# An analysis of the impacts of green mobility strategies and technologies on different European energy systems

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**Abstract:**
A successful decarbonization of the European Union, coupled with a high integration of renewable energy and ambitious targets for energy efficiency, can only be reached with a significant contribution from transport. This sector currently represents a quarter of the total greenhouse gas emissions and is shifting from fossil fuels to alternative energy carriers and propulsion systems. Decarbonizing this sector can follow multiple pathways, each having different costs, impacts and implications for the other sectors (industry, residential and services). This paper focuses on the impact of different decarbonization paths in the mobility sector on the whole energy system of a country. The hourly and monthly resolution model named EnergyScope was used and applied to three European countries with different characteristics, namely France, Germany and Switzerland. Their energy resources, demands and policies are strongly different, which has an impact on the preferred decarbonization pathway to follow, and on its final costs and environmental impacts.
Regardless of the case study, the most cost- and energy-efficient pathway to decarbonize road and rail mobility is through a heavy electrification, with short-range electric vehicles and buses for local mobility, and either hydrogen or long-range electric vehicles for long-distance. The most cost-optimum vehicle fleet depends strongly on the projected costs of fuel cell and batteries in the upcoming year, as well as on the wind and solar energy potential. Large-scale deployment of biofuels seems improper for road transport because of the small potentials for sustainable biomass harvesting and the high installation costs of direct air capture, but may be the only viable solution for aviation.

**Keywords:**
Energy transition; Energy system modelling; Mobility; Decarbonisation

## 1. Introduction

## 1.1. Background

The world's primary energy consumption has increased by a factor 2.4 over the last 40 years and is driven at more than 80 % by the use of fossil fuels such as coal, natural gas and oil [1]. The 2000-2010 period was characterised by a strong rise in the use of coal, especially in China, and was followed by an exponential growth of renewable energies with a penetration slightly above 5 % in 2019.

In the European Union (EU), the growing concerns over climate change and security of energy supply have pushed politicians and stakeholders to commit to a shift from fossil fuels to renewable energies, as shown with the "Energy Roadmap 2050" within the "European Green Deal" [2]. This transition will consist of a reduction in the final energy consumption in all sectors (industry, households, services, agriculture and transport) and the development of renewable energies. Although the average share of renewable energy in the primary EU energy consumption was nearly 20 % in 2019, this value is strongly different at a national level, and from sector to sector.

For example, the transport sector represents about 30 % of the total EU final energy consumption (FEC) and about 25 % of the total EU greenhouse gas emissions (GHG). The share of renewable energy was less than 10 % in 2019 - petroleum-derived fuels such as diesel and gasoline represent the lion's share of the fuels in private and aviation mobility [3]. Regarding private mobility, the penetration of alternative vehicles is expected to increase strongly in the upcoming decade, as illustrated with the higher share of electric vehicles, hybrid

and alternative drives in the sales of new vehicles. Regarding aviation, the development of alternative fuels - biofuels and electrofuels - may put this sector on the way to decarbonisation.

Following these pathways will result in a growing demand on carbon-free electricity (nuclear or renewable) in a period during which (i) several countries, such as Germany and Switzerland, are shutting down nuclear power plants (reduction of installed power capacity of baseload facilities), (ii) the integration of intermittent renewable sources, such as wind and solar, creates stability changes of the electrical grid (need for control strategies, short- and long-term storage systems, peak facilities), (iii) security of supply is increasingly becoming a key issue (reduction of energy imports), and (iv) other sectors, such as the residential and service ones, are getting electrified (higher electricity demand). Electrification of the transportation sector may possibly compete with the electrification of other sectors and impact the deployment of energy conversion and storage technologies. These challenges underline the necessity of analysing cross-sectoral interactions, and therefore of modelling the entire energy system of a country, considering all *sectors* and *energy vectors*.

## 1.2. Literature review

Energy models are well-known in energy planning studies: they are developed widely used as decision-support tools, for example for investigating possible pathways towards zero-emission energy systems. They may consider (i) one specific sector (e.g. industry) (ii) one energy vector (e.g. electricity), (iii) one end-use demands, simplifying the others (e.g. mobility), focus on simulation or optimisation of investment costs or operating ones only [4]. The present work aims at addressing the above-mentioned points by using the open-source model EnergyScope, developed on a month-resolution basis by Moret et al. [5, 6] and on a hourly basis (typical day approach) by Limpens et al. [4]. The model was adapted at a further stage to map $CO_2$-flows and split mobility into short- and long-distance mobility, as presented in Schnidrig et al..

The impact of a shift towards greener mobility, through a combination of electric vehicles (EV), hydrogen fuel cell cars (FCV) and alternative fuels has not been studied in details, although the deployment of the relevant infrastructure is of strong interest for the European Commission [7]. Most focus has been on the large-scale deployment of electric cars, which are the alternative vehicles most deployed at present, with the exception of some countries such as Brazil with ethanol-fuelled cars. A higher penetration of synthetic fuels (biofuels and hydrogen) will likely result in a greater electricity demand, on an *energy* basis, but may not cause disruptive or spiked power peaks as expected with EVs.

As shown with analyses at a city-level by Nematchoua et al. [8] and by Mohammadi and Taylor [9], it is evident that electric vehicles will result in a greater energy use. However, as mentioned by Dixon and Bell [10], the resulting electric demand (amount and shape) from a higher penetration of electric vehicles will change substantially with the individuals' charging behaviours, with peak demands possibly coinciding with residential ones. This is also highlighted in the work of Muratori and Mai [11], where it was shown that the shape of EV charging is highly uncertain, dependent on supply and on the type of interactions with the electric grid, such as vehicle-to-grid services (V2G). The impact of the latter and possible coupling between renewable energy sources and EVs was discussed by Bracco et al. [12] and by Calise et al. [13].

The impact of private mobility electrification was not investigated in details in European countries, although it was analysed in the United States by Muratori [14]. The authors suggest that electrification could shift natural gas consumption between sectors, which shows how the transport sector can be connected to others.

