E-12
GWP Car HEV	2.6E158	7.8E158	5.2E158	-4.7E-14	1.7E-12	7.0E-13
GWP Car NG	1.7E159	5.1E159	3.4E159	2.1E-19	7.7E-13	3.5E-13
GWP Car PHEV Bi	2.6E160	7.8E160	5.2E160	4.2E-13	1.2E-12	3.5E-13
GWP Car PHEV Mo	2.6E161	7.8E161	5.2E161	-5.6E-13	7.2E-06	1.0E-06
GWP Coach CNG	5.8E161	1.7E162	1.2E162	-1.0E-14	1.8E-13	6.9E-14
GWP Coach Diesel	5.8E162	1.7E163	1.2E163	-8.4E-14	4.2E-13	1.5E-13

Parameter	Min	Max	Base	μ	σ	μ^*
GWP Coach EV Bi	9.0E163	2.7E164	1.8E164	-1.6E-13	4.5E-06	1.1E-06
GWP Coach EV Mo	9.0E164	2.7E165	1.8E165	-2.5E-06	5.2E-06	7.4E-07
GWP Coach FC	6.4E165	1.9E166	1.3E166	2.3E-14	4.3E-13	1.6E-13
GWP Coach Hy	5.7E166	1.7E167	1.1E167	7.4E-07	1.6E-06	2.2E-07
GWP dec Solar	1.1E168	3.3E168	2.2E168	8.0E-14	8.5E-06	2.0E-06
GWP DHN Boiler Gas	6.1E167	1.9E168	1.2E168	-1.1E-15	2.0E-07	2.9E-08
GWP DHN Boiler Oil	6.1E168	1.9E169	1.2E169	-8.7E-08	2.9E-07	7.4E-08
GWP DHN Boiler Wood	1.5E170	4.3E170	2.9E170	2.6E-15	8.3E-07	1.2E-07
GWP DHN Cogen Gas	2.5E172	7.4E172	4.9E172	4.4E-14	6.7E-13	1.3E-13
GWP DHN Cogen Waste	3.2E173	9.7E173	6.5E173	-1.0E-12	2.2E-12	8.6E-13
GWP DHN Cogen Wood	8.2E173	2.5E174	1.7E174	0.0E172	3.2E-13	9.4E-14
GWP DHN Geothermal	4.1E175	1.2E176	8.1E175	7.3E-14	4.1E-13	1.1E-13
GWP DHN HP	8.8E175	2.6E176	1.8E176	-2.1E-13	2.9E-06	4.1E-07
GWP Geothermal	1.2E179	3.7E179	2.5E179	9.0E-12	8.4E-04	2.6E-04
GWP Hydro Dam	8.4E178	2.5E179	1.7E179	1.3E-05	4.3E-05	1.1E-05
GWP Hydro River	6.3E179	1.9E180	1.3E180	-5.7E-13	3.0E-05	5.9E-06
GWP IND Cogen Gas	5.1E180	1.5E181	1.0E181	0.0E178	1.1E-12	2.2E-13
GWP IND Cogen Waste	3.2E181	9.7E181	6.5E181	2.9E-13	1.8E-12	6.7E-13
GWP IND Cogen Wood	8.2E181	2.5E182	1.7E182	4.5E-14	2.5E-13	5.4E-14
GWP PV	1.0E184	3.1E184	2.1E184	-1.5E-08	7.3E-05	2.3E-05
GWP Train Elec	1.3E183	3.8E183	2.5E183	-3.4E-07	7.2E-07	1.0E-07
GWP Train Freight	1.3E184	3.8E184	2.5E184	-2.3E-15	8.3E-14	3.3E-14
GWP Train Freight Diesel	1.3E185	3.8E185	2.5E185	-9.0E-15	5.4E-14	1.8E-14
GWP Tramway	5.5E185	1.7E186	1.1E186	1.0E-15	1.8E-07	2.6E-08
GWP Truck	5.7E187	1.7E188	1.1E188	3.1E-14	1.9E-06	2.6E-07
GWP Truck CO2	5.7E188	1.7E189	1.1E189	1.1E-13	3.3E-13	9.8E-14
GWP Truck EV Bi	1.2E190	3.7E190	2.4E190	-1.6E-06	5.7E-06	1.4E-06
GWP Truck EV Mo	1.2E191	3.7E191	2.4E191	-1.5E-12	3.3E-12	7.0E-13
GWP Truck FC	8.0E191	2.4E192	1.6E192	0.0E190	1.1E-13	3.9E-14
GWP Truck SNG	5.7E192	1.7E193	1.1E193	-3.1E-14	2.5E-13	7.7E-14
GWP Wind	3.1E194	9.3E194	6.2E194	1.4E-05	2.6E-05	6.8E-06
Share Freight Train Max	2.3E-01	8.0E-01	5.2E-01	-7.7E-04	6.7E-04	7.4E-04
Share Heat DHN Max	1.5E-01	7.5E-01	4.5E-01	-7.5E-04	1.2E-03	3.1E-04
Share Mobility Local Public Max	2.1E-01	4.0E-01	3.1E-01	-3.4E-03	1.7E-03	3.3E-03
Share Mobility Longd Public Max	2.1E-01	5.0E-01	3.6E-01	-4.9E-03	2.5E-03	4.4E-03

