Study on the “Potential of a full EV-power-system-integration in Europe & how to realise it”

Study by Fraunhofer ISE & Fraunhofer ISI

on behalf of Transport & Environment

Place: Karlsruhe

Date: 30/10/2024

Status: Public

Imprint

Potential of a full EV-power-system-integration in Europe and how to realise it

Project coordination

Fraunhofer Institute for Solar Energy Systems ISE

Heidenhofstrasse 2, 79110 Freiburg, Germany
Dr. Matthias Kühnbach, matthias.kuehnbach@ise.fraunhofer.de

Fraunhofer Institute for Systems and Innovation Research ISI

Breslauer Strasse 48, 76139 Karlsruhe, Germany
Dr. Marian Klobasa, marian.klobasa@isi.fraunhofer.de

Responsible for content

Matthias Kühnbach, matthias.kuehnbach@ise.fraunhofer.de; Marian Klobasa, marian.klobasa@isi.fraunhofer.de; Annegret Stephan, annegret.stephan@isi.fraunhofer.de; Benjamin Lux, Benjamin.lux@isi.fraunhofer.de; Fabio Frank, fabio.frank@isi.fraunhofer.de; Arne Surmann, arne.surmann@ise.fraunhofer.de; Janis Kähler, janis.kaehler@ise.fraunhofer.de; Wolfgang Biener, wolfgang.biener@ise.fraunhofer.de; Zeliha Kamaci, zeliha.kamaci@ise.fraunhofer.de; Robert John, robert.john@ise.fraunhofer.de

Compiled on behalf of

Transport & Environment Europe

Square de Meeûs 18, 1050 Brussels, Belgium

Recommended citation

Kühnbach, M.; Klobasa, M.; Stephan, A.; Lux, B.; Frank, F.; Surmann, A.; Kähler, J.; Biener, W.; Kamaci, Z.; John, R. (2024): Potential of a full EV-power-system-integration in Europe and how to realise it. Study on behalf of Transport & Environment (T&E) Europe. Freiburg, Karlsruhe (Germany): Fraunhofer Institute for Solar Energy Systems ISE, Fraunhofer Institute for Systems and Innovation Research ISI.

Published

10/2024

Notes

Contents

List of abbreviations

Abbreviations	
AFIR	Alternative Fuels Infrastructure Regulation
aFRR	Automatic Frequency Restoration Reserve
BET	Battery electric truck
CHI	Calinski-Harabasz Index
DSO	Distribution system operator
EV	Electric vehicle
EVSE	Electric vehicle supply equipment
FCR	Frequency containment reserve
PV	Photovoltaic
SOC	State of charge
TCO	Total cost of ownership
ToU	Time-of-use
TSO	Transmission system operator
V1G	Vehicle-1-grid, smart charging from the grid
V2H	Vehicle-to-home
V2G	Vehicle-to-grid
V2L	Vehicle-to-load
V2X	Vehicle-to-everything

Executive Summary

This study investigates the impact of smart and bidirectional charging (Vehicle-to-X) on the European power system and the grid and analyses how users of electric vehicles can reduce their electricity costs by benefitting from smart and bidirectional charging.

Bidirectional charging, involving the use of electric vehicles (EVs) to both draw power from and return power to the grid, is emerging as a promising technology with potential environmental, economic and grid management benefits. Its implications vary significantly across different areas including the power market, grid infrastructure and user experience.

Bidirectional charging is currently undergoing testing and early commercial trials in Europe, with increasing industry recognition of its potential. However, most new EV models focus on vehicle-to-load, enabling vehicles to charge electric appliances and vehicle-to-home (V2H) applications, rather than vehicle-to-grid (V2G). Furthermore, the availability of supporting infrastructure such as bidirectional wallboxes is still limited. Despite technical, regulatory and acceptance barriers, vehicle-to-X offers socio-technical-economic benefits such as CO_2 emission reductions, integration of renewable energy and grid relief.

In terms of technology, both AC and DC bidirectional charging solutions are supported by vehicle manufacturers. AC charging is less hardware-intensive and suitable for residential and slow charging, making it – in view of the authors – more cost-effective in the long term. DC charging, although currently leading in development in terms of both hardware and communication protocols (e.g. ISO 15118-20), will remain more expensive due to additional hardware requirements and will thus be used mainly for fast charging. While the technical solutions currently available for bidirectional charging mainly use proprietary standards, it is a prerequisite for a broad diffusion and acceptance of bidirectional charging that both EVs and wallboxes support standardised communication protocols.

Power market implications of bidirectional charging

The electrification of the mobility sector leads to an increase in electricity demand, and therefore to a larger demand for renewable energy generation, if CO_2 emission reduction goals are to be realised. Furthermore, this can result in a greater dependency on electricity network expansion, if the best renewable locations across Europe are used. Smart charging and bidirectional charging technologies offer significant benefits in alleviating pressure during this transformation. They contribute to a decrease in curtailment and electricity network expansion, facilitate better integration of photovoltaic (PV) capacity, allowing more capacity to be installed and reduce the need for alternative flexibility resources within the system. This leads to less reliance on stationary battery storage, electrolysis and the electrification of hydrogen and natural gas. System cost savings of more than 10 % can be realized, if smart and bidirectional charging is implemented. In the decade from 2030 to 2040 the cost difference could be over EUR100b in energy system costs, if relative savings of 2030 are used.

Compared to smart charging alone, bidirectional charging offers additional advantages, such as decreasing the need for backup capacity from gas and hydrogen power plants and lowering the use of power generation from these sources. The opportunity to integrate PV capacity more effectively is seen as the biggest value of the charging flexibility provided by electric cars, especially when they are connected during the day. This represents a key advantage of electric cars over the charging flexibility of trucks that charge mainly at nighttime. This is the reason why the flexibility of trucks adds only marginal value to the power system (if passenger cars are already equipped with bidirectional capabilities). Consequently, the additional value of bidirectional charging decreases with a larger share of electric vehicles. The modelling results indicate that a large part of the benefits of bidirectional charging can be realised even without truck flexibility.

Grid implications of bidirectional charging

The impact of bidirectional charging on distribution grids is examined through two use cases:

1) Economically optimised charging of electric cars and using the battery to feed electricity back to the household.

Economically optimised charging assumed dynamic retail tariffs for EV users (vehicle-to-home). Although this meant that the local grid situation is not considered for the charging schedule, this approach does not produce negative effects. Instead, marginally positive effects on peak loads are observed, facilitating the integration of PV generation and decreasing grid load. However, this benefit is highly grid-specific.

2) Grid-friendly charging.

Grid-friendly charging, where transformer loading is monitored to prevent overloading, also reduces but does not eliminate grid overloads. This approach involves postponing charging processes during overloads without reducing the target state of charge (SOC) and charging plugged-in vehicles during feed-in overloads where possible. Overall, various grid-specific conditions, including PV installations, heat pumps and EVs, dictate the need for grid extensions. This limits the overall contribution of bidirectional charging. Nevertheless, on average, grid extension costs are slightly reduced.

User perspective – smart charging & vehicle-to-home

In general, smart and bidirectional charging at home offers significant cost-saving potentials. The highest benefits stem from increased self-consumption of PV energy, while dynamic electricity prices also offer considerable savings. Savings from smart and bidirectional charging range from EUR30 to EUR430 per year for smaller EVs (4 – 34 % cost savings) and from EUR78 to EUR780 per year for larger EVs (7 – 35 % cost savings) compared to not-optimized charging. The impact of bidirectional charging is greater than that of smart charging with cost savings increasing by around 5%. Bidirectional cost savings are related to a vehicle-to-home use case that is analysed in detail. Additional savings from arbitrage trading with electricity feed back into the grid could further increase benefits for users. For this use case no model results are calculated, but a literature review indicated potential revenues.

Savings vary by household type, with smaller households achieving lower savings (both relative and absolute) than larger households. In countries with lower electricity costs, such as Poland and France, absolute cost reductions are lower, making vehicle-to-home (V2H) less attractive for the same investment.

The battery life of an EV can be extended by an average of 40% by lowering the target state of charge (SOC) from 100% to 80% upon departure. Controlled charging extends battery life by a further 5-10%, compared to uncontrolled charging, with bidirectional charging slightly underperforming unidirectional charging.

1 Introduction

Electric vehicles (EVs) can decrease emissions and support the integration of volatile renewable energy sources by flexibly changing their charging pattern [1, 2]. Bidirectional power flows, i.e. EVs not only drawing energy from the grid but also inducing energy from the battery back to the grid or to other consumers such as electric devices, households or larger (office) buildings or sites, could increase this effect [3]. The concept of bidirectional charging (in this study also referred to as vehicle-to-X (V2X)) has been a topic of discussion for over two decades [4]. Main concepts include V2G (vehicle to grid), V2H (vehicle to home) and V2L (vehicle to load), in which energy from the vehicle's battery is fed back into the electricity grid, used either as supplement power supplier to the home or used to directly power an adjacent load, respectively [5]. Despite its high flexibility potential and an increasing number of trials in Europe and beyond [6], the commercial availability and widespread implementation of bi-directional charging is still scarce. Extant work has shown that there is a high level of uncertainty regarding the effects of bidirectional charging on battery degradation [7], and that V2X implementation is still hampered not only by technical, but also regulatory and social challenges [3].

Beyond these barriers directly related to bidirectional charging, the pure number of available electric vehicles was – until recently –limited, while the additional need for flexibility in the power system was low, as flexibility was effectively provided by conventional power plants. However, driven by the increasing demand for flexibility in the current and future energy system, the urgency to explore bidirectional charging has grown substantially. Additionally, technical and market design advances, such as the introduction of aggregation concepts, make it possible to realise the potential of bidirectional charging in a coordinated and efficient manner.

From the perspective of battery technology, electric vehicles and charging infrastructure, bidirectional charging is on the brink of becoming a commercially viable solution. The rationale behind this shift is compelling – electric vehicles (EVs) spend approximately 95% of their time idle [8]. EV battery capacities are significantly larger than common household batteries and could cover a household's electricity demand for multiple days.

This study investigates the potential of bidirectional charging of EVs applying three perspectives:

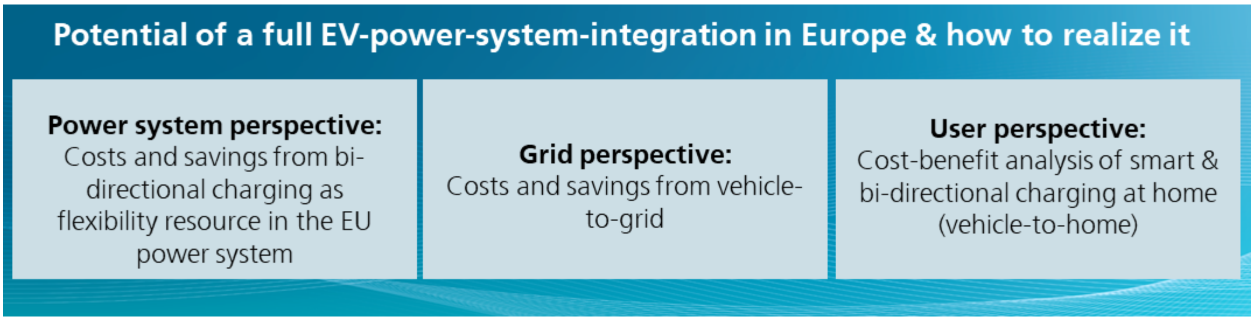


Figure 1: Scope and perspectives of this study

Regarding these perspectives on bidirectional charging, the following aspects will be investigated within this study:

- What are barriers for the realisation of the V2X potential, considering power system design, grid framework, vehicle availability and lack of awareness?
- What is the theoretical and usable flexibility potential of bidirectional charging of passenger cars and electric trucks in the EU power market and in its Member States? How does bidirectional charging enable the system integration of renewable energy sources?
- What are the costs and savings generated through a large-scale application of bidirectional charging, particularly with regard to the electrical power system?
- What are the potential gains for EV users when applying smart unidirectional or bidirectional charging at home? Does the resulting charging behaviour align with the system requirements? How does battery size and degradation affect bidirectional charging?
- What are the current technological trends regarding bidirectional charging infrastructure? How do AC and DC systems compare in terms of cost and communication standards?

Section 2 provides an overview of the drivers and barriers to V2X implementation, as well as an overview on the regulatory framework in Europe. Following this, Section 3 addresses bidirectional charging within the European power system, while Section 0 explores its potential for grid support. In Section 5, we evaluate vehicle-to-home (V2H) applications, discuss future trends in charging infrastructure development and conduct a cost-benefit analysis of V2H for EV users with varying battery capacities. Based on the analysis, we draw recommendations and concluding remarks on how power systems can benefit best from V2X technology (Section 6)

Our grid and user level analyses cover France, Germany, Italy, Poland, Spain and the United Kingdom. The power system is modelled for the entirety of Europe, with detailed analysis of the aforementioned countries.

2 Promise of V2X: Drivers and Barriers

The realization of V2X technology promises large potential for improving power system efficiency and reducing CO_2 emissions. However, several barriers hinder its full implementation. The following chapter analyses the current status of V2X and identifies main benefits, barriers and regulatory conditions for its implementation.

2.1 State-of-the art/current industry activities

Currently, V2X is in the testing phase in many countries across Europe. While most of the piloted activities (the database V2G-Hub[1] comprises 142 projects globally) still aim to proof the concept, some commercial trials have already been conducted [9]. The projects test different services, with time shifting of power, frequency response and distribution services being the most investigated ones [10]. In Europe, the projects BDL[2], UnIT-e²[3] and EUREF-campus[4] (Germany), Powerloop[5] (UK), BD4OPEM by Nuuve[6] (Denmark and global), Flexitanie Project[7] (France), EVVE[8] (France and EU), DrossOne V2G Parking Project (Italy)[9] and the SCALE[10] (Netherlands and EU) are among the most prominent ones.

Industry has recognised the potential of V2X and has started to develop the respective hard- and software. Although the availability of cars capable of V2X is still scarce in Europe, several V2X car models have recently been announced or are already available on the European market (Table 1)—some of them, however, only for specific V2X applications. TESLA has realized bidirectional charging (V2L, V2H and vehicle-to-vehicle) in its Cybertruck in the US market, the developments for further models and for the European market are yet unclear tesla [11].