## 1.3. Objectives and contributions

The present paper aims at comparing the *impacts* of a large-scale deployment of various mobility technologies, such as electric vehicles, hydrogen fuel cell cars and alternatively-fuelled vehicles, on the *entire* energy system. These alternatives will be compared based on (i) the need for additional infrastructure, (ii) the installed capacities of energy conversion technologies for electricity and heat production, (iii) the economic costs and environmental impacts of the resulting energy system. To this end, various scenarios with regards to the penetration of each vehicle type and charging strategies were developed for two case studies, France and Germany, which are characterised by different energy systems and policies.

The novel contributions of this paper lie in:

- the use of a multi-sectoral approach for investigating the impact of mobility technology shifts on the entire energy system;
- the systematic comparison of alternative vehicle and propulsion technologies in both public and private

mobility, split into short- and long-distance mobility;

- the application of optimisation and uncertainty tools to depict the most influential parameters when moving towards green mobility
- the application to the case studies of France and Germany

# 2. Methods

## 2.1. Modelling

**Energy system** The present work is based on the use of the open-source energy model EnergyScope, which was used successfully to assess various pathways of the energy transition for countries such as Switzerland and Belgium. The time resolution of the model is either a hourly basis (use of typical days for day clustering over a year) as described in Limpens et al. [4] or a monthly basis, as originally proposed by Moret [6]. The two model versions are characterised by different resolution times (from a few seconds to several minutes) and were both used in this work to assess whether a monthly resolution could be sufficient to predict properly the sizing and operation of a given energy system.

The energy system of a country is represented into three parts: resources (e.g. fossil fuels, renewables and uranium), conversion technologies (e.g. power plants) and demands (e.g. heating, electricity, mobility and non-energy use). The mathematical problem is formulated as a mixed integer linear programming problem (**MILP**) - it aims at *satisfying the demands* by optimising both the design and operation of energy conversion technologies to reduce the system total costs or global warming potential. The demands are formulated as *end-use demands* (EUD), i.e. the actual user demands, and not as *final energy consumption* (FEC). For example:
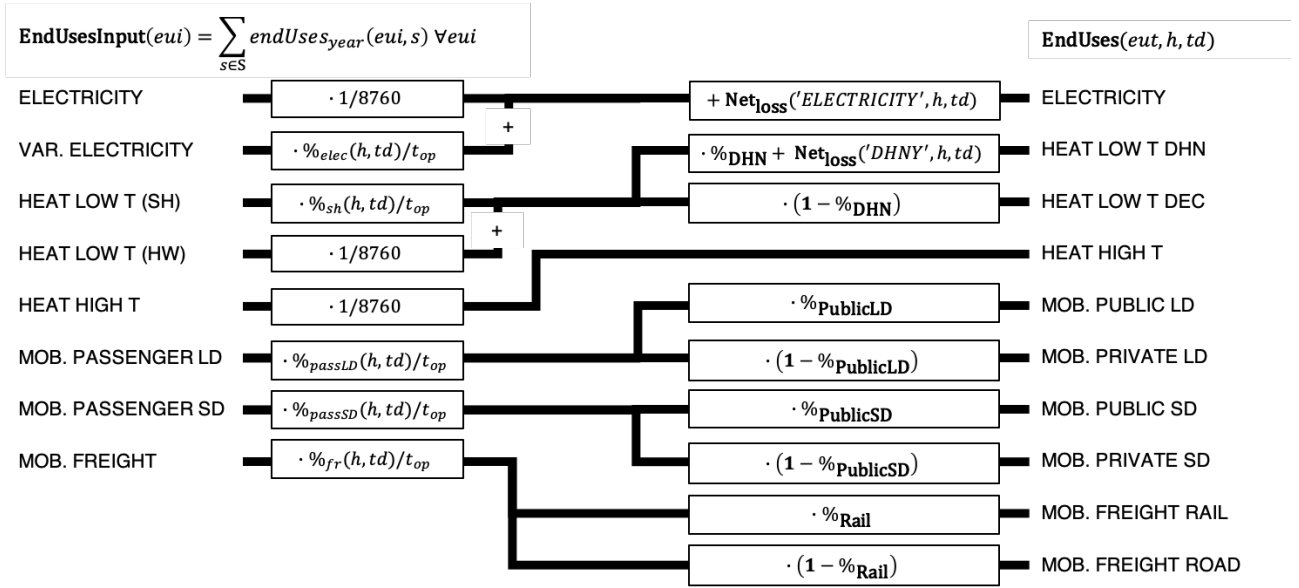
- electricity consumed by a heat pump for space heating is considered as FEC and not EUD, the actual EUD being the need for low-temperature heat in the house;
- gasoline consumed in a car engine is a FEC and not an EUD, as the actual service needed by the user is to move from one place to another.

Four types of end-use demands are considered, namely the electricity, heat, mobility and non-energy demands - they are further split into low- and high-temperature heating, passenger and freight mobility, plastics and other chemicals. Low-temperature heat, for space heating (SH) or hot water (HW) production, can be supplied using centralized (cogeneration plants with district heating) or decentralised (small-scale heat pumps or individual boilers) technologies. Passenger mobility corresponds to the movement of people, by opposition to freight mobility, which corresponds to the transport of goods, and can be either public or private, and for either short or long distances.

End-use demands are usually available in official statistics or EU reports, but are given on a *yearly basis* (e.g. the Statistical Pocketbook Directorate-General for Mobility and Transport [15]) - it is, however, necessary to derive these demands on a *hourly basis* to size properly energy conversion and storage facilities. First of all, regarding the *demands*, there is a higher need for space heating in winter, especially in the morning, than in summer, or of long-distance mobility during weekends and holidays. Regarding *resources*, renewable sources such as wind and solar are intermittent, facing significant variations on a hourly, daily and monthly basis. Hourly profiles are therefore necessary - in the case of the mobility demands, those were derived based on traffic measurements of cities in France and Germany that were assumed representative for the case studies of interest, and the procedure to derive hourly demands from yearly ones is presented in Figure 1.