Appendix G

Monte Carlo

Table G.1: Monte Carlo input parameters Germany

Parameter	Base	Dev	StDev
Cinv_Car_BEV_LR_Mo	5.5E2	1.65E2	9.53E1
Cinv_Car_BEV_MR_Mo	1.33E4	3.99E3	2.3E3
Cinv_Car_FC	1.45E5	4.35E4	2.51E4
demand_mob_pass_sd	1E8	3E7	1.73E7
demand_mob_pass_ld	4.03E8	1.21E8	6.98E7
demand_mob_freight	3.97E9	1.19E9	6.88E8
demand_elec_hh	1.36E10	4.08E9	2.36E9
demand_hltsh_hh	1.39E12	4.17E11	2.41E11
demand_hlthw_hh	6.92E12	2.08E12	1.2E12
demand_elec_se	1.58E13	4.74E12	2.74E12
demand_hltsh_se	1.19E15	3.57E14	2.06E14
Cop_Uranium	4.1E-03	1.23E-03	7.1E-04
Cinv_dec_Solar	7.68E14	2.3E14	1.33E14
Cinv_Geothermal	1.15E17	3.45E16	1.99E16
Cinv_Hydro_Dam	4.83E17	1.45E17	8.37E16
Cinv_Hydro_River	5.39E18	1.62E18	9.34E17
Cinv_PV	1E19	3E18	1.73E18
Cinv_Wind	1.47E20	4.41E19	2.55E19
Cmaint_Geothermal	4.65E20	1.4E20	8.05E19
fmax_PV	1.5E21	4.5E20	2.6E20
fmax_Wind_On	1.07E22	3.21E21	1.85E21
fmax_Wind_Off	1.06E23	3.18E22	1.84E22

Table G.2: Monte Carlo input parameters France

Parameter	Base	Dev	StDev
Cinv_Car_BEV_LR_Mo	5.5E2	1.7E2	9.5E1
Cinv_Car_BEV_MR_Mo	1.33E4	3.99E3	2.30E3
Cinv_Car_FC	1.45E5	4.35E4	2.51E4
demand_mob_pass_sd	6.851E8	2.0553E8	1.186E8
demand_mob_pass_ld	6.939E9	2.0817E9	1.201E9
demand_mob_freight	4.747E10	1.4241E10	8.222E9
demand_elec_hh	5.4E10	1.62E10	9.353E9
demand_hltsh_hh	2.912E12	8.736E11	5.0437E11
demand_hlthw_hh	4.47E12	1.341E12	7.7422E11
demand_elec_se	1.124E14	3.372E13	1.946E13
demand_hltsh_se	1.238E15	3.714E14	2.144E14
Cop_Uranium	4.1E-03	1.2E-03	7.1E-04
Cinv_dec_Solar	7.68E14	2.30E14	1.33E14
Cinv_Geothermal	1.15E17	3.45E16	1.99E16
Cinv_Hydro_Dam	4.83E17	1.45E17	8.37E16
Cinv_Hydro_River	5.39E18	1.62E18	9.34E17
Cinv_PV	1E19	3E18	2E18
Cinv_Wind	1.47E20	4.41E19	2.55E19
Cmaint_Geothermal	4.65E20	1.40E20	8.05E19
fmax_PV	3.5E21	1.05E21	6.06217782649107E20
fmax_Wind_On	8.13E22	2.439E22	1.408E22
fmax_Wind_Off	1.75E23	5.25E22	3.03E22