Table 1: Available car models capable of V2X or V2X-capability announced in Europe [12–14]

[1] Model not available anymore, V2L= Vehicle-to-load, V2H = **Vehicle-to-home**, V2G = Vehicle-to-grid, individual sub-models are not listed

OEM	Model	V2X Capability	Introduction in Europe	Charging Standard
Audi	Q4	V2H and V2G announced	2023	CCS
BYD	Atto 3	V2L	2023	CCS
BYD	Dolphin	V2L	2024	CCS

[1] https://www.v2g-hub.com/insights/

[2] https://www.ffe.de/projekte/bdl/

[3] https://unit-e2.de/

[4] https://www.mobilityhouse.com/de_de/unser-unternehmen/referenzen/artikel/euref-campus

[5] https://octopusev.com/powerloop

[6] https://nuvve.com/projects/

[7] https://www.flexitanie.fr/projet-flexitanie

[8] https://www.edf.fr/en/the-edf-group/inventing-the-future-of-energy/electric-mobility-for-today-and-tomorrow/edf-launches-europes-first-bidirectional-charging-demonstrator/evve-an-ambitious-project

[9] https://www.esolutions.free2move.com/eu/en_it/drossone-v2g-project/

[10] https://scale-horizon.eu/

OEM	Model	V2X Capability	Introduction in Europe	Charging Standard
BYD	HAN	V2L	2023	CCS
BYD	SEAL 82.5 kWh	V2L	2023	CCS
Cupra	Born (with 77 kWh and VW-Software 3.5)	V2H	2023/2024	CCS
Cupra	Tavascan	V2H and V2G announced	2024	CCS
Dacia	Spring	V2L	2024	CCS
Ford	F-150 Lighting	V2H	2023	CCS
Genesis	GV60, GV70, G80	V2L	2022	CCS
Hyundai	IONIQ 5/6	V2L	2022/2023	CCS
Hyundai	Kona Electric 65 kWh	V2L	2023	CCS
Kia	EV9 AWD/GT-Line	V2L, V2H, V2G	2023	CCS
Kia	Niro EV	V2L	2022	CCS
KGM	Torres EVX	V2L	2024	CCS
Lucid Air	Grand Touring	V2L and V2H and V2G announced	2023	CCS
Lucid Air	Pure RWD	V2L and V2H and V2G announced	2024	CCS
MG	MG4, MG5, Marvel	V2L	2022	CCS
Mitsubishi	Outlander[1], eMIEV[1]	V2G	2010	CHAdeMO
Nissan	Leaf	V2G	2013	CHAdeMO
Nissan	Leaf e+	V2H, V2G	2022	CHAdeMO
Nissan	eNV200[1]	V2G	2020	CHAdeMO
Peugeot	e-3008/5008	V2L	2024	CCS
Polestar	3	V2L and V2H and V2G announced	2022	CCS
Polestar	4	V2L	2024	CCS
Renault	5 E-Tech	V2L and V2H and V2G announced	2024	CCS
Skoda	Enyaq (with 77 kWh and VW- Software 3.5)	V2H and V2G announced	2023	CCS
Smart	#1, #3	V2L	2024	CCS

OEM	Model	V2X Capability	Introduction in Europe	Charging Standard
Volkswagen	ID.3, ID.4, ID.5, ID.7, ID Buzz (with 77 kWh and VW—Software 3.5)	V2H and V2G announced	2022-2024	CCS
Volvo	EX90	V2L and V2H and V2G announced	2022/2023	CCS
XPENG	G6/G9 RWD	V2L	2024	CCS

As for vehicles, the availability of V2X-capable charging stations on the market is limited (Table 2). On the European market, only two manufacturers, EVTEC and Alpitronic, offer V2X capable DC charging stations (05/2024). Several other models from various manufacturers are announced to be released, some in 2024. A similar situation applies to AC charging stations, with the market release of various models announced, but so far only two available models by Entratek and openWB. Both describe their product as "V2X ready", meaning that the software implementing the norm ISO15118-20 is still in test phase and not installed yet.

Table 2: Available and announced charging stations capable of V2X [15–17]

OEM	Model	V2X Capability	AC/ DC	Charging Standard	Max Output Power (DC)	Comments
Wallbox	Quasar	V2G/V2H	DC	CHAdeMO	7.4 kW	Announced
Wallbox	Quasar 2	V2G/V2H	DC	CCS	11.5 kW	Announced
Kostal	BDL Wallbox	V2G	DC	CCS	11 kW	Announced
ionix	AVA	V2G	DC	CCS	25 kW	Announced
evtec	Sospeso &charge	V2X	DC	CCS/ CHAdeMO	10 kW	Available
Alpitronic	HYC 50	V2G/V2H	DC	CCS	50 kW	Available
Ambibox	Ambicharge	V2G/V2L	DC	CCS	11/22 kW	Announced
Enercharge	DCW20/DCW40	V2G/V2H	DC	CCS	20/40 kW	
Volvo	Bidi-Charger	V2G/V2H	AC			Announced
E3/DC	S10 M	V2G/V2H				Announced
E3/DC	Edison DC Connect	V2H	DC	CCS	11 kW	Announced
eaton	Green Motion DC 22	V2G	DC	CCS/ CHAdeMO	22 kW	Announced

OEM	Model	V2X Capability	AC/ DC	Charging Standard	Max Output Power (DC)	Comments
BorgWarner	RES-DCVC125-480-V2G	V2G	DC	CCS	60 kW	
BorgWarner	RESDCVC60-480-V2G	V2G	DC	CCS	125 kW	
dcbel	r16	V2H/V2G ready	AC/DC	CCS/ CHAdeMO	15.2 kW	Announced
Enteligent	Hybrid DC Bidirectional Fast EV Charger	V2G/V2H	DC	CCS	15/25 kW	Announced
AME	V2G 3p10kW V2X Charger	V2G	DC	CHAdeMO	10 kW	Announced
Ford	Charge Station Pro	V2H	DC	CCS	19 kW	Available, no certificate for Europe
Nuvve	RES-HD60-V2G	V2G	DC	CCS	60 kW	Announced, for North America
Nuvve	RES-HD125-V2G	V2G	DC	CCS	125 kW	Announced, for North America
Silla	Duke 44	V2G/V2H/V2V	DC	CCS	2x22 kW	Announced
SolarEdge	Ladestation BIDI	V2G/V2H	AC	Type 2	22 kW	Announced
Endphase	Bidirectional EV charger	V2G/V2H	DC	CCS/ CHAdeMO		Announced
Enovates	Single Wallbox	V2G	AC	Type 2	22 kW	
Mobilize	Powerbox	V2G/V2H	AC		22 kW	Announced
ABB	V2G Wallbox					Announced
Delta	Bidirectional Charger	V2G/V2H	DC		22 kW	Available in Australia/Indonesia

OEM	Model	V2X Capability	AC/ DC	Charging Standard	Max Output Power (DC)	Comments
Fermata Energy	FE-15	V2G/V2H	DC	CHAdeMO	15 kW	Announced, for North America
Fermata Energy	FE-20	V2G/V2H	DC	CHAdeMO	20 kW	Announced, for North America
Indra		V2H	DC	CHAdeMO	7 kW	Announced
Nichicon	EV Power Station	V2H	DC	CHAdeMO	6 kW	
openWB	Pro	V2G/V2H	AC	Type 2	22 kW	Available, without V2X Software
Smartfox	Pro Charger 2	V2G/V2H				Announced
Sigenergy	Sigen EV DC Charging Modul	V2G/V2H	DC	CCS/ CHAdeMO	25 kW	Announced
sun2wheel	Two-way-10	V2G/V2H	DC	CCS/ CHAdeMO	10 kW	Announced
VW	ID. Charger	V2G/V2H				Announced
Sono	Wallbox	V2G/V2H	AC	Type 2	11 kW	For Sion EV only (discontinued)
Entratek	Power Dot Fix - BIDI	V2G/V2H	AC	Type 2	22 kW	Available, without V2X software

2.2 Socio-techno-economic benefits

Controlled charging, in particular V2X, can have several social, technical and economic benefits. Yet, the effect that controlled charging, including V2X, can have also varies due to differences in EV deployment, regulatory conditions, cost or how EV charging is managed. Accordingly, differences in assumptions and use cases render comparability of studies difficult. In line with this, also the benefits of V2X over unidirectional smart charging strongly depend on the specific situation [18].

Key benefits that have been identified by extant work are integrating higher shares of variable renewable energies, e.g. by reducing variable renewable energy curtailment and increasing CO_2 reduction [18].Both are of high value in the context of climate change mitigation. Additionally, the studies identified that V2X can have several technical benefits. V2G can reduce peak loads, at both transmission and distribution system level as well as congestion at distribution grid level [18]. A study focusing on Switzerland finds that the typical evening peak occurring at home charging stations with uncontrolled charging can be reduced or even prevented using V2G [19]. Furthermore, V2G can also help to increase minimum voltages and reduce energy losses. V2H can increase the self-consumption of photovoltaic (PV) power [20] and, thereby, also reduce the amount of electricity needed from the grid and/or also reduce PV supply peak, which both can relieve grid components. Yet, the scale of the technical effect, i.e. the flexibility potential, depends on many situation-specific aspects such as the charging strategy, when and where the car is plugged in for charging during the day (i.e. the plug-in behaviour which relates to the driving patterns), battery sizes, EV and infrastructure deployment, the grid area (e.g. urban vs. rural), or the combination with other storage or flexibility technologies [19, 21].

However, controlled charging and, in particular V2X, can also have negative technical effects on (distribution) grids. For controlled unidirectional charging, for example, increasing load peaks caused by a so-called over-coordination effect have been found in several studies as a result of simultaneous charging of many vehicles when switching from high to lower tariffs in the case of time-variable charging tariffs [21, 22]. For V2X in particular, the overload of grid components, in particular transformers and especially in grid situations with low transformer capacity coupled with a high number of households and EVs in the respective grid area [23], as well as potential high load peaks during lunchtime caused by a charging management shifting loads from evening to typical photovoltaic power production times [19], have been identified as barriers. Nevertheless, these drawbacks are typically more than compensated for by an overall more favourable electricity system.

While economic benefits can relate to general system benefits such as substantial savings in operating the electricity system [18] or reductions in grid reinforcement cost [19], potential revenues or charging cost savings are also of particular importance from a consumer perspective. In general, the economic benefits depend on the specific grid and household/building situation (e.g. the availability of photovoltaic power plants, stationary storage, grid connection capacities), the amount of flexibility provided (depending on charging strategies and plug-in behaviour [19], as well as on the remuneration or savings (depending on the use case).

While controlled charging can already result in substantial economic benefits, such as reductions of unit rate costs [21], bidirectional charging typically reinforces these effects. Several studies exist that focus on bidirectional charging and passenger cars, i.e. EVs, while the evidence for bidirectional charging and medium- and heavy-duty vehicles, i.e. BETs, are still scarce. Moreover, studies in this field typically show revenues or savings in charging cost and hence, neglect additional investment cost applying for the required charging infrastructure and measurement technology, which are expected to decrease from currently around EUR6,000 per charging point to EUR3,000 per charging point in 2025 for DC chargers [20] and even below EUR1,500 per charging point for AC chargers.

Revenues from bidirectional charging differ depending on the use cases and if electricity is induced back to the household or to the building (V2H) resp. back to the grid for arbitrage trading on power markets (V2G).

For the first case (V2H) for passenger cars and Germany, the BDL project had simulated V2H applications (i.e. the increase of PV self-consumption with a 5.5 kWp[11] PV plant) and calculated average revenues of around EUR310 per EV and year (60 kWh battery, 11 kW charging power, medium-sized household with an annual electricity demand of 3,800 kWh, non-commuter)[12]. The revenue will decrease if the EV will be used for commuting and in case of the availability of further flexibility technologies such as heat pumps or stationary batteries [20].

For the second case (V2G), for day-ahead arbitrage, the BDL project simulated revenues of around EUR400 per EV and year (100 kWh battery, 11 kW charging power), which decrease if commuters or

[11] Kilowatt peak (kWp) is used to describe the peak power output of the system.

[12] A publicly available calculator for V2H potential for the case of Germany can be found here: https://v2h.ffe.de/home

smaller batteries are considered and increase when considering other markets such as intraday trading or higher charging capacities up until more than 1,200 EUR/year combining trades at different spot markets. Moreover, these revenues also strongly depend on regulation (e.g. regarding taxes and levies) and price volatilities. A field trial at the EUREF-campus together with The Mobility House results in revenues of around EUR600 per year and EV already today (intraday trading), and simulations suggest a potential of even around EUR1,500 per year and EV (73 kWh battery, 11 kW charging power). For the UK, the Sciurus trial has identified around EUR380 per year and EV as realistic in the case of arbitrage (intraday trading), which can result in around EUR800 per year and EV when combined with automatic Frequency Restoration Reserve (aFRR), i.e. secondary control reserve—and can even be higher due to the specific conditions of COVID-19 during the trial period [24]. A future cost-optimised energy system will include around 30% of bidirectional electric vehicles, with variations across different member states [20].

As a conclusion of the literature overview, revenues for bidirectional charging can be substantial for EV users and can differ according to the considered use case. Revenues from use case that induce electricity back in the household or in the building (V2H) range from EUR150 per EV and year to EUR400 per year and vehicle (and are not very sensitive to battery size). Higher revenues are estimated in literature from use cases providing electricity back to power markets for arbitrage trading (V2G) that can reach more than 1000 EUR per year and vehicle. Here, revenues are highly dependent on price expectations on day-ahead and intraday power markets and regulatory conditions on fiscal and non-fiscal charges for electricity. With low numbers of electric cars participating in arbitrage trading, impacts on power price are neglectable, but would increase with higher shares.

For medium and heavy-duty vehicles, considerable revenues for different V2X services are found, as recent studies in the field indicate. Similar to electric cars, the revenues differ according to bidirectional charging use cases. If electricity is induced back into the grid (V2G), relevant revenues can be generated in the reserve market or with arbitrage.

A study conducted by Daimler and TenneT, focusing on the ancillary services in Germany, finds a maximum possible reduction of 3-7.5 EURct/kWh[13] for the total cost of ownership (TCO) in the case of a line haul 2 truck (i.e. a one-shot drive from depot to depot or a special delivery with return trip) and aFRR; frequency containment reserve (FCR), i.e. primary control reserve, would result in a reduction of 1-2 EURct/kWh [25] TCO. Other use cases of medium and heavy-duty vehicles such as buses and other trip configurations also result in TCO reductions but to a smaller extent. For depot charging (30 BETs, with 30% 250 kWh battery and 70% 500 kWh battery, 100 kW max. charging power) and based on real-life data, a recently published study calculates savings of EUR3,000-10,000 per year and BET[14], resulting from a combination of the different use cases self-consumption optimisation, peak shaving, tariff-optimised charging and arbitrage trading [26].

2.3 Barriers for V2X adoption

Despite these socio-techno-economic potentials, V2X has not been widely deployed and is mostly still in a trial stage. Technical and social challenges still hamper widespread V2X adoption in Europe and beyond. In addition, the regulatory environment sets the boundary conditions for V2X deployment; regulatory aspects differ between countries and can either represent a barrier or driver for V2X deployment. Hence, this section highlights selected technical and social barriers. The regulatory environment will be discussed in more detail in Section 2.4—on a European level as well as in the focus countries.

[13] relating to 2020 and 2021 prices, respectively

[14] relating to 2021 and 2022 costs and prices, respectively

Technical barriers consist of the uncertainties around the technical potential of V2X (see also Section 2.2) and its potential effect for distribution grid reinforcements deferral and mitigation. In addition, and related, also the future flexibility supply from other technologies is highly uncertain, in particular in distribution grids. Battery degradation caused by V2X has often been perceived as a technical challenge and studies in this field have emphasised the uncertainties [27, 28]. Recent studies and simulations show that V2X does not substantially increase battery degradation, that capacity losses could even be reduced compared to conventional (uncontrolled) charging, and that lifetime may even be extended [29].

Social barriers have been studied less extensively than technical barriers [30]. One of the most critical aspects to leverage the technical potential of V2X is the willingness of the EV users to participate in controlled and bidirectional charging [19, 31], which can be incentivised by appropriate tariffs. Hence, several recent studies have investigated the acceptance of EV users of different smart and bidirectional charging tariffs. They find, for example, that remuneration or savings are typically the most important aspect for EV users [32, 33] and that a substantial number of users also wants to have control over the charging process [33]. Survey results of a recent study indicate that requirements regarding data sharing and range anxiety might also present potential barriers for the adoption of V2X [33]. This, together with generally little knowledge about V2X and how the system works [3], calls for more education and information transparency. In addition, the plug-in rate of EV users as well as the option to interfere with the charging processes, e.g. via an intermediate charge button, might also hamper harnessing the V2X potential [3].

Many of the persisting barriers directly relate to economic barriers. For example, uncertainties in flexibility supply and its remuneration (e.g. because of volatile markets at transmission grid level or non-existing markets on distribution grid level), unfavourable regulation (see Section 2.4) as well as uncertain consumer acceptance make it difficult to calculate economic benefits and lead to a high degree of uncertainty in business models.