**Mobility** The present work is based on the EnergyScope model to which the following modifications were made to better represent mobility demands and technologies:

- passenger mobility demand was split into short- and long-distance mobility, with their respective demand profiles, as several models of electric vehicles may be preferably used for short distances only, and create specific spatial and temporal peak demands;
- vehicles running on alternative synthetic fuels, such as blends of ammonia, ethanol, methanol with gasoline, with different fractions were added to the list of energy conversion technologies;
- fuel synthesis processes to produce electrofuels and biofuels were also added to better analyse possible biomass conversion routes and investigate the competition between chemical demands in the transport

3

$$EndUsesInput(eui) = \sum_{s \in S} endUses_{year}(eui, s) \; \forall eui$$

$EndUses(eut, h, td)$

| | | |
|---|---|---|
| ELECTRICITY | $\cdot 1/8760$ | $+ \mathbf{Net_{loss}}('ELECTRICITY', h, td)$ → ELECTRICITY |
| VAR. ELECTRICITY | $\cdot \%_{elec}(h, td)/t_{op}$ | $\cdot \%_{\mathbf{DHN}} + \mathbf{Net_{loss}}('DHNY', h, td)$ → HEAT LOW T DHN |
| HEAT LOW T (SH) | $\cdot \%_{sh}(h, td)/t_{op}$ | $\cdot (1 - \%_{\mathbf{DHN}})$ → HEAT LOW T DEC |
| HEAT LOW T (HW) | $\cdot 1/8760$ | HEAT HIGH T |
| HEAT HIGH T | $\cdot 1/8760$ | $\cdot \%_{\mathbf{PublicLD}}$ → MOB. PUBLIC LD |
| MOB. PASSENGER LD | $\cdot \%_{passLD}(h, td)/t_{op}$ | $\cdot (1 - \%_{\mathbf{PublicLD}})$ → MOB. PRIVATE LD |
| MOB. PASSENGER SD | $\cdot \%_{passSD}(h, td)/t_{op}$ | $\cdot \%_{\mathbf{PublicSD}}$ → MOB. PUBLIC SD |
| MOB. FREIGHT | $\cdot \%_{fr}(h, td)/t_{op}$ | $\cdot (1 - \%_{\mathbf{PublicSD}})$ → MOB. PRIVATE SD |
| | | $\cdot \%_{\mathbf{Rail}}$ → MOB. FREIGHT RAIL |
| | | $\cdot (1 - \%_{\mathbf{Rail}})$ → MOB. FREIGHT ROAD |

**Figure 1**: End-uses calculation starting from yearly demand model inputs (*endUsesInput*). Adapted from Limpens et al. [4]. Abbreviations: space heating (sh), district heating network (DHN), hot water (HW), passenger long distance (passLD), passenger short distance (passSD) and freight (fr).

and non-energy sectors;

- infrastructure costs for the construction of additional charging stations (electric and hydrogen) and for possible changes in user behaviour (higher share of public mobility, multi-modal mobility and higher demand) were assessed and included;
- charging profiles for electric vehicles were derived based on the mobility profile demands for short- and long-distance mobility and on the existing literature in this field.

The methodology details are presented extensively in Schnidrig et al. (2021) and are briefly recalled in the following sections for ease of reading.

**Mobility demands**  The mobility demand is generally expressed in person-km (pkm) for passenger mobility and tons-km (tkm) for freight mobility - passenger mobility was further split into short- and long-distance mobility, based on a threshold value of 80 km to distinguish both [16].

**Hourly profiles of mobility**  The annual mobility demands, whether given for previous years, or predicted over the horizon of 2050, which corresponds to the year that the EU aims to be climate-neutral, were derived on a hourly basis - which is essential to size the mobility infrastructure (charging stations), predict peak electricity demands and better analyse bidirectional electricity transfers between electric vehicles and the power grid (V2G). The short- and long-distance profiles were derived based on traffic measurements for Germany (1513 measurement points) (BAST [17]) and France (367 measurements points) (Opendata Paris [18]).

**Future mobility demands**  The EnergyScope model is a *snapshot* model, meaning it is applied to a specific year, in this case 2017 for model validation and 2050, to derive an energy system without assessing the necessary steps year-by-year to reach it. Energy policies and strategies to achieve those are taken into account in the model by setting constraints on the minimum/maximum capacity or share of a given power plant type - for example, in the case of Germany, all nuclear power plants will have been decommissioned by 2050 without addition of new ones. The projected energy demands were derived using historical data and deriving multi-parameter regressions - in the case of mobility, it was assumed that it is correlated to the gross domestic product (GDP), number of households and population [19]. They are presented in details, for all types of EUD, in Table 5.

**Mobility technologies**    Energy conversion technologies in the EnergyScope model are represented as input-output models, for which a given amount of resources is consumed to generate one to several products. Mobility technologies were modelled as black-boxes, consuming resources such as gasoline, ethanol, ammonia, diesel or a combination of several fuels to satisfy a service expressed in person-km or tons-km. They are associated with a given fuel consumption (fuel efficiency), investment and maintenance costs, and global warming potential. The following vehicles were considered for private mobility: battery electric vehicles with short- and medium-range, fuel cell cars, gasoline and diesel cars, alternatively-fuelled (E10, E90, A10, A80, M10 and M80 - blends of ethanol, ammonia and methanol with diesel at 10, 80 or 90 % volume). Their efficiencies were derived based on informed estimates, assuming the motor efficiency for synthetic fuels would be in the same range as for diesel-run cars, and their costs in 2050 were projected based on learning curves, which are a power function relating the price of a car and the cumulative production at a given year (Weiss et al. [20] for EV and Ruffini et al. [21] for FCV). The $CO_2$-equivalent emissions associated with the construction of cars and batteries were calculated using the Ecoinvent Database .

Electric vehicles may be categorised into two main types, depending on whether the vehicle can only take power from the grid and store it in a battery, to be further used (unilateral transfers - V1G) or if they can communicate with the distribution network and return electricity, which means these batteries can be used as additional grid storage (bidirectional transfers - V2G).

**Infrastructure**    A shift in mobility behaviour and vehicle fleet will induce modifications to the current infrastructure, with possibly more maintenance of railways and roads, deployment of fuel production units and charging stations, etc.. The investment costs of the current *road infrastructure* (roads, railways, waterways) were not taken into account in the energy system cost and assumed depreciated. These costs were therefore estimated neglecting the construction of new roads, assuming that only yearly maintenance is needed with values estimated from historical data [22]. The costs of charging stations (electric) and of fuel production systems were estimated from actual case studies and literature data.