Appendix H

Vehicle databases

H.1 Electric vehicles data

H.1.1 Battery Electric vehicles

Collected data for the battery electric vehicles (Table 2.4).

Table H.1: Database battery electric vehicles

Type	Seg.	Range [km]	Battery Capacity [kWh]	Price [kCHF]
Aiways U5 [70]	c	340	65	35
Audi e-tron GT [71]	f	425	93.4	125
Audi e-tron Q4	d	400	82	55
Audi e-tron 50	e	285	71	69.1
Audi e-tron Sportback 55	e	385	95	83.15
Audi e-tron 55	e	370	95	80.9
Audi e-tron Sportback 50	e	290	71	71.35
Audi e-tron s Sportback 55	e	370	95	105
Audi e-tron s 55	e	355	95	102
BMW i3 [72]	b	235	42.2	38
BMW i3s	b	230	42.2	41.6
BMW i4	d	450	80	65
BMW iX2	d	350	80	70
Byton M-Byte 4WD [73]	e	390	105	64
Byton M-Byte 2WD	e	400	105	62
Byton M-Byte 72 2WD	e	325	80	53.5
Citroën C-Zero [74]	a	90	16	21.8
DS 3 Crossback E-Tense [75]	b	275	50	35.25
Ford Mustang ER [76]	d	430	98.8	62.9
Ford Mustang SR	d	340	75.7	54

Type	Seg.	Range [km]	Battery Capacity [kWh]	Price [kCHF]
Ford Mustang SR RWD	d	360	75.7	46.9
Ford Mustang ER RWD	d	450	98.9	54.75
Honda e [77]	b	200	35.5	33.85
Honda e-Advance	b	200	35.5	36.85
Hyundai IONIQ [78]	c	260	38.3	34.9
Hyundai Kona 39	b	250	42	34.4
Hyundai Kona 64	b	400	67.1	41.4
Jaguar I-Pace [79]	e	370	90	79.45
Kia e-Niro 64 [80]	c	375	67.1	39.1
Kia e-Niro 39	c	240	42	35.29
Kia e-Soul 64	b	370	67.1	37.79
Kia e-Soul 39	b	230	42	33.99
Lexus UX 300e [81]	d	425	54.3	45
Lightyear One [82]	f	575	60	149
Lucid Air [83]	f	350	75	75
Mazda MX 30 [84]	c	180	35.5	33.9
Mercedes-Benz EQA [85]	c	350	60	45
Mercedes-Benz EQC	d	360	85	71.28
MG ZS EV [86]	b	230	44.5	30
Mini Cooper SE	b	185	32.6	32.5
Nissan Evalia [87]	n	190	40	43.433
Nissan Leaf	c	220	40	36.8
Nissan Leaf e+	c	330	62	44.7
Opel Ampera e [88]	b	345	60	42.99
Opel Corsa e	b	290	50	29.9
Peugeot e-2008 [89]	b	275	50	35.25
Peugeot e-208	b	295	50	30.45
Peugeot iON	a	90	16	21.8
Peugeot Tepee	n	110	22.5	30.47
Polestar 2 [90]	d	425	78	58.9
Porsche Taycan Turbo S [91]	f	380	93.4	185.45
Porsche Taycan 4S	f	370	79.2	105.607
Porsche Taycan Cross T	f	385	93.4	150
Porsche Taycan 4S +	f	430	93.4	112.128
Porsche Taycan Turbo	f	395	93.4	152.136
Renault Kangoo ZE	n	165	33	38
Renault Twingo ZE	a	130	23	21.5
Renault Zoe R110 [92]	b	320	55	31.99