2.4 Regulatory environment

The feasibility as well as the benefits of V2X are strongly affected by the regulatory environment. Key aspects to be considered are the general rules of the electricity market and how demand side flexibility in general and V2X in particular are included in the electricity market. Charging infrastructure targets and specified technical requirements as well as tariff and taxation structures define further regulatory conditions that influence the implementation of V2X concepts. Relevant regulation can be found both at EU level and in the individual member states. While we briefly summarise relevant aspects of regulation on EU-level, we also focus on the selected countries and their regulatory structure with reference to V2X.

On the EU level, the internal electricity market directive, the **EU's Directive on the common rules for the internal market for electricity (2019/944) and Regulation (EU 2019/943)**, establishes common rules for the energy market. In addition to energy generation, transmission, distribution and storage, it contains several provisions for the development of demand side flexibility. It requires non-discriminatory access to all electricity markets and full recognition of (independent) aggregators as market participants. In July 2024, the reform of the EU electricity market entered into force, which contains requirements for the Member States to set indicative national objectives for non-fossil flexibility, including demand side response and energy storage and for system operators to propose peak-shaving products that result in a reduction of electricity demand to be activated in electricity price crisis situations. In addition, peak-shaving products that could also be applied under normal circumstances should be assessed [34].

European Network Codes are a set of rules drafted by European Network of Transmission System Operators (ENTSO-E) to facilitate the harmonisation, integration and efficiency of the European electricity market. More details on the impacts of European Network Codes on the integration of V2X are summarised in Section 4.1.

The **Alternative Fuels Infrastructure Regulation (AFIR)** regulates the deployment of recharging and refuelling stations across Europe, in particular for public and publicly accessible private charging infrastructure. Implemented since mid-April 2024, the AFIR contains regulations regarding the payment system and the applicable tariffs as well as the technical requirements for EV charging stations—in addition to specific charging station deployment targets e.g. for cars, vans and heavy-duty vehicles. The AFIR requires member states to include bidirectional charging in their resource adequacy assessments and mandates infrastructure deployment targets for EVs.

Further regulations (can) have points of contact with V2X. The **Renewable Energy Directive (RED)** is the legal framework for the development of clean energy across all sectors. The revised directive (**RED III**) entered into force in November 2023 and includes the introduction of a credit mechanism for operators that supply public charging stations with renewable electricity [35]. Moreover, the **Energy Performance of Buildings Directive (EPBD)** promotes energy efficient and decarbonised buildings. A revision of the EPBD entered into force in May 2024 [36] Article 12 of this agreement contains specifications regarding intelligent (mandatory) and bidirectional (optional) charging as well as requirements for the protocols and standards to be used in compliance with AFIR [37]. Also relevant for V2X is the proposal for the revision of the **Energy Taxation Directive (2003/96/EC) (ETD)**, including measures to prevent double taxation [38], which is currently stalled in Council.

Despite the regulatory environment at EU level, individual member countries still differ substantially in their preparedness for V2X. We focus on the selected examples of Germany, France, Italy, Poland, the United Kingdom and Spain. Yet, the regulatory and market environments of other countries such as Sweden or Norway seem to be particularly favourable for V2X [12]. In the following, we summarise recent report from DNV, an independent assurance and risk management provider, on behalf of smartEn, the European business association for digital and decentralised energy solution [12], as well as from ACER, the European Union Agency for the Corporation of Energy Regulators [39], complemented with further sources if indicated.

Germany is one of the few countries to highlight the potentially important role of bidirectional charging in its planning strategies (i.e. in the charging infrastructure masterplan II [40], the Advisory Board of the National Centre for Charging Infrastructure has recently presented the recommendations for action to introduce bidirectional charging to the government [41]. While V2H use cases have hardly any regulatory barriers [20], V2G is hampered because, for example, mobile electricity storage systems are not yet exempted from (double) taxation, levies, surcharges and grid fees, lowering their economic attractiveness. Despite its strategic relevance, there is no legal framework for V2G to participate in wholesale electricity markets and Germany also lacks a market-based procurement of local flexibility that V2G could participate in. While dynamic tariffs are required for larger suppliers—and also for smaller ones starting in 2025—, most residential consumers still have static tariffs. In addition, emergency measures protect consumers from price peaks, all disincentivising V2X. In addition, while network charges only apply to the withdrawal charge, network tariffs are still almost entirely volume-based (price structure is expected to change in 2025), disincentivising V2G. Moreover, Germany has a very low smart meter penetration (<1% in 2022, should be used nation-wide in households and businesses by 2032 [42]), and the German calibration law ("Eichrecht") requires the re-certification of all meters for bidirectional charging.

France still lacks a legal framework for V2X. Yet, avoiding double-taxation for charged and discharged energy has been agreed by the government and has started to be implemented for stationary storage. Consumers can choose between regulated and non-regulated tariffs, with regulated tariffs being the most popular choice. While time-of-use (ToU) tariffs with specific tariffs containing high peak prices incentivise flexibilities, emergency measures protecting consumers from electricity price peaks (will be phased out in 2024) disincentivise V2X. In addition, France has capacity-based components in its network tariffs potentially incentivising the efficient use of the network. Yet, network charges are applied for charging and discharging storage devices connected at transmission level; for storage connected at distribution-level, network charges only apply for discharging. V2G and other distributed energy resources are allowed to participate in wholesale and ancillary markets, and the first aggregator to provide V2G services was qualified in 2022. In addition, V2G is allowed to access local flexibility markets. Smart meters in France (rollout >90%) have local interfaces for data access by energy management systems.

Spain does not have specific V2X policies in place, but regulatory conditions favour V2X. V2G can participate in ancillary markets, but minimum bid size is 1 MW, potentially requiring an aggregator. There are no local flexibility markets for V2G to participate in. Spain is one of the few countries that has eliminated double charges already in 2020. Domestic customers can choose a dynamic electricity tariff, providing some incentive for V2X applications. The network tariffs in Spain consist of capacity and volumetric compounds and incentivise V2X. According to [39], network charges apply neither to injection nor to withdrawal charges for storage devices in Spain. Smart meters are rolled-out nation-wide (nearly 100%) and are interoperable regarding data sharing at the central system layer.

While **Italy** does not have explicit V2G policies in place, it has conducted some of the largest V2G trials, such as the Fiat-Chrysler V2G Project and the DrossOne V2G Parking Project [43]. Italy has removed double-taxation, improving the economic attractiveness of V2G. In Italy, variable energy prices are offered and represent a combination of fixed, ToU charges and nearly dynamic prices. The remuneration of PV power is relatively low, which incentivises V2H. Demand-side response technologies, including V2G, can participate in capacity markets as well as wholesale markets via aggregators (threshold 10 MW). Regarding local flexibility markets, DSOs are allowed to conduct trials using local flexibility services. According to the Integrated Electricity Dispatching Act (TIDE), which enters into force in 2025, all resources incl. V2G will be allowed to provide flexibility services. According to [39], network charges apply neither to injection into nor to withdrawal from storage devices in Italy. Smart meters are rolled-out nation-wide (nearly 100%) and Italy conducts proactive measures to adapt those smart meters that are not suitable for Energy Management Systems.

Poland does not have V2X policies in place. In addition, the current Polish Energy Law would have to be changed for the implementation of a proposed V2G technology programme. The authors are not aware of ongoing V2X trials in Poland. ToU tariffs should be introduced in 2024, incentivising V2G. According to [39], network charges are energy- and power-based and apply only to energy withdrawal for storage devices. Participation of V2G in wholesale and balancing markets is currently not possible in Poland; there are no local flexibility markets. In addition to the relatively low smart meter roll-out (approximately 20%), the centralised data acquisition system does not support high-speed services requiring small sampling periods.

In its EV Smart Charging Action Plan, the **United Kingdom** emphasises V2X, including the strategic target of reaching commercial deployment of bidirectional V2X [44]. The UK has a specific Vehicle-to-X innovation programme" to address barriers to wide-scale deployment specific to this technology by 2025" [44] and to identify, monitor and address barriers impeding V2X implementation. Yet, bidirectional charging is not included in the currently valid smart charging legislation setting the requirements for the smart functionality of charging points. The UK is the country with the largest number of V2X trials [43]. One example is the Powerloop trial (see section 2.1), and the government has recently supported several new trials [45]. Consumers with specific meters can choose a ToU tariff, which is not very common yet. Dynamic tariffs are offered for industrial customers but are still scarce for residential customers. High flexibility in electricity prices incentivises V2X. However, emergency measures protected consumers from price peaks, disincentivising V2X. Double taxation still occurs in the UK. Aggregated assets behind-the-meter can participate in wholesale markets via so-called Virtual Lead Parties. While balancing markets are accessible for V2G in principle, some services have specific requirements that cannot be fulfilled by demand side response aggregators. Local flexibility markets have started to scale up; V2G can participate. Smart meter penetration is above 50% and new systems are required to be interoperable with energy management systems.

Overall, the selected EU countries differ in their V2X-friendliness with regard to regulatory, policy and market considerations. For example, some of the considered countries stand out positively regarding the existence of V2X strategies and policies (e.g. Germany and the UK), others are rather favourable in terms of economic attractiveness due to the elimination of double taxation (e.g. Italy and Spain), again others allow for V2G participation in wholesale and balancing, as well as local flexibility markets (e.g. France and the UK). In addition, smart meter penetration is substantially higher in France, the UK and Spain than in the UK, Poland and Germany.

V2X is currently in a testing phase in many countries in Europe, and first commercial trials can be seen. In recent years, industry has increasingly recognized the potential and started to develop cars and charging points capable of bidirectional charging. Yet, many of the (announced) car models focus on V2L/V2H use cases, and the availability of cars that are capable of V2G is still scarce. Similarly, many of the announced bidirectional wallboxes are not available yet.

Previous work shows that V2X can have several socio-technical-economic benefits, such as increasing CO_2 emission reductions, integrating high shares of renewable power production or peak shaving and grid relief. However, the extent of the positive effects depends strongly on the individual case, and a comparison of existing studies is only possible to a limited extent. Recent studies have identified substantial economic potential for users with revenues ranging between approximately EUR300-1,500 per car and year, and between approximately EUR3,000-10,000 per truck and year in the case of depot charging.

In addition to technical barriers and potential acceptance issues, the current regulatory, policy and market environment defers or impedes V2X deployment. Regulation on EU-level has increasingly considered V2X, and recent regulatory revisions are conducive to V2X (e.g. the internal electricity market directive, the AFIR, the RED III, the EPBD and the ETD—once agreed upon). Yet, national law still must adapt accordingly in many cases. EU countries differ in their V2X-friendliness regarding regulatory, policy and market considerations.

3 Power system perspective: Bidirectional EV charging as flexibility resource in the EU power system

Bidirectional charging promises benefits for the power system, since electrified vehicles can function as moving batteries and offer the possibility of better integrating fluctuating renewable energies. This section examines the effects of smart charging and V2G on the European energy supply system in a model-based scenario study and assess what benefits flexibility from V2G can bring. The analysis looks in detail also on country level, considering differences in renewable energy generation, in the portfolio of power plant capacity and in the structure of electricity demand.

3.1 EV diffusion and future scenarios of V2G potential

3.1.1 Modelling approach

The analyses of the systemic effects of smart charging and V2G are carried out using a combination of the models ALADIN for the diffusion of cars, vans, light and heavy trucks with alternative drive systems and their load curves and Enertile for energy system development. The modelling approaches of both models are outlined below.

3.1.1.1 Aladin

ALADIN (Alternative automobiles diffusion and infrastructure) is a market diffusion model for alternative fuel vehicles. Using a utility maximization approach for passenger cars and a total cost of ownership approach for vans, light and heavy trucks, it models the purchase decision of individual users in an agent-based simulation of real-world driving profiles to derive market shares of the different drive technologies for each simulated year, distinguishing different user groups and vehicle sizes. Annual new registrations are aggregated to a vehicle stock. Using large data sets for individual user driving behaviour, ALADIN provides both the energy demands required by different drive technologies in the vehicle stock in the simulated years and aggregated driving and load profiles for the EV fleet throughout the year. This information is used as input parameters in the energy system cost minimisation of the Enertile model.

3.1.1.2 Enertile

The Enertile optimisation model is used to describe scenarios for the long-term transformation of the energy supply system in Europe. The aim of the optimisation is the cost-minimized, interlinked supply of electricity, heat and hydrogen in every hour of a year. For these three energy forms, Enertile takes the expansion and use of conversion, storage and transmission grid technologies into account. Costs considered include financing costs for investments in generation units and infrastructure (capital expenditures) as well as operational costs like fuel costs and maintenance costs of generation units, storage and electricity, hydrogen and heating grids.

The modelling covers the countries of the European Union as well as Norway, Switzerland and the United Kingdom. Central inputs include the techno-economic parameters of the modelled system components, fuel and CO_2 prices. Political goals for CO_2 reduction and development of renewable energies can be considered as political constraints.

3.1.2 Scenario framework

The benefits of V2X are expected to increase in future energy systems. For the assessment of potential benefits of V2X, the development of the power system must be projected into the future up to 2050. To do this, the model calculations are based on assumptions and energy demand projections of the S2 scenario derived in the TransHyDe project. This fulfils the policy goal of a GHG-neutral scenario for Europe by 2050. Further details are given in [46]. The following sections outline the development of final energy demand across all sectors, describe the assumptions for electricity demand and the flexibility potential of cars and trucks and define the scenario variants examined.

3.1.2.1 Final energy demand

Figure 2 shows the assumed development of final energy demands across the sectors industry, buildings and transport for the EU and the United Kingdom. Three interlinked developments can be observed. Firstly, fossil energy forms are exiting the system. While they still dominated the final energy demand with a share of 67% in 2020, they complete a full phaseout by 2050. Secondly, the reduction of fossil energy is partly substituted through the use of electricity. The deployment of electricity occurs both directly in electrified end-uses and indirectly through electricity-based hydrogen and its derivatives. In total, the final energy demand for electricity grows to 4,352 TWh, and the demand for electricity-based fuels increases to 2,396 TWh by 2050. Thirdly, electrification is accompanied by significant efficiency gains. Across all sectors, European final energy demand decreases by 4,205 TWh or 31% by 2050.