**Hourly profiles of electricity demand**    The hourly profiles of electricity demand for V1G vehicles were derived based on the assumptions that (i) the electricity purchase price is lower in the night time than in the day time, (ii) this price is deemed constant over this period, and the electricity demand in the night for charging of electric vehicles is taken as constant, (iii) battery cars have a cycle behaviour over 24 hours, with a storage level subject to optimisation, but same at 6 AM of every day.

## 2.2.  Optimisation

Several performance indicators were used to assess systematically the economics and environmental impacts of various energy system designs.

**Economic assessment**    The yearly system total cost $\mathbf{C_{tot}}$ is defined as the sum of the investment $\mathbf{C_{inv}}$ annualised with a factor $\tau$ and maintenance $\mathbf{C_{maint}}$ for each technology (tec $\in$ **TEC**) with an installed capacity $\mathbf{F}$, and of the operating costs $\mathbf{C_{op}}$ associated with the consumption $\mathbf{F_t}$ of each resource ($r \in$ **RES**), for each hour ($h \in$ **TIMES**) of each typical day ($td \in$ **PERIODS**).

$$\forall \quad r \in \mathbf{RES},\ tec \in \mathbf{TEC},\ h \in \mathbf{H},\ td \in \mathbf{TD}$$

$$\mathbf{C_{tot}} = \sum_{tec} \mathbf{C_{inv}}(tec) \cdot \boldsymbol{\tau}(tec) + \mathbf{C_{maint}}(\mathbf{tec}) + \sum_{r} \mathbf{C_{op}}(r) \tag{1}$$

$$\mathbf{C_{inv}}(tec) = c_{inv}(tec) \cdot \mathbf{F}(tec) \tag{2}$$

$$\mathbf{C_{maint}}(tec) = c_{maint}(tec) \cdot \mathbf{F}(tec) \tag{3}$$

$$\mathbf{C_{op}}(r) = \sum_{h,td} c_{op}(r) \cdot \mathbf{F_t}(r,h,td) \cdot t_{op}(h,td) \tag{4}$$

**Environmental impacts** The yearly system environmental impact $\mathbf{GWP_{tot}}$ is assessed in terms of $CO_2$-equivalent emissions and is defined as the sum of the global warming impacts during the construction $\mathbf{GWP_{constr}}$ and operation $\mathbf{GWP_{op}}$ phases due to the consumption of carbonaceous fuels.

$$\forall \quad r \in \mathbf{RES}, \; tec \in \mathbf{TEC}, \; h \in \mathbf{H}, \; td \in \mathbf{TD}$$

$$\mathbf{GWP_{tot}} = \sum_{tec} \mathbf{GWP_{constr}}(tec) + \sum_{r} \mathbf{GWP_{op}}(r) \tag{5}$$

$$\mathbf{GWP_{constr}}(tec) = \mathrm{gwp_{constr}}(tec) \cdot \mathbf{F}(tec) \tag{6}$$

$$\mathbf{GWP_{op}}(r) = \sum_{h,td} \mathrm{gwp_{op}}(r) \cdot \mathbf{F_t}(r,h,td) \cdot \mathrm{t_{op}}(h,td) \tag{7}$$

## 2.3. Sensitivity

A Morris screening method [23] was applied to assess and rank the different parameters in terms of influence on the model's objective function value. Despite the drawback of the quantitative nature of the screening, the method allows to classify the parameters in influential and non-influential parameters with a small number of iterations compared to Sobol methods. These methods were used to better understand which factors will mostly influence the design and operation of our future energy systems if we aim at minimising the system costs and environmental impacts. They also allow us to better understand the role of mobility and the impacts of vehicle costs, efficiencies and types.

## 2.4. Case studies

### 2.4.1. France

**Policies** The current electricity generation system in France is mostly based on nuclear power (above 70 %), followed by hydropower. We built our analysis on the assumption that the amount of electricity produced by nuclear power plants will *not* increase above 63 GWh, which is the average value over the last 5 years, and that the share of nuclear will *not* represent more than 50 % by 2050, which corresponds to the commitments in the Programmation Plurianuelle de l'Energie for 2035 [24]. Natural gas and coal-fired plants are uncommon in France and it is not planned to build new ones. The maximum power produced from such plants in 2050 was assumed to be the current power produced by these thermal power plants as of 2017.
As the development of renewable energies, especially wind and solar, is encouraged both at local (regional) and national levels, the minimum capacities of these RES in 2050 were assumed to be at least the *existing ones* as of 2017. A similar reasoning was applied to private and public mobility technologies, for example, it was assumed that the share of electric vehicles in the future will be at least the one as of today, and that the penetration of diesel and gasoline-run cars will only decrease in the future.

**Potentials** The estimations of wind (Table 1) 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). The estimations of the hydroelectricity potential depend on whether technical and economic considerations are taken into account.
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 2). The capacity factors of hydropower vary widely depending on the year and type of plant (run-of-river or lake) [26]. 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.

### 2.4.2. Germany

**Policies** After the Fukushima accident in 2011, the German governments decided to shut down progressively nuclear power plants, and we therefore built our analysis on the assumption no electricity or heat in a future German energy system will come from nuclear.
As the development of renewable energies, especially wind and solar, is encouraged both at local (regional) and national levels, the minimum capacities of these RES in 2050 were assumed to be at least the *existing ones* as

**Table 1**: Potentials for renewable energy integration in France

| Resource | Minimum | Maximum |
|---|---|---|
| Geothermal | 0.73 | 1.39 [GW] |
| Hydro Dam | 19 | 23.354 [GW] |
| Hydro River | 6.33 | 6.33 [GW] |
| Plant | - | 131 [TWh/yr] |
| Solar thermal | 2.63 [GW] | 10.52 [GW] |
| Solar PV | 107 [GW] | 350 [GW] |
| Waste | - | 157 [TWh/yr] |
| Wet biomass | - | 40 [TWh/yr] |
| Wind onshore [25] | 25.4 | 813 [GW] |
| Wind offshore [25] | 6 | 175 [GW] |
| Wood | - | 120 [TWh/yr] |

**Table 2**: 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 |
| 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 |

of 2017. A similar reasoning was applied to private and public mobility technologies, it was assumed that the share of electric vehicles in the future will be at least the one as of today, and that the penetration of diesel and gasoline-run cars will only decrease in the future.