Type	Seg.	Range [km]	Battery Capacity [kWh]	Price [kCHF]
Renault Zoe R135	b	315	55	33.99
Renault Zoe ZE40	b	255	44.1	29.99
Seat el-Born [93]	c	350	62	37.5
Seat Mii E	a	200	36.8	20.65
Skoda CITIGOe	a	200	36.8	20.95
Skoda ENYAQ	d	400	82	35
Smart EQ forfour [94]	a	95	17.6	22.6
Smart EQ fortwo coupe	a	100	17.6	21.94
Smart EQ fortwo cabrio	a	95	17.6	25.2
Sono Sion [95]	c	225	35	25.5
Tesla Cybertruck Tri [96]	n	750	200	75
Tesla Cybertruck Single	n	390	100	45
Tesla Cybertruck Dual	n	460	120	55
Tesla Model 3 RD	d	460	75	54.77
Tesla Model 3 SR	d	265	50	43.55
Tesla Model 3 R+	d	315	50	46.77
Tesla Model 3 LR Perf.	d	445	75	58.77
Tesla Model S LR	f	525	100	86.8
Tesla Model S Performance	f	510	100	102.7
Tesla Model X Long Range	f	460	100	91.7
Tesla Model X Performance	f	445	100	107.6
Tesla Model Y Dual	d	425	75	58.62
Tesla Model Y Performance	d	410	75	65.62
Tesla Roadster	s	970	200	215
Volkswagen e-Golf [97]	c	190	35.8	31.9
Volkswagen e-Up!	a	200	36.8	21.97
Volkswagen ID.3 Pure	c	275	49	30
Volkswagen ID.3 Pro S	c	450	82	40
Volkswagen ID.3 Pro	c	350	62	35
Volkswagen ID.4	d	425	82	45
Volvo XC40 P8 [98]	c	375	78	62

H.1.2 Plug-In Hybrid Vehicles

Collected data for the battery electric vehicles (Table 2.4).

Table H.2: Database plug-in electric hybrid vehicles

Type	R. El. [km]	R. Fu. [km]	Bat. Cap. [kWh]	Price [kCHF]
Audi A3 etron	45	420	13	59.5
Audi A6 TFSI e	45	500	14.1	69.85
Audi A7 TFSI e	45	520	14.4	67.9
Audi A8 TFSI e	45	580	14.1	107.81
Audi Q5 TFSI e	45	540	14.1	61.35
Audi Q7 TFSI e	45	500	14.4	76.75
BMW 225 xe	37	270	10	40.25
BMW 330 e	45	320	12	43.2
BMW 530 e	43	370	12	53.35
BMW 530e xDrive	42	330	12	55.65
BMW 745e	34	310	12	87.7
BMW 745Le xDrive	34	300	12	95.4
BMW i8 Coupe	43	340	11.7	131.05
BMW i8 Roadster	40	320	11.7	144.7
BMW X1 xDrive25e	34	270	10	43.55
BMW X3 xDrive30e	35	350	13	54.2
BMW X5 xDrive45e	55	390	24	72
Hyundai IONIQ Plug-In	42	510	8.9	34.15
Kia Niro PHEV	35	470	8.9	36.4
Range Rover P400e	27	440	12.4	99.85
Range Rover Sport P400e	29	480	12.4	82.3
Mercedes C 300 de Saloon	40	630	13.5	49.05
Mercedes C300 de	39	600	13.5	50.4
Mercedes E300 de	35	520	13.5	56.65
Mercedes E300 de Saloon	37	570	13.5	54.4
Mercedes E300 e Saloon	39	440	13.5	54.1
Mini Countryman S E	26	300	7.6	36.35
Mitsubishi Outlander PHEV	37	350	13.8	41.9
Peugeot 3008 SUV HYbrid4	39	360	13.2	53.3
Porsche Cayenne E-Hybrid	31	400	14.1	76.55
Porsche Panamera 4 EHy	39	500	14.1	92.5
Porsche Panamera 4S T EHy	37	480	14.1	99.05
Porsche Panamera S T EHy	35	380	14.1	160.6