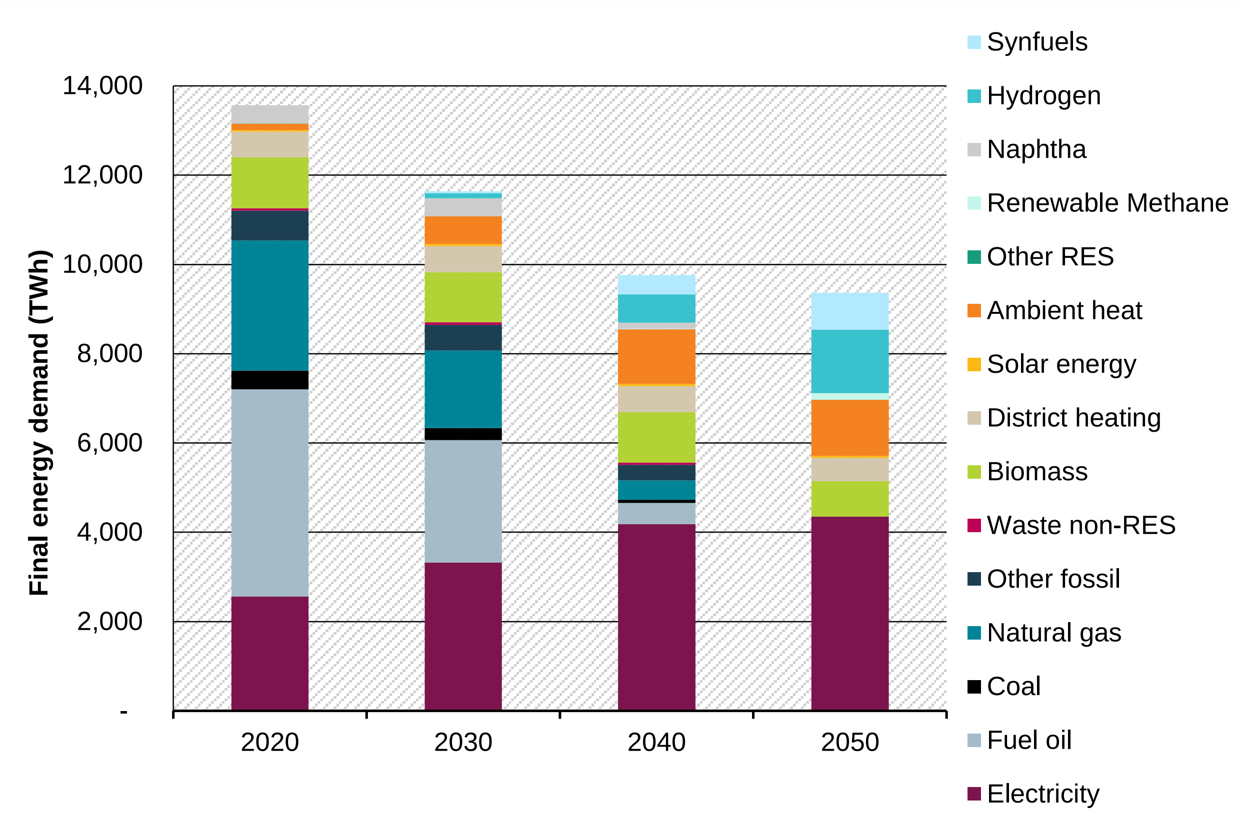


Figure 2: Assumed final energy demands across sectors in the European Union and the United Kingdom [46].

The high efficiency gains achieved through electrification occur to a large extent in road transport. In the underlying scenario of this study, a quasi-complete electrification of cars, vans, light and heavy trucks is assumed.

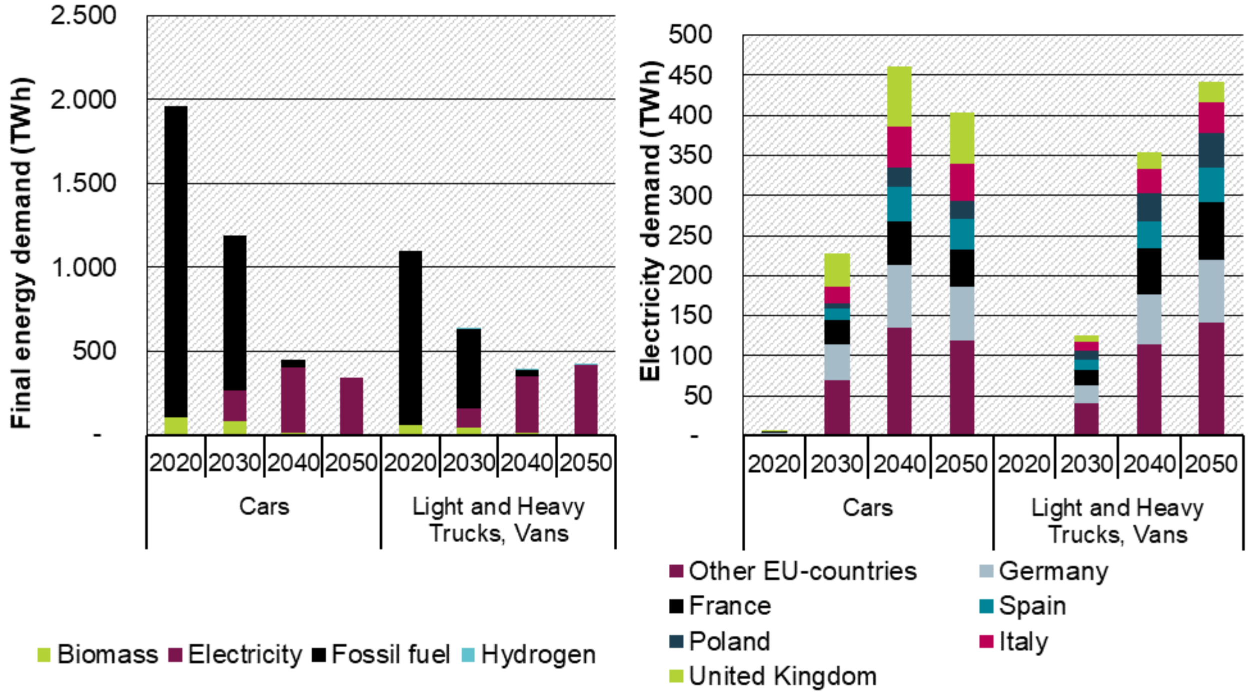


Figure 3 shows the projected development of energy demand (left) in the EU 27 and country-specific electricity demand (right) for cars, light and heavy trucks and vans. The switch from combustion engines to electric drives is the main factor causing the decline in energy demand in the EU 27 for cars from 1,964 TWh in 2020 to 340 TWh in 2050 and for trucks/vans from 1,098 TWh in 2020 to 418 TWh in 2050. The reduction in electricity demand by cars between 2040 and 2050 is based on the assumption that a modal shift from cars to others forms of mobility takes place and that sufficiency leads to less driven kilometers in total.

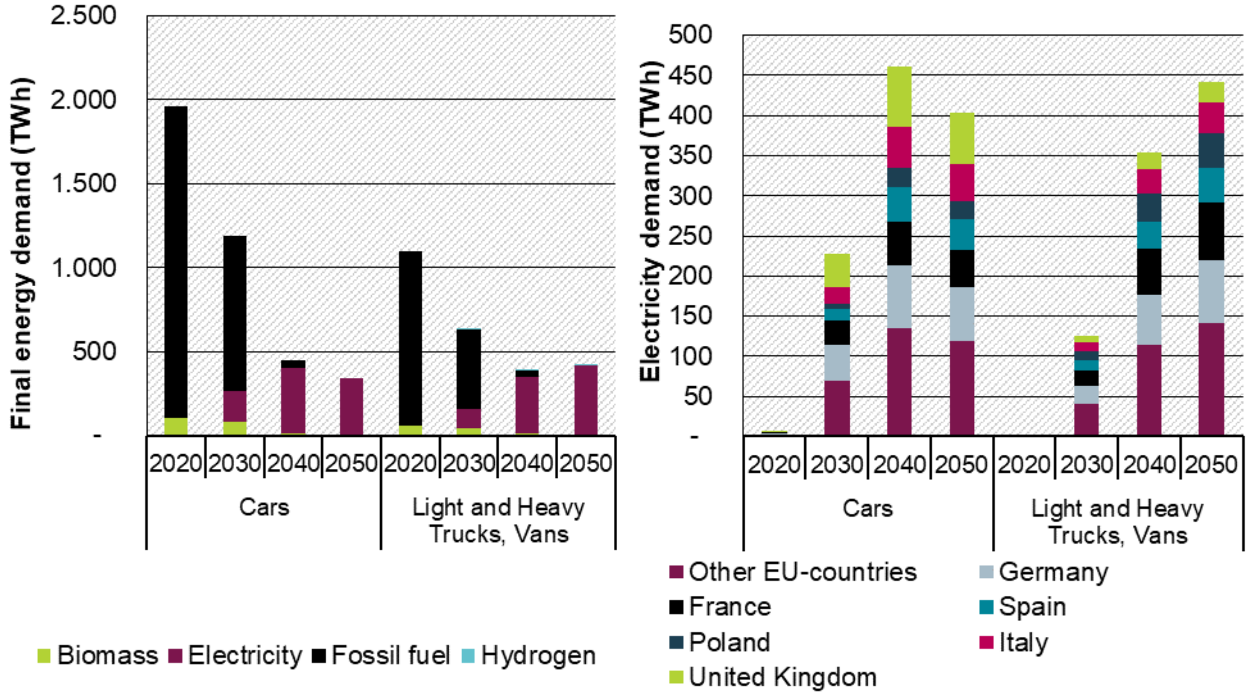


Figure 3: **Assumed projections of energy demand (left) in the European Union and country-specific electricity demand (right) for cars, light and heavy trucks and vans [46].**

3.1.2.2 Stock development

The bar graph in Figure 4 illustrates the projected vehicle stocks for cars and trucks[15] in the European Union EU 27 until 2050. The graph categorizes vehicles into three types: Battery electric vehicles (BEV), plug-in hybrid electric vehicles (PHEV) and others. It shows a strong increase in the stocks of BEVs for both cars and trucks. A share of 58 % of cars and 94 % of trucks including heavy and light trucks and vans is assumed to be equipped with batteries in 2040.

[15] Trucks include light and heavy duty vehicles.

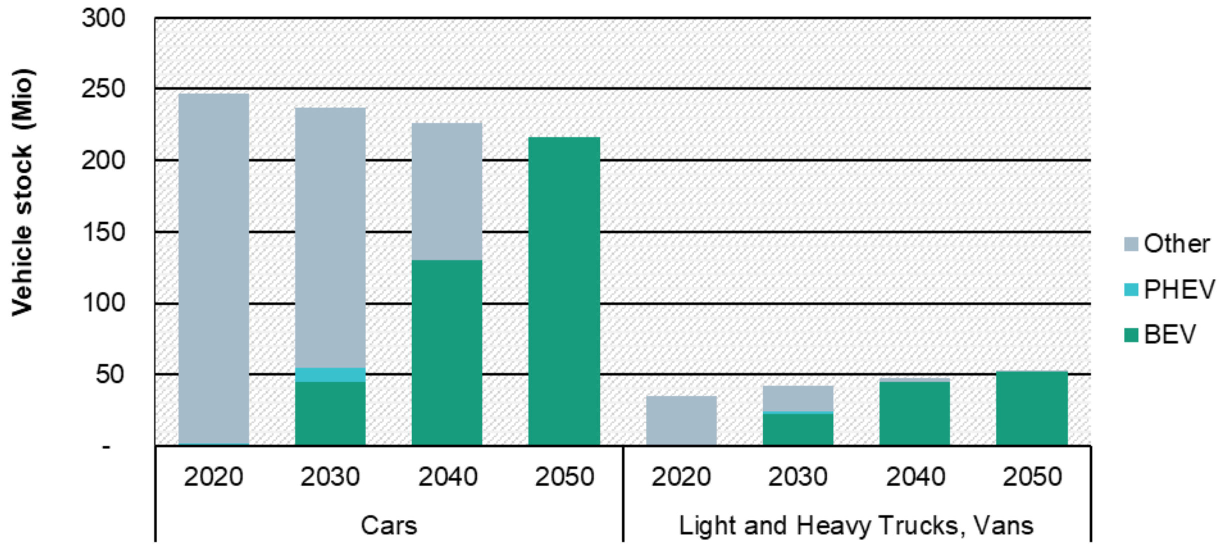


Figure 4: Assumed stock development of cars, light and heavy trucks and vans in the European Union [46].

3.1.2.3 Flexibility options and constraints in the energy supply optimisation

For the modelling analysis of the flexibility potential of bidirectional charging of passenger cars and electric trucks in the EU power system and in its Member States, the flexibility is defined by the following parameters and assumptions. Based on these assumptions, the benefit of bidirectional charging to integrate renewable energy sources is calculated.

Cars

The power system model is used to optimise the supply-side to fulfil the electricity demand at lowest costs. Bidirectional charging of cars provides flexibility to the power system and is implemented as an additional option with three main characteristics:

- All battery electric cars in a model region are aggregated into a mobile battery storage system. Driving cars is defined as an hourly, exogenous battery discharging process based on an aggregated driving profile.
- This battery storage system's minimum and maximum state of charge (SOC) for each time step are determined based on real driving profiles and with two contrasting charging strategies. For the maximum SOC, cars are assumed to charge as quickly and as much as possible as soon as they are connected to a power source. For the minimum SOC, it is assumed that only a sufficient amount is charged to complete the next journey(s) and that the battery is charged as late as possible, considering the following driving schedule and available charging options.
- Hourly charging and system-beneficial discharging capacities are limited by the cars' driving and parking times (Figure 5).

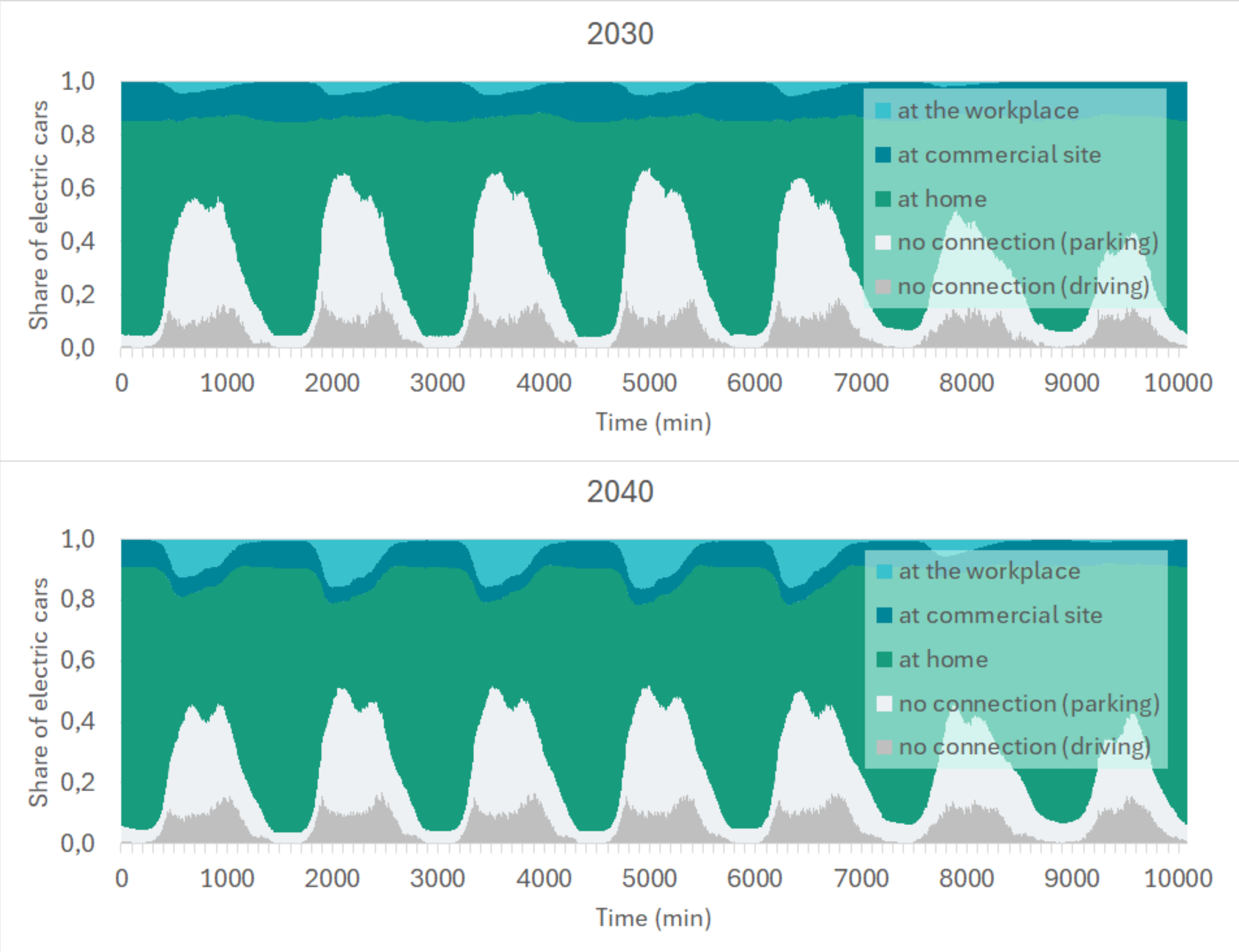


Figure 5: Assumed hourly share of battery electric cars connected to the grid, parking, or driving for one week in 2030 and 2040.