**Potentials**  The estimations of wind (Table 3) and solar potentials vary widely depending on the study and restrictions. 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 Bódis et al. [27], the technically exploitable potential is about 25-36 TWh per year, while the economically exploitable one is about 11-20 TWh.

**Table 3**: Potentials for renewable energy integration in Germany

| Resource | Minimum | Maximum |
|---|---|---|
| Hydro Dam | 11 | 11 [GW] |
| Hydro River | 5 | 5 [GW] |
| Solar PV | 107 [GW] | 350 [GW] |
| Biomass (all types) | - | 335 [TWh/yr] |
| Wind | 0 | 280 [GW] |

The average capacity factors of wind and solar [28] power plants on a typical day basis are derived from the measures of the average monthly capacity factors over the year 2017 (Table 4). For hydropower, the capacity factors vary widely depending on the year and type of plant (run-of-river or lake) [28]. 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 facilities in Germany but represent only about 10 % of the total installed capacity of such plants.

**Validation**  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. For both models,

**Table 4**: 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 |
| Hydro river | 27 | 41 | 57 | 44 | 63 | 60 | 53 | 55 | 59 | 46 | 49 | 55 |

**Table 5**: Projected end-use demands for Germany and France in 2050, excluding aviation and non-energy demands

|  | Households | | Services | | Industry | | Transport | |
|---|---|---|---|---|---|---|---|---|
|  | GER | FRA | GER | FRA | GER | FRA | GER | FRA |
| Electricity [TWh/year] | 35.0 | 54.0 | 152.4 | 112.4 | 272.5 | 192.2 | - | - |
| Heat High T [TWh/year] | 0 | 0 | 0 | 0 | 722.0 | 297.1 | - | - |
| Heat Low T SH [TWh/year] | 312.6 | 291.2 | 193.1 | 123.8 | 61.2 | 79.2 | - | - |
| Heat Low T HW [TWh/year] | 69.2 | 44.7 | 18.8 | 31.0 | 6.4 | 19.8 | - | - |
| Short-distance passenger mobility [Gpkm/year] | - | - | - | - | - | - | 930.1 | 693.9 |
| Long-distance passenger mobility [Gpkm/year] | - | - | - | - | - | - | 284.8 | 474.7 |
| Freight mobility [Gtkm/year] | - | - | - | - | - | - | 988.4 | 685.1 |

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 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).

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.

## 2.5. Scenarios

A *reference scenario* was defined to take into considerations the policies, strategies and constraints (renewable energy potentials and capacities) of France and Germany for the year 2050, and was then used as a baseline to which other scenarios are compared. Various possible scenarios were simulated to investigate the impact of large-scale deployment of specific vehicle fleets or of given energy policies (Table 7).

## 3. Results and discussion

This section presents the main results obtained when optimising potential energy systems in France and Germany - the *optimised* energy systems for the horizon 2050 when minimizing the total system costs or impacts are presented at first. We then illustrate the trade-offs between these optimisation goals in the form of Pareto fronts, where one possible design presents a better-off with respect to the first objective and a worse-off with respect to the second one, when it is compared to the other designs on the same border. These designs are compared regarding the technologies that are deployed and the resources that are consumed, and the impact of

Table 6: 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 (MtCO$_2$/y) | - | - | 556/555 | 448/303 | - | - |

Table 7: Summary of the considered scenarios.

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

various vehicle fleets is assessed in details. Finally, the sensitivity of these results is analysed through Morris screening methods, showing which factors have the biggest impact on the final costs and emissions.

### 3.1. 2050 scenarios

**Cost-optimized scenarios** A cost-optimised energy system, for both France and Germany, in 2050, corresponds to a *large-scale deployment of electric vehicles* in the transport sector, which can be explained by the low costs of EVs, which are predicted to be in the same order of magnitude as of conventional ICEs, and lower

than FCVs. The primary energy usage rate ranges between 1600 and 2000 TWh/year for both countries, which corresponds roughly to the aim of a 2000 W society (Figure 2). The differences between scenarios with different fleet compositions are generally minor ($\pm$ 400 TWh), with the exceptions of scenarios in which cars running on synthetic fuels such as ammonia or methanol in ICEs are promoted, or in which non-renewable fuels (coal, natural gas, oil and uranium, but *not* synthetic gas produced from biomass) are banned. Large-scale deployment of synthetic fuels are associated with greater use of primary energy because of the need for electricity and possibly carbon from biomass to produce them through electrolysis (hydrogen generation).
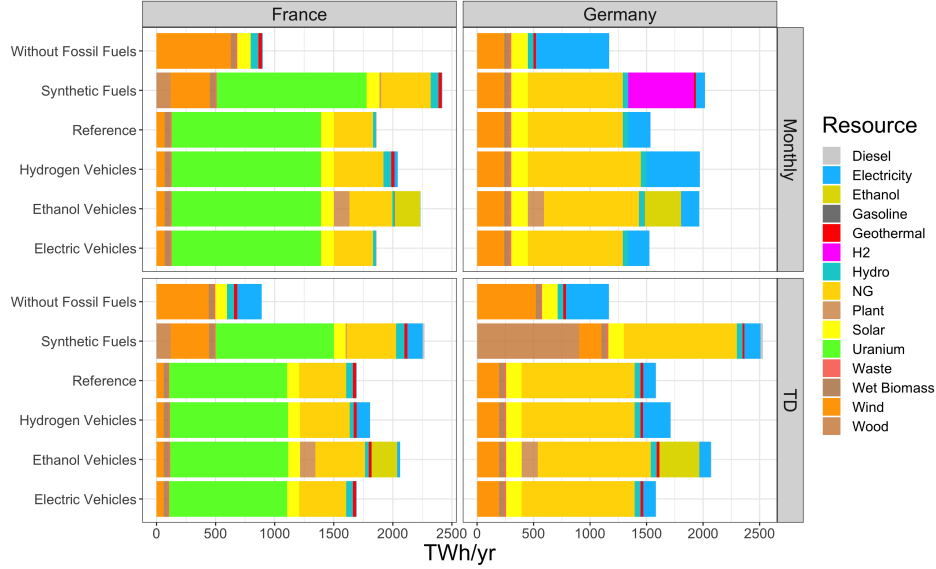


**Figure 2**: Primary energy consumption in France and in Germany for the evaluated 2050 scenarios, cost-optimised, with monthly- and hourly-based models