Type	R. El. [km]	R. Fu. [km]	Bat. Cap. [kWh]	Price [kCHF]
Porsche Panamera T S EHy	35	430	14.1	158.15
Skoda Superb iV Estate	40	410	13	42.55
Skoda Superb iV Hatch	43	420	13	41.1
Toyota Prius PHEV	40	520	8.8	36.6
Vauxhall Grandland X Hy 4	39	360	13.2	40.55
Volkswagen Passat GTE B	40	410	13	43.65
Volkswagen Passat GTE C	43	420	13	41.7
Volvo S60 Polestar	35	520	11.6	63.95
Volvo S60 T8	35	520	11.6	56.8
Volvo S90 T8	35	480	11.6	65.75
Volvo V60 Polestar	34	520	11.6	65.2
Volvo V60 T8	34	520	11.6	58.05
Volvo V90 T8	32	480	11.6	68
Volvo XC40 T5	29	400	10.3	46.65
Volvo XC60 Polestar	27	560	11.6	73.6
Volvo XC60 T8	29	570	11.6	62.7
Volvo XC90 T8	26	520	11.6	76

H.2 Combustion vehicles

The data figured in table H.3 corresponds to the natural gas cars available in Switzerland on 01 January 2020.

Table H.3: Database natural gas combustion engine cars Switzerland (2020).

Type	Power [kW]	Consumption [kg/100km]	Range [km]	CO2 emission [g/km]	Price [kCHF]
Audi A3 Sportback g-tron	96	3.5	490	95	38.12
Audi A4 Avant g-tron	125	4	468	105	49.64
Audi A5 Sportback g-tron	125	4	468	104	51.75
Fiat Panda Natural Power	52	3.5	340	97	12.59
Fiat Qubo Natural Power	51	4.9	300	109	15.64
Fiat Doblo Natural Power	88	5.9	270	161	19.2
Lancia Ypsilon EcoChic	52	3.5	340	97	16.92
Opel Astra 1.4 ECOTEC	81	4.1	420	113	19.99
Opel Combo 1.4 CNG	88	4.97	325	134	18.45
Seat Mii Ecofuel	50	3	360	82	16.28
Seat Ibiza TGI	66	3.3	410	92	15.55
Seat Leon TGI	96	3.5	480	98	22.35
Seat Arona TGI	66	3.5	410	98	17.85
Skoda Citigo G-TEC	50	2.9	350	81	17.2
Skoda Octavia G-TEC	81	3.5	410	97	37
Volkswagen eco up!	50	2.9	360	81	16.11
Volkswagen Polo TGI	66	3.3	390	88	23.76
Volkswagen Golf TGI	96	3.6	490	95	32.7
Volkswagen Variant TGI	81	3.6	480	99	37.78
Volkswagen Caddy TGI	81	4.6	600	126	29.62

H.3 Global Warming Potential

Table H.4: Specific Global warming potential private mobility vehicles construction `https://www.ecoinvent.org/home.html`.

	gwp weight [kg $CO_{2,\mathrm{equ}}/\mathrm{kg}$]	gwp battery [kg $CO_{2,\mathrm{equ}}/\mathrm{kWh}$]	gwp other [kg $CO_{2,\mathrm{equ}}/\mathrm{unit}$]
BEV LR	9.1442	168	-
BEV MR	9.1442	168	-
PHEV	9.1442	168	-
NG & Gasoline	8.2413	-	-
Diesel	8.3278	-	-
Fuel Cell	8.2413	-	21119
Other	8.2413	-	-