Trucks (light and heavy trucks, vans)

The flexibility of electric trucks as an option in the power system model is implemented with the following main characteristics:

- Only private slow charging of trucks (private, <44kW), defined in Speth and Plötz (2024), is available for flexible, bidirectional charging in the power system optimisation model [47]. All other charging processes are assumed to be uncontrolled. Figure 6 shows the assumed hourly distributions of driving and charging behaviour and normalised load curves prior to the system optimisation of battery electric trucks.
- Based on Figure 6, we simplify by defining that bidirectional charging is only possible overnight between 5 p.m. and 5 a.m.
- All trucks applicable to flexible (dis-)charging in a model region are aggregated into a virtual, mobile battery storage system. Truck driving is defined as an hourly, exogenous battery discharging process based on an aggregated driving profile.
- Hourly charging and system-beneficial discharging capacities are limited by the trucks' driving and parking times (Figure 6).

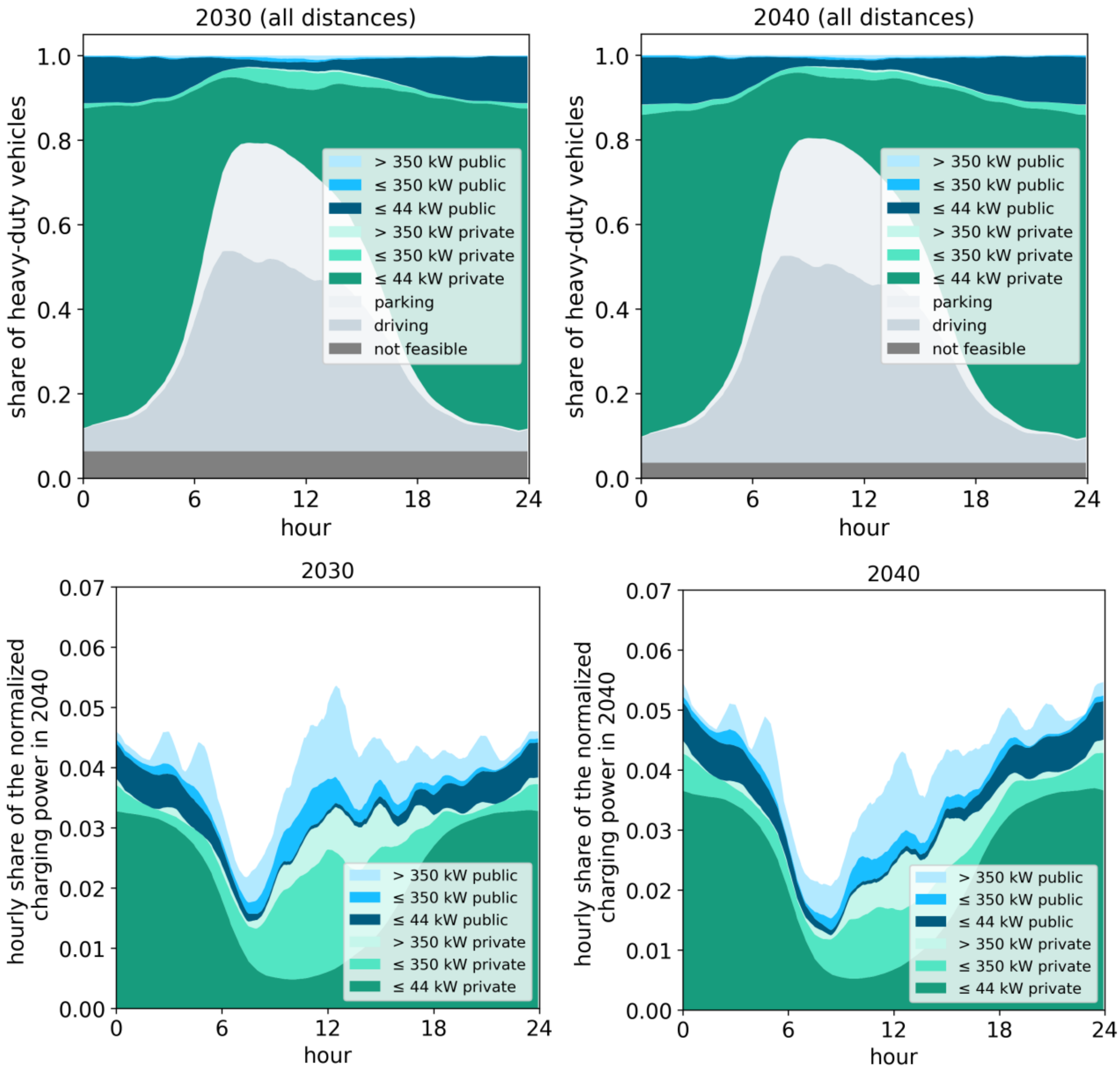


Figure 6: Assumed hourly driving and charging shares (top) and normalized load curves prior to the system optimisation (bottom) of battery electric trucks in 2030 (left) and 2040 (right). Source: [47].

3.1.2.4 Scenario variants

The benefits for bidirectional charging are calculated in 5 different scenarios with increasing shares of cars and trucks that could be used to provide flexibility. Results are derived for 2030 and 2040 based on the electricity demand projections for cars and trucks from the TransHyDE S2 scenario (section 3.1.2.1) and the assumptions on driving profiles and charging strategies (section 3.1.2.3), comparing results from the 5 scenario variants that differ in the penetration of vehicles able to charge in a controlled and bidirectional way. The starting point of the analysis is a reference scenario in which uncontrolled charging is assumed for both cars and trucks (see Table 3). In the Car I scenario, 25% in 2030 and 35% in 2040 of electricity demand from cars are capable of smart charging and V2X in accordance with the BDL scenario in the FfE study [20]. In the Car II scenario, 50% of the electricity demand of cars can be used for V2X and 84% (in 2030) resp. 72% (in 2040) for smart charging. The shares for smart charging and V2X in this scenario correspond to scenario Sen2 of the FfE study [20].

It is assumed that trucks charge uncontrolledly in both scenarios. In the Truck scenario, it is assumed that only truck batteries are available for system flexibilization with 50% of their electricity demand. The shares of the energy volumes available for system-beneficial bidirectional charging are derived from energy volumes in Speth and Plötz (2024) that are drawn from private charging points <44 kW [47]. The Car II & Truck scenario combines the flexibility potentials of the Car II scenario and the Truck scenario.

Table 3: Scenario variants for share* of cars and trucks with smart charging and V2X capabilities for 2030 and 2040

Scenario		Reference		Car I		Car II		Truck		Car II & Truck	
Year		2030	2040	2030	2040	2030	2040	2030	2040	2030	2040
Cars	Smart charge	0%	0%	25%	35%	84%	72%	0%	0%	84%	72%
	V2X	0%	0%	25%	35%	50%	50%	0%	0%	50%	50%
Light and Heavy Trucks, Vans	Smart charge	0%	0%	0%	0%	0%	0%	50%	55%	50%	55%
	V2X	0%	0%	0%	0%	0%	0%	50%	55%	50%	55%

** Share is related to the energy demand of the vehicles (cars and trucks) that can be charged in a smart resp. bidirectional way. Optimization considers also driving profiles and battery restrictions.*

3.2 Impacts of bidirectional charging on power system and renewable integration

The usage of flexibility from bidirectional charging allows the power system model to optimise the supply side and reduce the costs to fulfil the electricity demand. The investment in generation units is adapted and the operation of the units also change. Detailed results for the EU including Norway, Switzerland and UK and for single countries are modelled.

3.2.1 Aggregate power system in the EU

Figure 7 and Figure 8 show the modelled, joint electricity balances and electric capacities for the EU 27 in the Reference scenario and their changes in the analysed scenario variants.

The results of the Reference scenario reflect the effects of the progressive direct and indirect electrification of applications in the energy demand sectors: electricity supply in Europe increases to over 3,500 TWh in 2030 and to over 5,100 TWh in 2040. Renewable electricity generation technologies dominate the electricity mix in 2030 and increase their share until 2040. Onshore wind is the technology with the highest electricity generation, contributing 1,083 TWh in 2030 and 1,924 TWh in 2040. PV has the second largest contribution to the electricity mix, with 740 TWh in 2030 and 1,223 TWh in 2040. Due to the comparatively high costs, offshore wind is only expanded up to the exogenously specified minimum capacities of 71 GW in 2030 and 168 GW in 2040. It accounts for 277 TWh in 2030 and 694 TWh in 2040 of European electricity generation in the model results. The highest electricity generation from remaining fossil sources originates from nuclear energy: 635 TWh in 2030 and

453 TWh in 2040. Gas and hydrogen power plants balance the electricity system in hours of high residual loads and jointly generate 173 TWh in 2030 and 97 TWh in 2040. The joint capacity of these backup power plants is 168 GW in 2030 and 200 GW in 2040. In the model results of the Reference scenario, stationary battery storage systems offer short-term flexibility and have volumes of 173 GWh in 2030 and 149 GWh in 2040.

Four key effects can be observed in the European electricity system, as the flexibility offered by bidirectional charging of cars increases. Firstly, optimisation extensively uses vehicle batteries and, particularly, V2X for system services. In the Car I (Car II) scenario, cars feed 47 TWh (124 TWh) back into the system in 2030. Compared with total electricity supply, this corresponds to a share of 1% (3%) in the Car I (Car II) scenario. In 2040, this figure increases to 339 TWh (519 TWh) or 6% (9%) in the Car I (Car II) scenario. Secondly, the mobile battery storages of electric vehicles are displacing alternative flexibility and storage options:

- The volume of stationary battery storage decreases in the Car I (Car II) scenario to 72 GWh (12 GWh) in 2030 and 12 GWh (12 GWh) in 2040.
- The capacity and deployment of flexible hydrogen technologies are reduced. In the Car I (Car II) scenario, the capacity of electrolysers decreases by 2 GW (8 GW) in 2030 and 54 GW (69 GW) in 2040; the capacity of hydrogen power plants in the Car I (Car II) scenario decreases by 8 GW (18 GW) in 2030 and 82 GW (108 GW) in 2040.
- Concentrated solar power (CSP), the renewable power generation technology with integrated heat storage, is reduced by 5 GW (19 GW) in 2030 and 48 GW (61 GW) in 2040 in the Car I (Car II) scenario.

Thirdly, in the renewable power generation portfolio, system optimisation swaps onshore wind for PV. While the PV capacity in the Car I (Car II) scenario increases to 694 GW (782 GW) in 2030 and 1,379 GW (1,556 GW) in 2040, the onshore wind capacity decreases to 429 GW (412 GW) in 2030 and 685 GW (651 GW) in 2040. The car batteries help to integrate high PV peaks. The provision of stored solar power in more hours displaces onshore wind feed-in. Lastly, the additional storage option by cars reduces the curtailment of renewable electricity in the Car I (Car II) scenario by 2 TWh (11 TWh) in 2030 and 28 TWh (39 TWh) in 2040.

The flexibility potential of light and heavy trucks and vans, as modelled in this study, changes the electricity generation only slightly. The electricity balances in the Truck scenario are very similar to those of the Reference Scenario. Furthermore, the electricity balance of the Car II & Truck scenario differs little from that of the Car II scenario. However, the truck batteries displace other flexible capacities in 2040: Compared to the Reference scenario, the volume of stationary batteries in the truck scenario decreases by 72 GWh, the capacity of hydrogen power plants by 21 GW and the capacity of electrolysers by 10 GW.

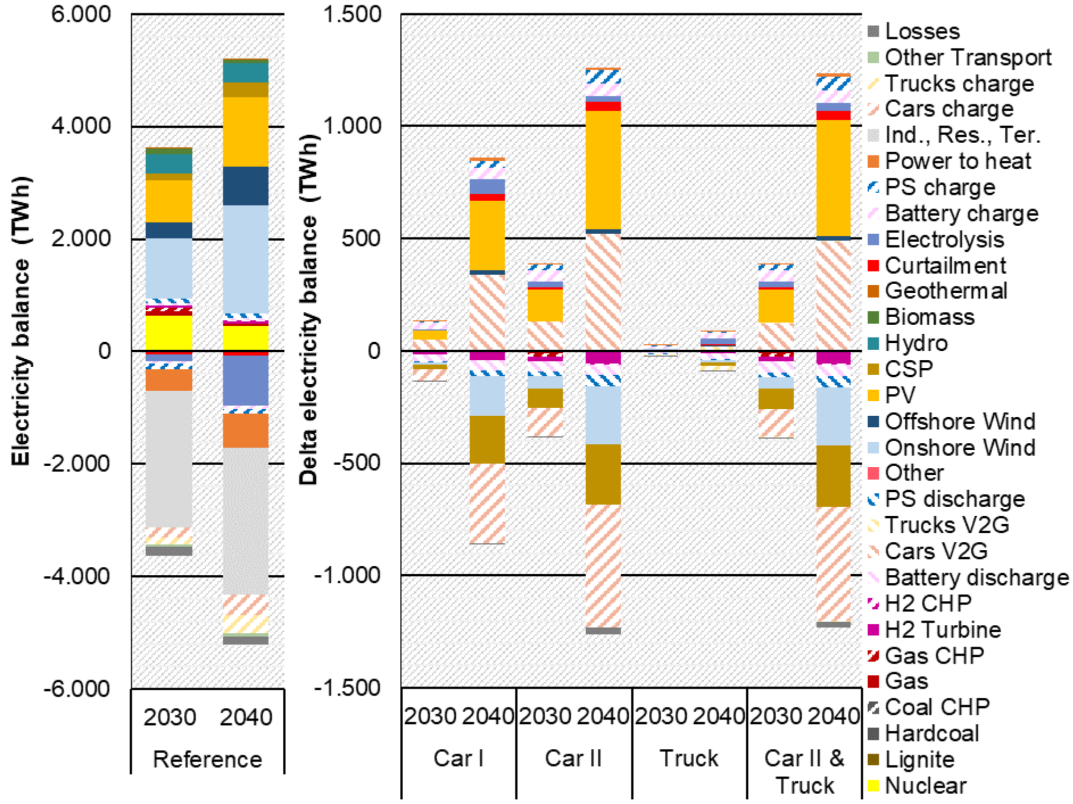


Figure 7: **Joint electricity balances and changes in the scenario variants for the EU 27**

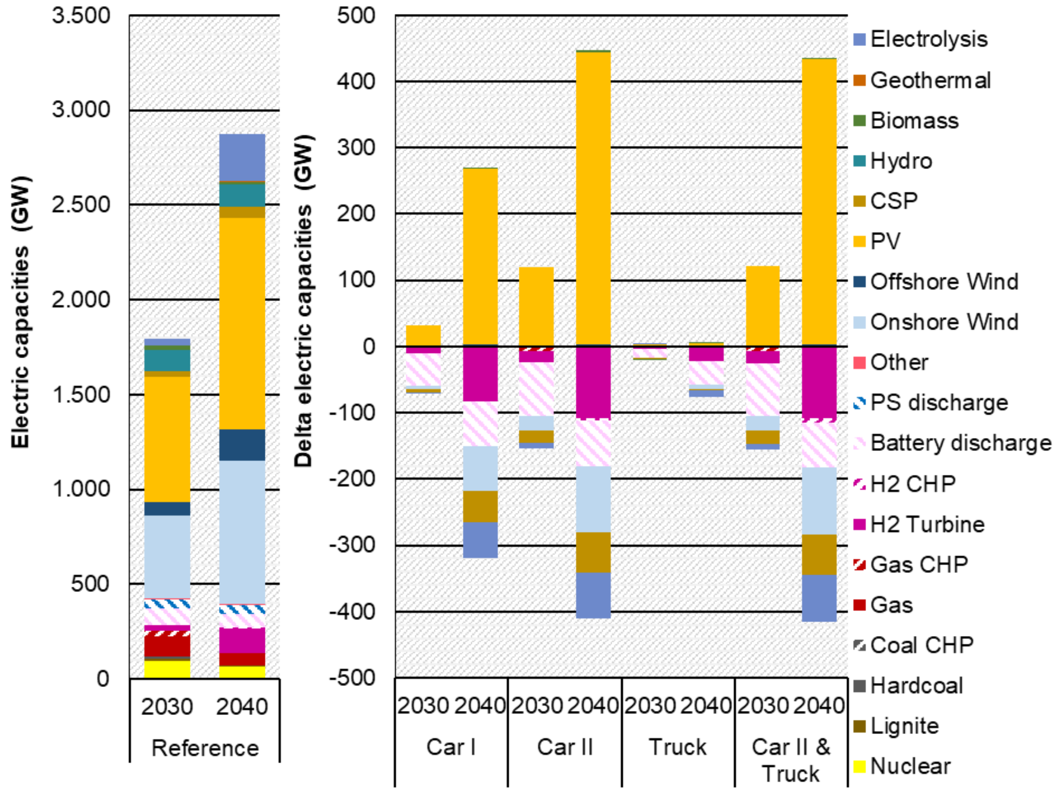


Figure 8: **Electric capacities and changes in the scenario variants for the EU 27**

3.2.2 Germany

Figure 9 and Figure 10 show the electricity balance and electric capacities for Germany in the Reference scenario and their changes in the analysed scenario variants.