Without any limitation on $CO_2$-emissions or on resource import, natural gas is one of the most used resource, as it is one of the cheapest fuels and that the associated technologies are mature enough, assuming the price of natural gas does *not* increase significantly by 2050. France seems to build on the use of nuclear as backbone, coupled with the integration of wind and solar for electricity generation and natural gas for heating. On the opposite, Germany seems to rely on a more extensive use of natural gas and wind. It may though import higher quantities of electricity from the neighbouring countries *because of* the lower potential for implementation of solar and wind facilities *and if* the import price of electricity of the neighbouring countries is lower than the cost of electricity from wind and solar. Germany's electricity-producing renewable energy technologies are, independent of the scenario and model, at its maximum potential of 430 TWh/yr. This maximum potential corresponds to the potential deemed economic at present with the current installation restrictions (e.g. distance between windmills and households, protected areas), but these estimates may be different in the future. These trends clearly show how energy policies, taxes and subsidies will impact the design of our future energy systems.

A comparison of the results obtained with the monthly- and hourly-based resolution models shows no major differences for France, but pinpoints differences in the case of Germany when it comes to the penetration of each type of energy source. The *monthly* model suggests the import of hydrogen for the generation of synthetic fuels, whilst the *hourly* 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 *hourly* 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.

The Morris screening method was proved to be efficient to conduct a preliminary identification of influential and non-influential parameters in the case of France. Based on the ranking of these parameters, it is seen that the *resource cost of uranium* is the most influential parameter on the value of the *total system costs*. This can be explained by the large penetration of nuclear power in France and the need for a deeper electrification of its energy system as there is a shift towards heat pumps for heating and electric vehicles for mobility.

Other parameters such as the investment costs of solar PV ($C_{inv}^{PV}$), wind ($C_{maint}^{PV}$), hydro dams ($C_{inv}^{HD}$ and run-of-river ($C_{inv}^{HR}$) have an *influential* but *non-additive* impact. In other words, the potentials of combined solar, wind

and hydro are more than enough to cover the total electricity demand of France, and one energy source could easily be substituted for another one depending on the investment costs of each. This shows that the total cost of a future cost-optimised energy system, for France, may *not* necessarily increase with a higher cost of PV or windmills, and that the two latter may be in competition.

**GWP-optimized scenarios**   A GWP-optimised energy system, for both France and Germany, in 2050, also corresponds to a *large-scale deployment of electric vehicles* in the transport sector. The main differences between these two scenarios lie in the following points:

- the primary energy usage rate for the entire country is lower by about 200 TWh/year compared to the cost-optimised case for both France and Germany, with a bigger reduction, in absolute numbers, for the second country;
- natural gas consumption is negligible in these scenarios, which is as expected as the consumption of fossil gas results in $CO_2$-emissions;
- both French and German energy systems are more electrified (higher share of electricity in the final energy consumption) due to a greater use of electricity across all sectors (EVs in transport, heat pumps for heating in the residential and service sectors);
- solar and wind farms are integrated in both countries with a larger deployment of wind facilities;
- hydro is developed to its full potential in both countries;
- Germany reaches its maximum potential for the deployment of both wind and solar facilities (note that this is the potential judged *economic and socially acceptable* in European statistics);
- geothermal and electricity imports may be necessary in Germany to reduce the total GWP emissions, as the maximum potentials for integration of VRES are reached;
- reaching net-zero emissions is *not* feasible *without* a large-scale deployment of carbon capture and storage facilities based on *direct air capture*, as there are $CO_2$-emissions associated with the construction of each facility type and with the use of petroleum for plastic production.

As for the cost-optimised scenarios, the Morris screening method was used to rank all parameters by order of influence. It is evident that cost-related parameters do not have any impact on the minimisation of the total GWP, if no boundary of the total cost is set. The most influential parameters are the *residential* end-use heating and electricity demands, followed by the end-use demands in the other sectors, and the maximum potentials for installation of the variable renewable energy sources. This demonstrates, on the one hand, the obvious correlation between the environmental impact of an energy system and our demands, and, on the other hand, that large-scale deployment of VRES is an obvious path towards decarbonisation of a country, regardless of the sector under study. Limited VRES potentials result in either a greater need for electricity import, which may be associated with additional $CO_2$ emissions due to the production and transport, or in the use of fossil fuels in large-scale power plants for heating and electricity.

**Pareto trade-offs**   Pareto curves illustrate trade-offs between conflicting objectives, such as the minimisation of the total global warming potential and total costs. It is though interesting to evaluate how the *optimal* energy system changes in terms of design, operation and installed technologies when aiming at reducing the total costs while setting more stringent limits on the total GWP emissions. This is set, in terms of optimization, by performing single-objective optimisations with an $\varepsilon$-constraint. It is worth noting that the current energy systems of France and Germany, as of 2017, are *not* optimised neither from an economic nor from an environmental perspective.

The steps from the current energy systems to future ones with minimum GHG emissions are the following ones, from the highest to the lowest GWP - there are some differences between France and Germany as the policies and RES potentials are different:

- as the current energy system is *not* optimum - it is possible to reduce the total GHG emissions for the same total costs, which can be achieved by replacing *coal* and *oil* in the *heating* sector (mostly individual boilers) by *natural gas*;

- this goes in pair with *behavioural changes*, especially with multi-modal mobility and a higher shift towards public passenger mobility for both short-distance (tramways and buses) and long-distance (coaches and trains) mobility;
- battery electric vehicles should constitute the core of passenger mobility, instead of gasoline, diesel and natural gas-driven cars - in the case that BEVs are characterised by a lower annual cost (annualised investment, maintenance and fuel) than fossil fuel ones, which may be the case in 2050 depending on the *resource costs*, this shift towards electrical mobility is immediate, otherwise the priority is first to use more efficient vehicles with ICEs and *then* to use electric cars;
- technologies with higher *conversion efficiency* (same fuel and product, but with a lower consumption) should be implemented across all sectors, meaning:
  - centralised cogeneration units coupled to district heating networks, when possible, instead of individual boilers for heat production;
  - *renovation* of old buildings, when possible, to decrease the specific heating demands;
- the heating sector is then decarbonised through *electrification* - natural gas boilers are progressively replaced by electricity-driven heat pumps, and so are individual biomass boilers;
- when the resulting electricity demand, as final energy consumption, exceeds the amount of electricity that can currently be produced, there is a progressive installation of wind and solar plants, which goes in parallel with the reduction in the natural gas consumption;
- if the needs for electricity exceed the possible generation from wind and solar facilities due to limitations in potential, as it is the case of Germany, electricity imports are necessary;
- if the imported electricity is *not* carbon-free, there is a shift from electricity imports to geothermal power plants, which is, in practice, unlikely because of high costs and technical challenges;
- reaching net-zero emissions is feasible *only* with a large-scale deployment of carbon capture and storage facilities based on *direct air capture*, as there are $CO_2$-emissions associated with the construction of each facility type and with the use of petroleum for plastic production.

In addition, different cases for the reference scenario were simulated, considering, for example, the shut-down of nuclear power plants in the case of France, as this is unknown whether such plants will still be implemented (Figure 3).
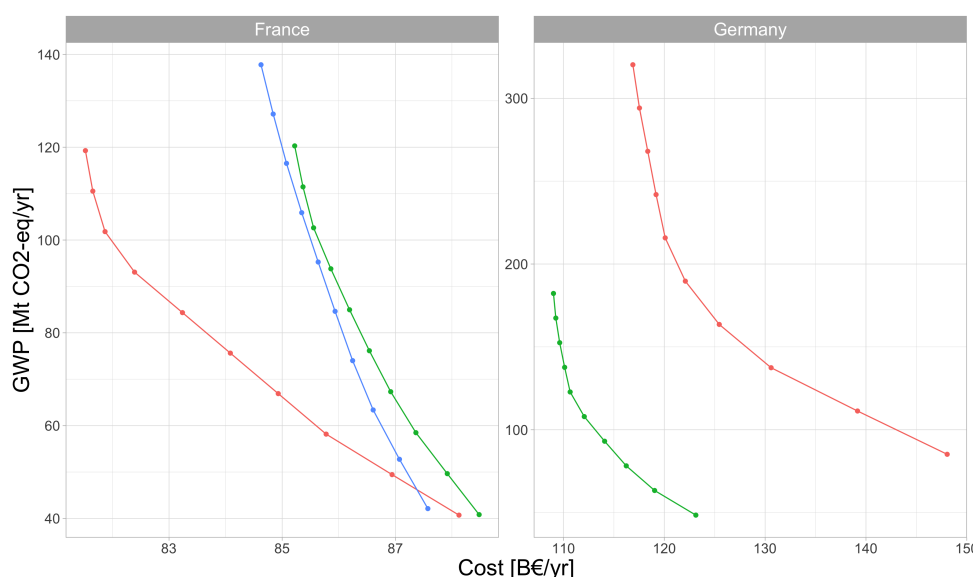


**Figure 3**: Pareto trade-offs for France (left) and Germany (right)

| Colour | France | Germany |
|--------|--------|---------|
| red | no constraints | no constraints, economic potential of wind and solar |
| green | no nuclear | no constraints, technical potential of wind and solar |
| blue | no nuclear, no electricity import | - |

The *GWP-optimum* energy system, for France, has an annual total cost of about 87 BEUR/year for emissions between 40 and 45 Mt $CO_2$-eq/yr. The cost-optimum energy system, for the same country, has emissions of about 120 MtCO2-eq/yr for a total annual cost below 83 BEUR/year. It is worth noting that the GWP-optimised systems with and without nuclear energy have roughly the same costs and emissions, meaning that, for ambitious climate targets, nuclear could be substituted for other sources.

The definition of economic potential for the penetration of solar and wind in Germany is open to debate - the comparison of the two Pareto curves shows that a greater implementation of these VRES can result in both a drop in costs (up to 30 %) and emissions - this suggests that the main barrier for a full exploitation of the German VRES potentials is rather social and legislative than economic.

## 3.2. Vehicle penetration

**Comparison** Different scenarios in terms of composition of the vehicle fleet and penetration of electric vehicles were simulated to better understand the impact of greener mobility on the design of the entire energy system (Figure 4). The integration of BEVs seems to be the reference solution for either cost- or GWP-optimised systems, followed by FCVs - in other words, a reduction of the penetration of EVs will be compensated by a higher penetration of FCVs.



(a) Electric vehicles     (b) Fuel Cell vehicles     (c) Internal combustion vehicles with biofuels
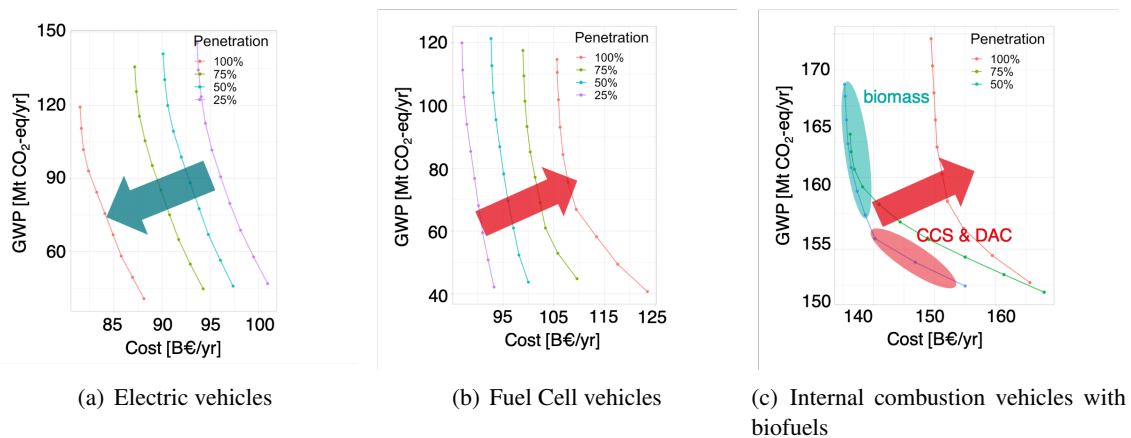
**Figure 4**: Pareto curves per vehicle type penetration