The results of the Reference scenario reflect the effects of the progressive direct and indirect electrification of applications in the energy demand sectors: electricity supply in Germany increases to over 750 TWh in 2030 and to over 1,150 TWh in 2040. Renewable electricity generation technologies dominate the electricity mix in 2030 and increase their share until 2040. Onshore wind is the technology with the highest electricity generation, contributing 285 TWh in 2030 and 386 TWh in 2040. PV has the second largest contribution to the electricity mix, with 203 TWh in 2030 and 361 TWh in 2040. Due to the comparatively high costs, offshore wind is only expanded up to the exogenously specified minimum capacities of 30 GW in 2030 and 70 GW in 2040. It accounts for 123 TWh in 2030 and 308 TWh in 2040 of the German electricity generation in the model results. In this scenario, Germany imports a net 37 TWh of electricity in 2030 and 44 TWh in 2040. Gas and hydrogen power plants balance the electricity system in hours of high residual loads and jointly generate 59 TWh in 2030 and 45 TWh in 2040. The joint capacity of these backup power plants is 34 GW in 2030 and 76 GW in 2040. In the model results of the Reference scenario, stationary battery storage systems offer short-term flexibility and have volumes of 83 GWh in 2030 and 12 GWh in 2040.

Three key effects can be observed in the German electricity system, as the flexibility offered by bidirectional charging of cars increases. Firstly, optimisation extensively uses vehicle batteries and, particularly V2X, for system services. In the Car I (Car II) scenario, cars feed 13 TWh (33 TWh) back into the system in 2030. Compared with the total electricity supply, this corresponds to a share of 2% (4%) in the Car I (Car II) scenario. In 2040, this figure increases to 62 TWh (82 TWh) or 5% (7%) in the Car I (Car II) scenario. Secondly, the mobile battery storages of electric vehicles are displacing alternative flexibility and storage options:

- The volume of stationary battery storage decreases in the Car I (Car II) scenario to 38 GWh (12 GWh) in 2030 and 12 GWh (12 GWh) in 2040.
- The capacity and deployment of flexible hydrogen technologies are reduced. In the Car I (Car II) scenario the capacity of electrolysers decreases by 1 GW (4 GW) in 2030 and 11 GW (15 GW) in 2040; the capacity of hydrogen power plants in the Car I (Car II) scenario decreases by 6 GW (11 GW) in 2030 and 51 GW (56 GW) in 2040.

Thirdly, net electricity imports decrease in 2030 and increase in 2040. In 2030, net transfer capacities to neighbouring countries are fixed to the expansion plans in the Ten Year Network Development Plan (TYNDP) 2020 and national network expansion plans. Net imports decrease in the Car I (Car II) scenario by 1 TWh (8 TWh). In 2040, optimisation expands 0.3 GW (1.6 GW) less NTC, although net imports increase by 23 TWh (35 TWh) in the Car I (Car II) scenario. The increase in net imports is mainly due to a reduction in exports.

As for the aggregate electricity balance of the EU, Norway, Switzerland and the UK, the flexibility potential of trucks changes the German electricity generation only slightly. However, the truck batteries displace other flexible capacities. In 2030, the volume of stationary batteries in the truck scenario decreases by 12 GWh. In 2040, the capacity of electrolysers decreases by 10 GW compared to the Reference scenario.

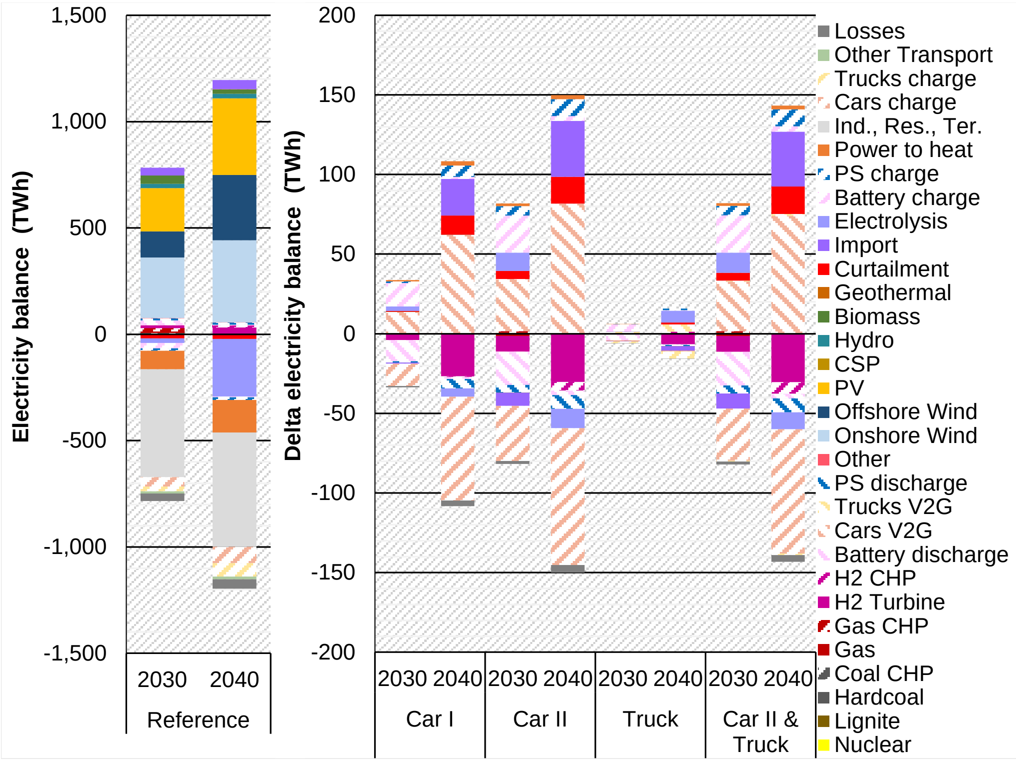


Figure 9: **Electricity balances and their changes in the scenario variants for Germany.**

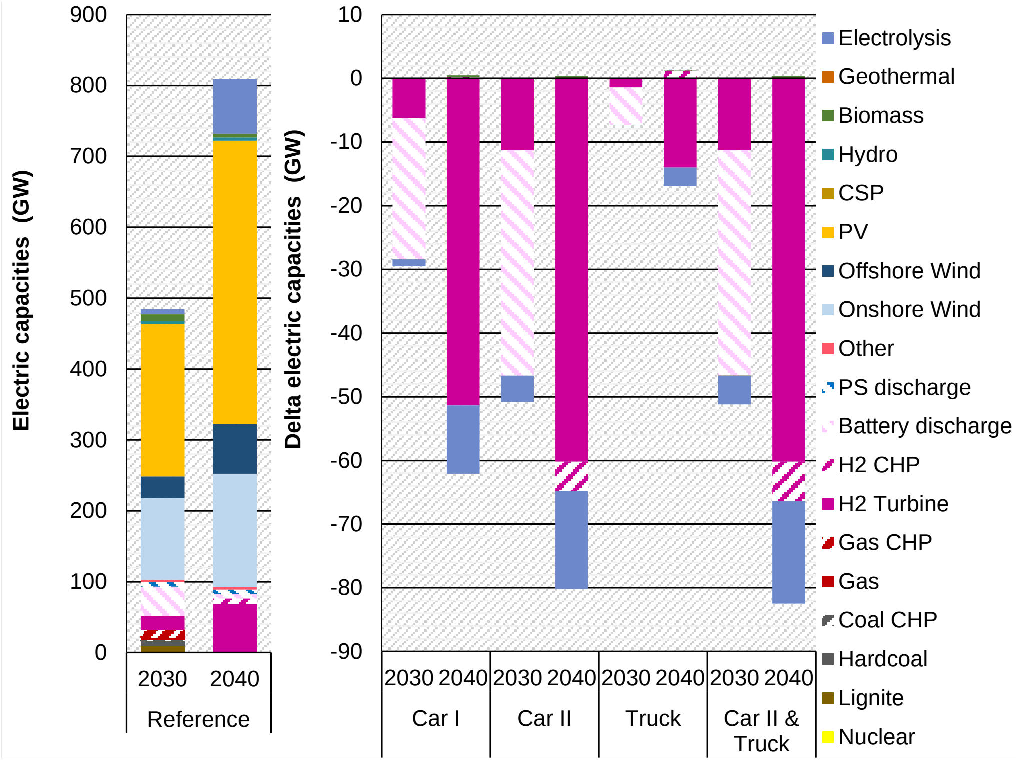


Figure 10: **Electric capacities and their changes in the scenario variants for Germany.**

3.2.3 France

Figure 11 and Figure 12 show the electricity balance and electric capacities for France in the reference scenario and their changes in the analysed scenario variants.

The results of the Reference scenario reflect the effects of the progressive direct and indirect electrification of applications in the energy demand sectors: electricity supply in France increases to over 650 TWh in 2030 and to over 950 TWh in 2040. Nuclear power dominates the electricity mix in 2030. It provides about 400 TWh of electricity. Renewable electricity generation technologies become major electricity suppliers in 2040. Onshore wind is the technology with the highest renewable electricity generation, contributing 131 TWh in 2030 and 466 TWh in 2040. PV has the second largest contribution of fluctuating renewables to the electricity mix, with 43 TWh in 2030 and 184 TWh in 2040. Gas and hydrogen power plants have a minor role in this electricity system as backup power plants, generating less than 1 TWh of electricity each in 2030 and 2040. The joint capacity of these power plants is 4 GW in 2030 and 9 GW in 2040. In this scenario, France is a net exporter of electricity, totalling 65 TWh in 2030 and 84 TWh in 2040. The optimisation does not use any stationary battery storage systems in France for these simulation years.

Four key effects can be observed in the French electricity system, as the flexibility offered by bidirectional charging of cars increases. Firstly, optimisation extensively uses vehicle batteries and particularly V2X for system services. In the Car I (Car II) scenario, cars feed 7 TWh (12 TWh) back into the system in 2030. Compared with the total electricity supply, this corresponds to a share of 1% (2%) in the Car I (Car II) scenario. In 2040, this figure increases to 53 TWh (64 TWh) or 5% (6%) in the Car I (Car II) scenario. Secondly, the mobile battery storages of electric vehicles are displacing alternative flexibility and storage options:

- The electricity generation of CSP plants decreases in the Car I and the Car II) scenario by 8 TWh in 2040.
- The capacity and deployment of flexible hydrogen technologies are reduced. The capacity of electrolysers in 2040 decreases by 2 GW in the Car I scenario and by 14 GW in the Car II scenario; the capacity of hydrogen power plants decreases by 7 GW in the Car I and the Car II scenario in 2040.

Thirdly, there is a trade-off in the renewable electricity generation portfolio. On the one hand, PV capacity increases substantially in the Car I (Car II) scenario by 8 GW (20 GW) in 2030 and by 64 GW (54 GW) in 2040. On the other hand, onshore wind capacity decreases in the Car I (Car II) scenario by 2 GW (6 GW) in 2030 and by 0 GW (8 GW) in 2040. Lastly, there is an increase in electricity exports to other European countries. Net exports in the Car I (Car II) scenario increase by 4 TWh (10 TWh) in 2030 and by 29 TWh (20 TWh) in 2040.

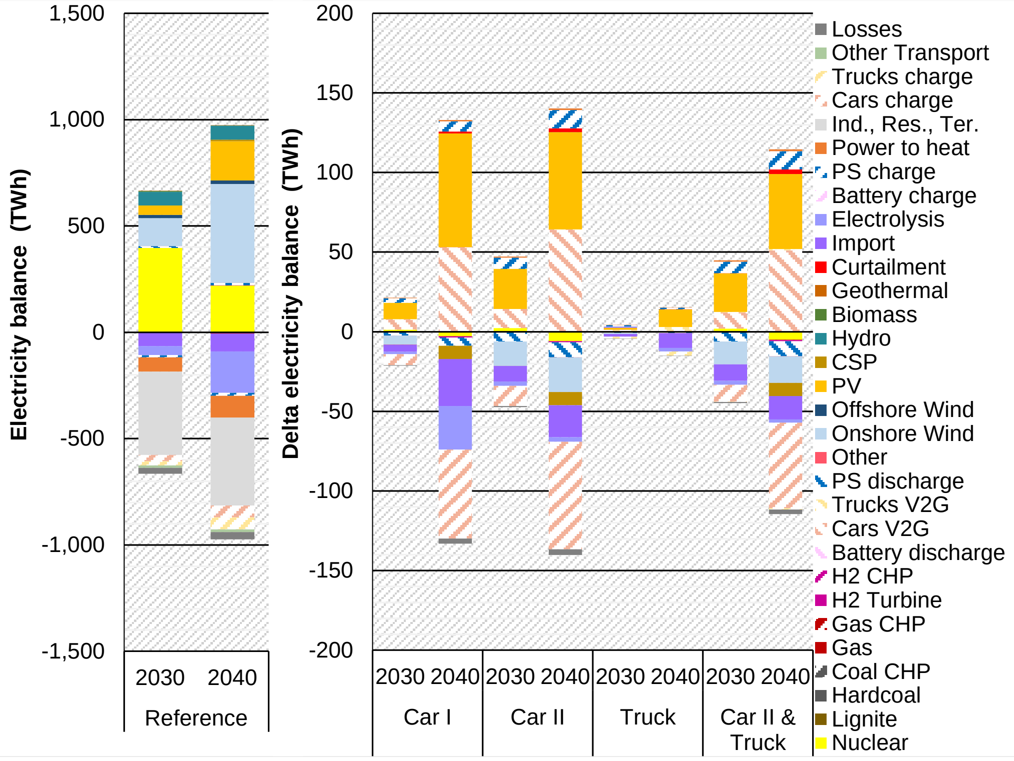


Figure 11: Electricity balances and their changes in the scenario variants for France.

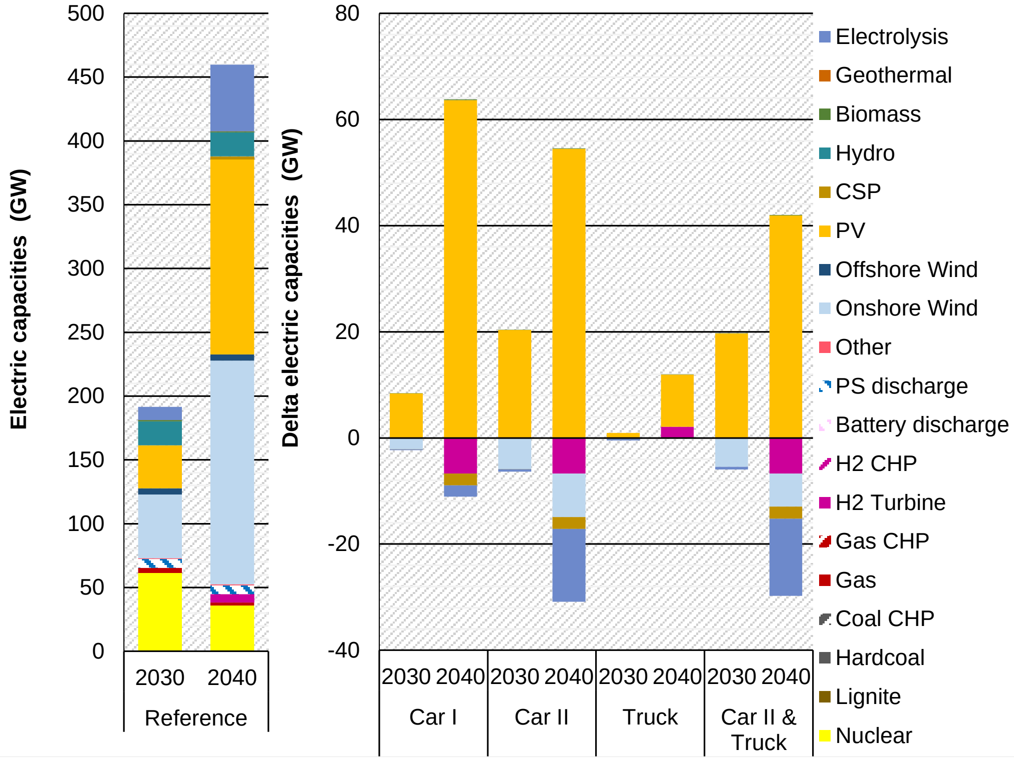


Figure 12: Electric capacities and their changes in the scenario variants for France.

3.2.4 Spain

Figure 13 and Figure 14 show the electricity balance and electric capacities for Spain in the reference scenario and their changes in the analysed scenario variants.

The results of the Reference scenario reflect the effects of the progressive direct and indirect electrification of applications in the energy demand sectors: electricity supply in Spain increases to over 320 TWh in 2030 and to over 450 TWh in 2040. Renewable electricity generation technologies dominate the electricity mix in 2030 and increase their share until 2040. Solar power technologies show the highest electricity generation, contributing 177 TWh in 2030 and 317 TWh in 2040. In the Reference scenario, in addition to PV, CSP particularly contributes to the electricity mix. CSP generates 87 TWh in 2030 and 205 TWh in 2040. Onshore wind makes the third largest contribution of fluctuating renewables to the electricity mix, with 78 TWh in 2030 and 102 TWh in 2040. In 2030, the highest electricity generation from other sources than wind and solar originates from nuclear energy providing 21 TWh. Gas and hydrogen power plants have a minor role in this electricity system as backup power plants, generating less than 3 TWh of electricity each in 2030 and 2040. The joint capacity of these power plants is 23 GW in 2030 and 21 GW in 2040. In this scenario, France is a net exporter of electricity totalling 11 TWh in 2030 and 32 TWh in 2040. The optimisation does not use any stationary battery storage systems in France for these simulation years.

Three key effects can be observed in Spain's electricity system, as the flexibility offered by the bidirectional charging of cars increases. Firstly, optimisation extensively uses vehicle batteries and, particularly, V2X for system services. In the Car I (Car II) scenario, cars feed 4 TWh (15 TWh) back into the system in 2030. Compared with the total electricity supply, this corresponds to a share of 1% (5%) in the Car I (Car II) scenario. In 2040, this figure increases to 50 TWh (98 TWh) or 10% (18%) in the Car I (Car II) scenario. Secondly, the mobile battery storages of electric vehicles allow a trade-off in the renewable electricity generation portfolio between CSP and PV. On the one hand, PV capacity increases substantially in the Car I (Car II) scenario by 9 GW (24 GW) in 2030 and by 78 GW (139 GW) in 2040. On the other hand, CSP capacity decreases in the Car I (Car II) scenario by 4 GW (13 GW) in 2030 and by 32 GW (45 GW) in 2040. Thirdly, net exports decrease in the Car I (Car II) scenario by 4 TWh (15 TWh) in 2030 and by 25 TWh (13 TWh) in 2040.

As for the aggregate electricity balance of the EU, Norway, Switzerland and the UK, the flexibility potential of trucks changes the Spanish electricity generation only slightly: For bidirectional charging of cars, there is a trade-off between CSP and PV. The PV capacity increases in the Truck scenario by 2 GW in 2030 and by 6 GW in 2040. The CSP capacity decreases in the Truck scenario by 1 GW in 2030 and by 3 GW in 2040.

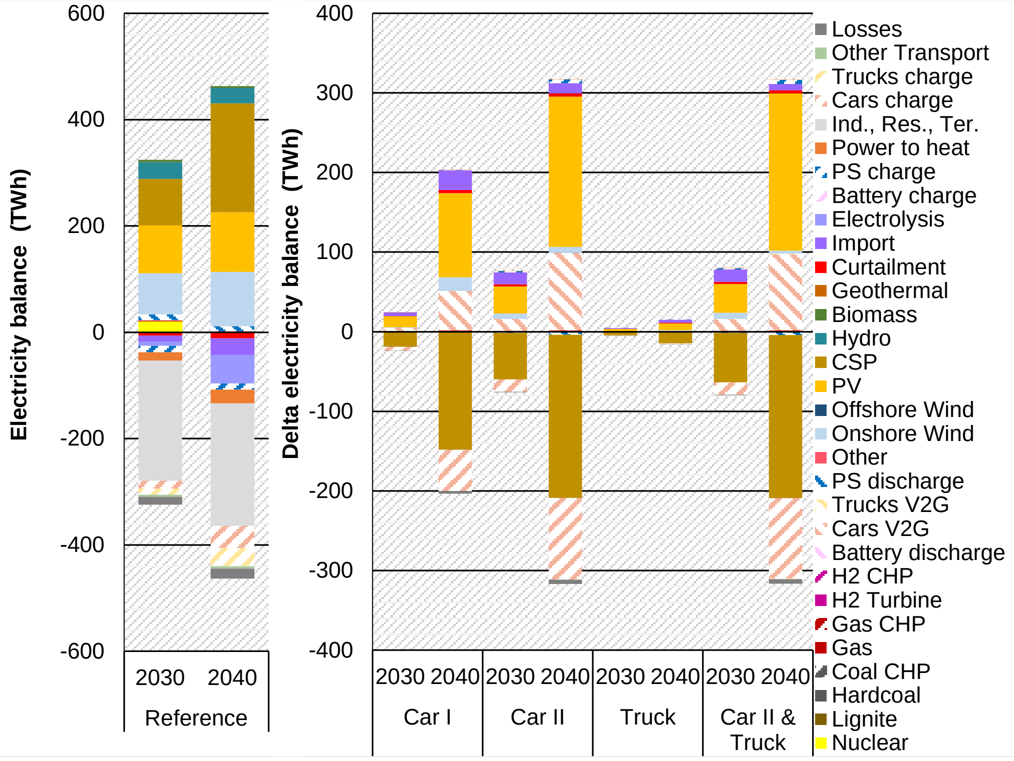


Figure 13: **Electricity balances and their changes in the scenario variants for Spain.**

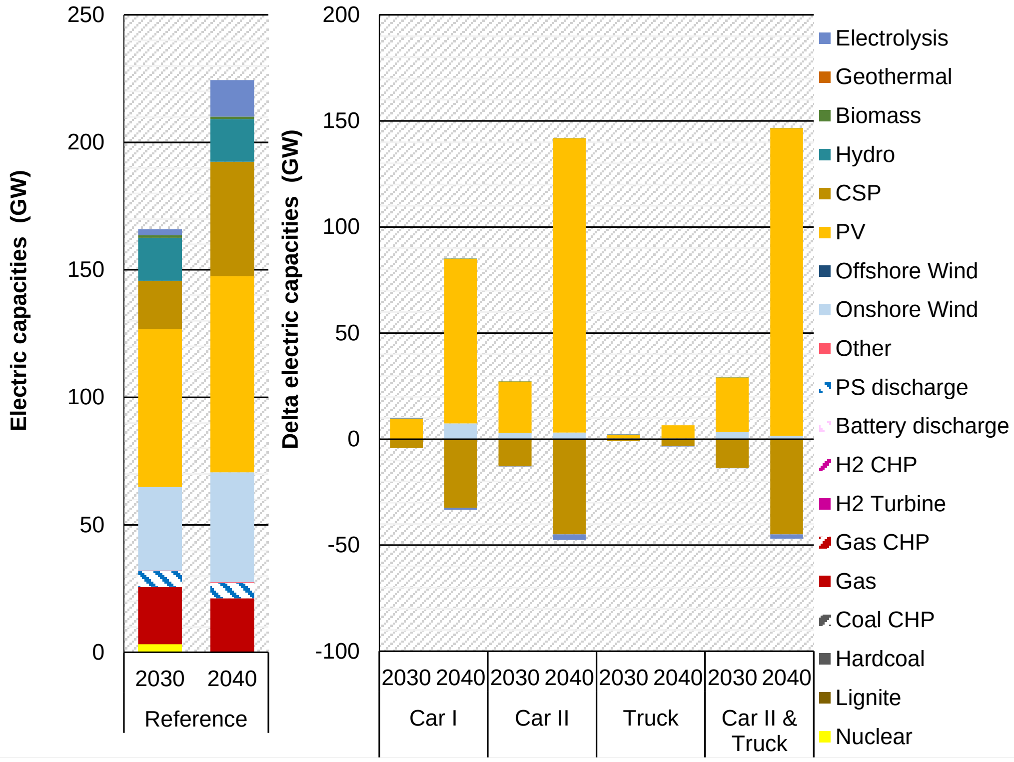


Figure 14: **Electric capacities and their changes in the scenario variants for Spain.**

3.2.5 Italy

Figure 15 and Figure 16 show the electricity balance and electric capacities for Italy in the reference scenario and their changes in the analysed scenario variants.

The results of the reference scenario reflect the effects of the progressive direct and indirect electrification of applications in the energy demand sectors: electricity supply in Italy increases to over 400 TWh in 2030 and to over 550 TWh in 2040. Renewable electricity generation technologies dominate the electricity mix in 2030 and increase their share until 2040. PV shows the highest electricity generation, contributing 159 TWh in 2030 and 260 TWh in 2040. Onshore wind has the second largest contribution of fluctuating renewables to the electricity mix, with 97 TWh in 2030 and 2040. In this scenario, Italy imports a net 17 TWh of electricity in 2030 and 42 TWh in 2040. Gas and hydrogen power plants balance the electricity system in hours of high residual loads and jointly generate 29 TWh in 2030 and 23 TWh in 2040. The joint capacity of these backup power plants is 39 GW in 2030 and 28 GW in 2040. In the model results of the Reference scenario, stationary battery storage systems offer short-term flexibility and have volumes of 53 GWh in 2030 and 119 GWh in 2040.

Three key effects can be observed in the Italian electricity system, as the flexibility offered by bidirectional charging of cars increases. Firstly, optimisation extensively uses vehicle batteries and, particularly, V2X for system services. In the Car I (Car II) scenario, cars feed 7 TWh (23 TWh) back into the system in 2030. Compared with the total electricity supply, this corresponds to a share of 2% (6%) in the Car I (Car II) scenario. In 2040, this figure increases to 65 TWh (120 TWh) or 12% (18%) in the Car I (Car II) scenario. Secondly, the mobile battery storages of electric vehicles displace stationary batteries. The volume of stationary battery storage decreases in the Car I (Car II) scenario to 15 GWh (0 GWh) in 2030 and 0 GWh (0 GWh) in 2040. Thirdly, PV capacity increases substantially in the Car II scenario by 21 GW in 2030 and by 94 GW in 2040. Thirdly, net electricity imports decrease in 2040 in the Car I (Car II) scenario by 8 TWh (36 TWh).

In the Truck scenario, the Italian electricity generation does not change compared to the Reference scenario in 2030. In 2040, the flexibility potential of trucks decreases the capacities of PV by 17 GW and of stationary batteries by 57 GWh.

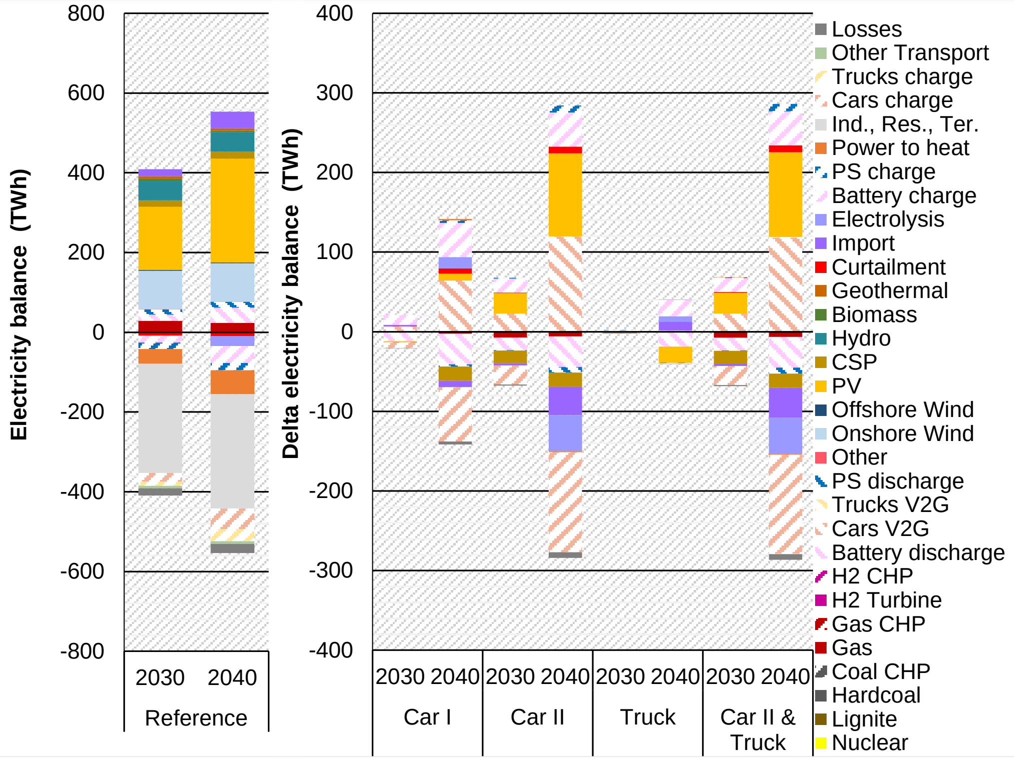


Figure 15: **Electricity balances and their changes in the scenario variants for Italy.**

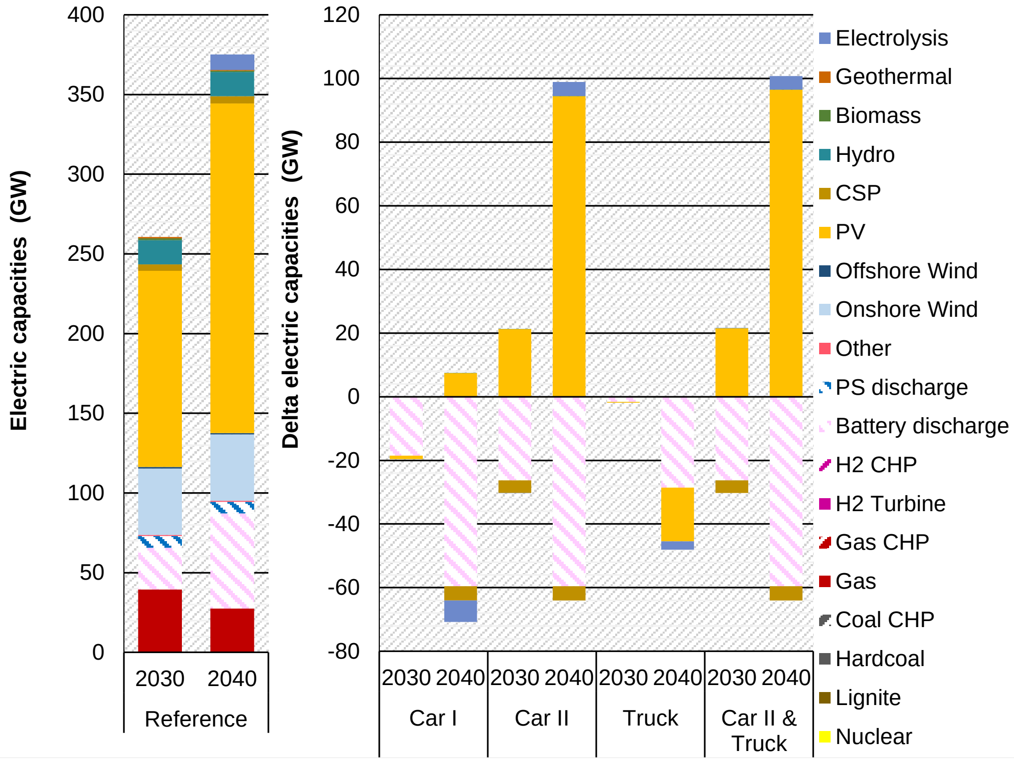


Figure 16: **Electric capacities and their changes in the scenario variants for Italy.**

3.2.6 Poland

Figure 17 and Figure 18 show the electricity balance and electric capacities for Poland in the Reference scenario and their changes in the analysed scenario variants.