**Synthetic fuels** The use of synthetic fuels such as *synthetic diesel and gasoline* presents the advantage of not changing the entire vehicle fleet and associated infrastructure, as it mostly consists of vehicles with internal combustion engines, which are well-known technologies. It also valorises the carbon recovered from carbon capture and storage units or from biomass, which means that the consumption of synthetic fuels is nearly $CO_2$-neutral. However, a large-scale deployment is deemed challenging, and an analysis of the Pareto borders shows that:

- the use of synthetic fuels is less cost-effective than the integration of EVs and FCVs, by up to 110 % in system costs and 300 % in total emissions;
- the production of synthetic carbonaceous fuels requires a source of carbon and of hydrogen, which comes, from the most to least cost-effective option - for carbon:
  - biomass resources (wood and waste) which are limited indigenous resources - and there is therefore competition between the use of biomass in biorefineries and in individual boilers for heating;
  - carbon capture from power plants and industrial factories, such as the cement industry - CCS in power generation is an expensive solution and is not relevant in 2050 energy systems with 100 % renewables;
  - carbon capture from direct air capture, which is not yet a mature technology.

and for hydrogen:
  - steam methane reforming, meaning that natural gas is consumed and that the produced synthetic fuel is not $CO_2$-neutral;

○ water electrolysis, which is a more expensive technology and consumes significant amounts of electricity, meaning that the decarbonisation of the transport sector is in competition with the heating one.

**Fuel cell cars**    Despite the initial high investment and maintenance costs, which are limited by the high cost of the fuel cell system, hydrogen-run FCVs are in competition with EVs - especially if long-range EVs are characterised by much higher prices than short-range ones. For GWP-optimised systems, both deployments of these vehicles require a heavy electrification of the entire energy system through either the direct use of electricity as fuel from renewable sources, or through the generation of hydrogen in electrolysis units. For cost-optimised systems, the resulting energy systems will build on the use of natural gas and biomass for heating and hydrogen generation, without any integration of electrolysis systems and heat pumps.

**Electric cars**    Electric vehicles are the most environmental (42 Mt $CO_2$-eq/year) and economic (81 B€/year) optimal vehicle technology for the future German and French energy systems. A large-scale deployment necessarily results in a greater electricity demand, supplied from renewable sources when possible, and completed by electricity imports in the case of Germany or nuclear power in the case of France. Full electrification of the transport sector is prioritised over a full electrification of the heat production systems, as (i) the transport sector depends at about 90 % on fossil fuels and uses conversion technologies with an energy efficiency of only up to 40 % and as (ii) there are efficient or sustainable alternatives for heat production, such as biomass-fuelled power plants and/or cogeneration facilities, with a fuel utilisation factor of up to 90 % (50 % heat and 40 % electricity).

The transport and heating sectors are in competition with each other in energy systems with full electrification of the latter, where electricity-driven heat pumps are preferred over cogeneration plants. This may not be problematic in countries such as France, which have enough wind and solar potential, but may become problematic in countries such as Germany, where these potentials are more limited.

In addition, the integration of smart charging systems with possible V2G technologies goes in parallel with the development of VRES, as the car batteries can be used as buffers and will allow more grid flexibility. They can help in levelling down the power peaks ($-49\%$), especially those induced by needs for short-distance mobility, and result in cost and $CO_2$-savings by avoiding the installation of large-scale stationary batteries.

## 4.    Conclusion

A successful decarbonization of the European Union, coupled with a high integration of renewable energy and ambitious targets for energy efficiency, can only be reached with a significant contribution from transport. Regardless of the case study, the most cost- and energy-efficient pathway to decarbonize road and rail mobility is through a heavy electrification, with short-range electric vehicles and buses for local mobility, and either hydrogen or long-range electric vehicles for long-distance. The most cost-optimum vehicle fleet depends strongly on the projected costs of fuel cell and batteries in the upcoming year, as well as on the wind and solar energy potential. The *GWP-optimum* energy system, for France, has an annual total cost of about 87 BEUR/year for emissions between 40 and 45 Mt $CO_2$-eq/yr. The cost-optimum energy system, for the same country, has emissions of about 120 Mt CO2-eq/yr for a total annual cost below 83 BEUR/year. The *GWP-optimum* energy system, for Germany, has an annual total cost of about 100 BEUR/year for emissions between 50-70 Mt $CO_2$-eq/yr. The cost-optimum energy system, for the same country, has emissions of about 200 Mt CO2-eq/yr for a total annual cost below 110 BEUR/year.

## Acknowledgements

# Appendix 1: Case study - France

## End-use demands in 2017

**Heating**   The heating end-use demand (Table 8) corresponds to space heating, which is considered as variable over seasons, hot water, which is assumed constant over months, and high-temperature heating for industrial processes. The cooling end-use demands are neglected.

**Table 8**: 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 9) 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 9**: 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. It was taken from the French statistics of the INSEE [29], excluding airline transport. The split between short- and long-distance mobility in terms of passenger-kilometers is taken to 60 %-40 % [30].

**Table 10**: 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 |

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 [? ] for the year 2017 (Table 17). There is supposedly no demand associated with the other sectors.

**Table 11**: End-use freight mobility demands in France, expressed in tpkm (2017)

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

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 [? ], an occupancy rate of 80 % and a heating value of jetfuel, which is the most common airplane fuel, of 10.4 kWh/l (Table 12).

**Non-energy use**   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 13).

**Table 12**: 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 |

**Table 13**: 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 |

# Appendix 2: Case study - Germany

## End-use demands in 2017

**Heating**  The corresponding end-use demands are given in Table 14 based on the German Statistics in 2017.

**Table 14**: 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 |

**Electricity**  The electricity end-use demand (EUD) (Table 15) is strongly different from the electricity final consumption (FEC).

**Table 15**: 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 demand is taken from the German statistics [31], 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 % [32]. 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 [33].

**Table 16**: 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 |

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 [31] for the year 2017 (Table 17). There is supposedly no demand associated with the other sectors.

**Table 17**: End-use freight mobility demands in Germany, expressed in tpkm (2017)

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

The air transport demand is about 67.5 Mpkm in 2017 [31] and the equivalent fuel demand, according to the official statistics is 426 PJ or 118 TWh. This value includes international air transport and may be modified further.

**Table 18**: 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 thinner 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 19).

**Table 19**: Non-energy end-use demand in Germany, expressed in TWh (2017)

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

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