The results of the Reference scenario reflect the effects of the progressive direct and indirect electrification of applications in the energy demand sectors: electricity supply in Poland increases to over 230 TWh in 2030 and to over 350 TWh in 2040. Renewable electricity generation technologies dominate the electricity mix in 2030 and increase their share until 2040. Onshore shows the highest electricity generation, contributing 122 TWh in 2030 and 218 TWh in 2040. PV has the second largest contribution of fluctuating renewables to the electricity mix, with 54 TWh in 2030 and 59 TWh in 2040. In this scenario, Poland imports a net 26 TWh of electricity in 2040; in 2030, Poland's net trading is balanced. Based on existing plans, Poland will begin nuclear power generation by 2033 and, therefore, shows in this scenario an electricity generation of 36 TWh in nuclear power plants in 2040. Gas and hydrogen power plants balance the electricity system in hours of high residual loads and jointly generate 29 TWh in 2030 and 7 TWh in 2040. The joint capacity of these backup power plants is 12 GW in 2030 and 15 GW in 2040. In the model results of the Reference scenario, stationary battery storage systems offer short-term flexibility and have volumes of 18 GWh in 2030 and 0 GWh in 2040.

Three key effects can be observed in the Polish electricity system, as the flexibility offered by bidirectional charging of cars increases. Firstly, optimisation extensively uses vehicle batteries and, particularly, V2X for system services. In the Car I (Car II) scenario, cars feed 2 TWh (6 TWh) back into the system in 2030. Compared with total electricity supply, this corresponds to a share of 1% (2%) in the Car I (Car II) scenario. In 2040, this figure increases to 15 TWh (12 TWh) or 5% (4%) in the Car I (Car II) scenario. Secondly, the mobile battery storages of electric vehicles are displacing alternative flexibility and storage options:

- The volume of stationary battery storage decreases in the Car I (Car II) scenario to 15 GWh (0 GWh) in 2030 and 0 GWh (0 GWh) in 2040.
- The capacity and deployment of flexible hydrogen technologies are reduced in 2040. The capacity of electrolysers decreases by 10 GW in the Car I scenario and by 12 GW in the Car II scenario. The capacity of hydrogen power plants decreases by 10 GW in the Car I scenario and by 15 GW in the Car II scenario.

Thirdly, there is a trade-off between electricity imports and electricity generation by onshore wind in 2040. On the one hand, net electricity imports increase in the Car I scenario by 26 TWh and by 40 TWh in the Car II scenario in 2040. On the other hand, the onshore wind capacity in the Car I (Car II) scenario decreases by 22 GW (20 GW) resulting in 54 TWh (50 TWh) less electricity generation.

The flexibility potential of trucks has slight impacts on the Polish power system. In 2030, the volume of stationary batteries in the truck scenario decreases by 3 GWh. In 2040, the capacity of electrolysers decreases by 2 GW, and the capacity of hydrogen power plants decreases by 6 GW compared to the Reference scenario.

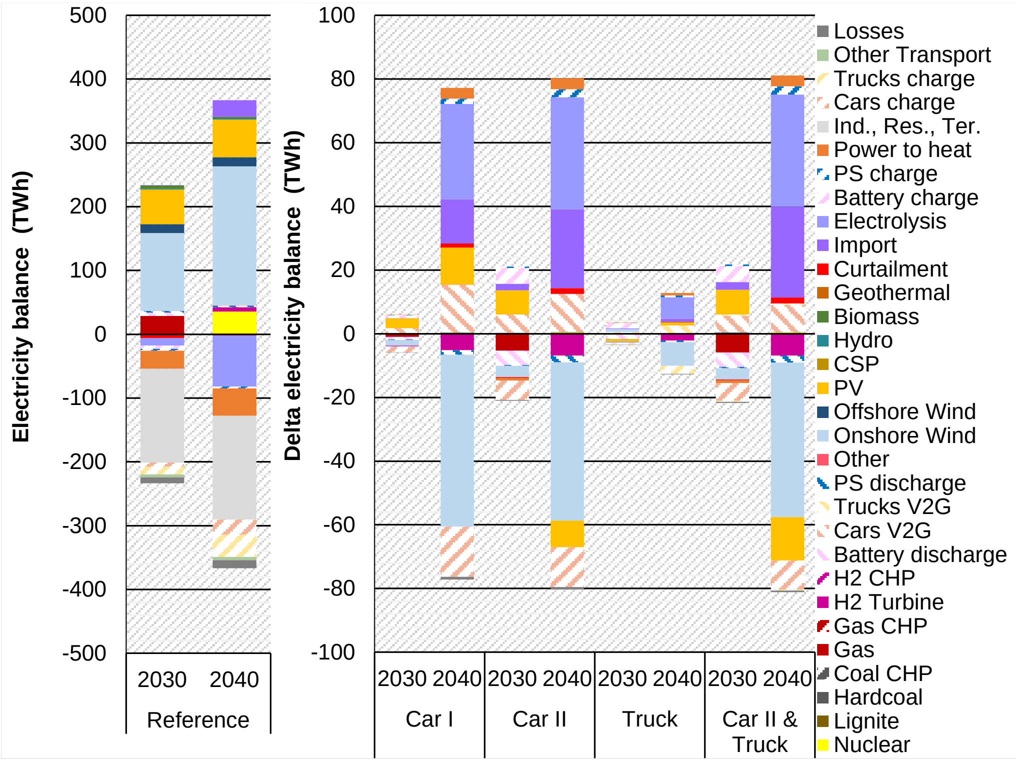


Figure 17: **Electricity balances and their changes in the scenario variants for Poland.**

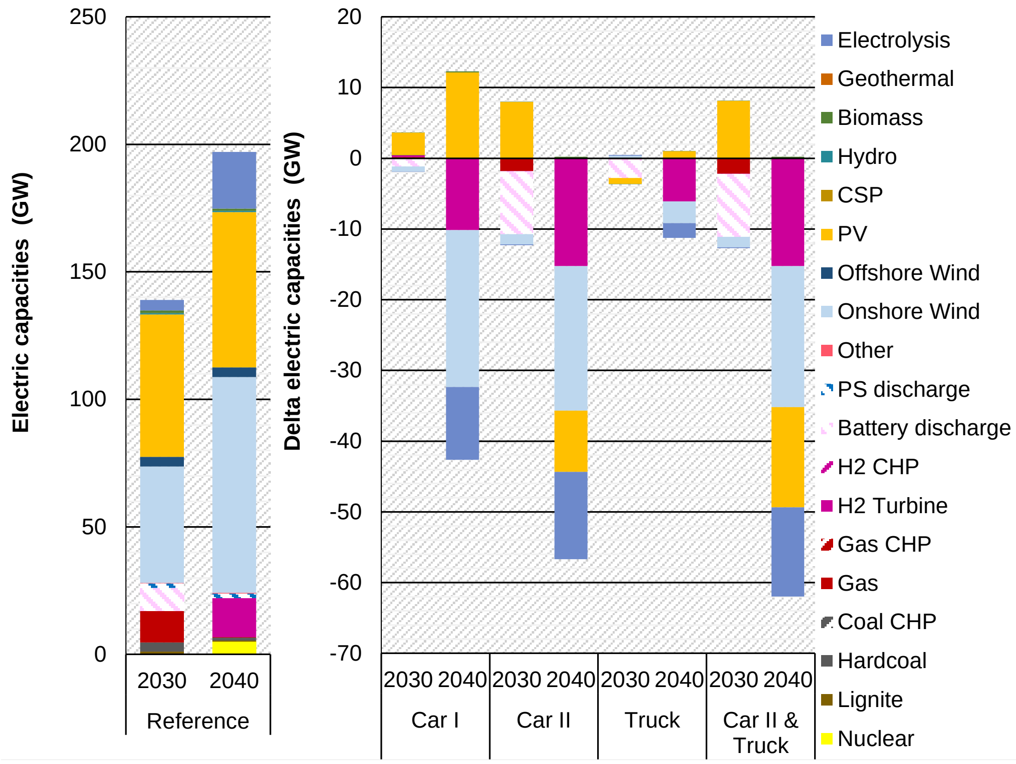


Figure 18: **Electric capacities and their changes in the scenario variants for Poland.**

3.2.7 United Kingdom

Figure 19 and Figure 20 show the electricity balance and electric capacities for the United Kingdom in the Reference scenario and their changes in the analysed scenario variants.

The results of the Reference scenario reflect the effects of the progressive direct and indirect electrification of applications in the energy demand sectors: electricity supply in the UK increases to over 450 TWh in 2030 and to over 680 TWh in 2040. Renewable electricity generation technologies dominate the electricity mix in 2030 and increase their share until 2040. Wind power technologies show the highest electricity generation, contributing 328 TWh in 2030 and 554 TWh in 2040. In the reference scenario, in addition to onshore wind, offshore wind contributes strongly to the electricity mix. Offshore wind generates 167 TWh in 2030 and 183 TWh in 2040. PV has the third largest contribution of fluctuating renewables to the electricity mix, with 30 TWh in 2030 and 63 TWh in 2040. In this scenario, the UK is a net exporter of electricity totalling 11 TWh in 2030 and 28 TWh in 2040. Gas and hydrogen power plants balance the electricity system in hours of high residual loads and jointly generate 16 TWh in 2030 and 4 TWh in 2040. The joint capacity of these backup power plants is 27 GW in 2030 and 20 GW in 2040. The optimisation does not use any stationary battery storage systems in UK for these simulation years.

Three key effects can be observed in the British electricity system, as the flexibility offered by bidirectional charging of cars increases. Firstly, optimisation extensively uses vehicle batteries and, particularly, V2X for system services. In the Car I (Car II) scenario, cars feed 6 TWh (6 TWh) back into the system in 2030. Compared with total electricity supply, this corresponds to a share of 1% (1%) in the Car I (Car II) scenario. In 2040 this figure increases to 22 TWh (19 TWh) or 3% (3%) in the Car I (Car II) scenario. Secondly, the mobile battery storages of electric vehicles are displacing alternative flexibility and storage options: The capacity and deployment of flexible hydrogen technologies are reduced. In the Car I (Car II) scenario, the capacity of electrolysers decreases by 5 GW (10 GW) in 2030 and 16 GW (33 GW) in 2040; the capacity of hydrogen power plants in the Car I (Car II) scenario decreases by 14 GW (14 GW) in 2040.

Thirdly, there is a reduced expansion of renewable power technologies:

- Onshore wind capacities are reduced by 8 GW (11 GW) in the Car I (Car II) scenario in 2030 and by 5 GW (19 GW) in 2040,
- Offshore wind capacities are reduced by 0 GW (0 GW) in the Car I (Car II) scenario in 2030 and by 3 GW (3 GW) in 2040,
- PV capacities are reduced by 5 GW (44 GW) in the Car I (Car II) scenario in 2040.

The flexibility potential of trucks has almost no impact on British electricity generation.

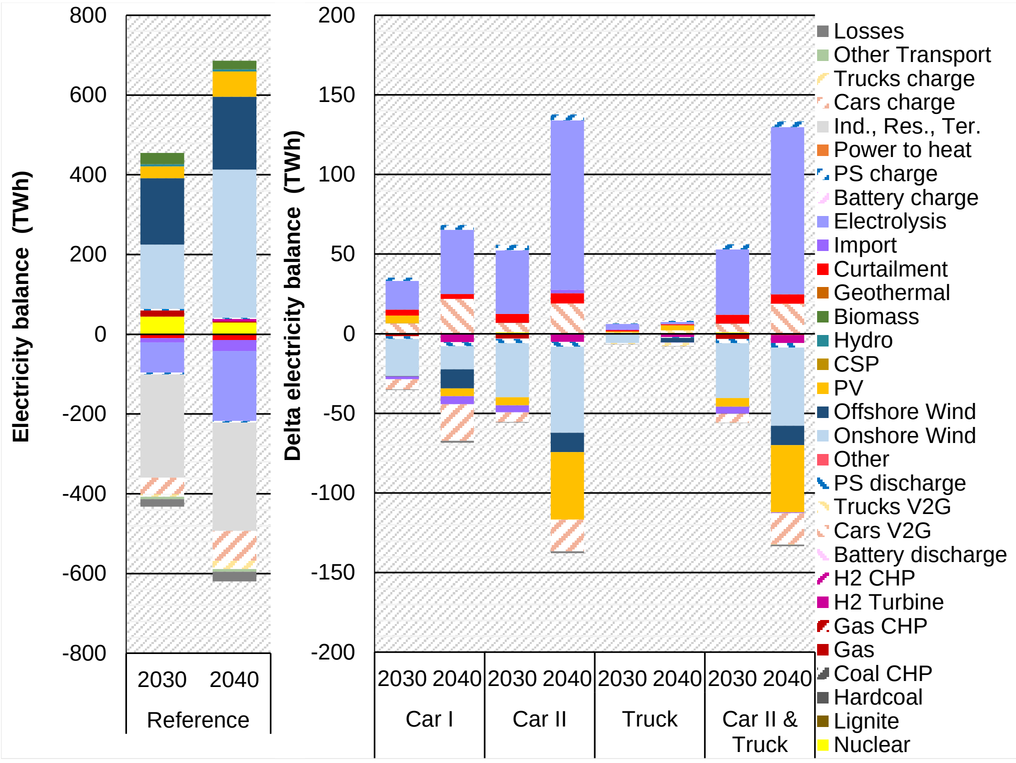


Figure 19: **Electricity balances and their changes in the scenario variants for the United Kingdom.**

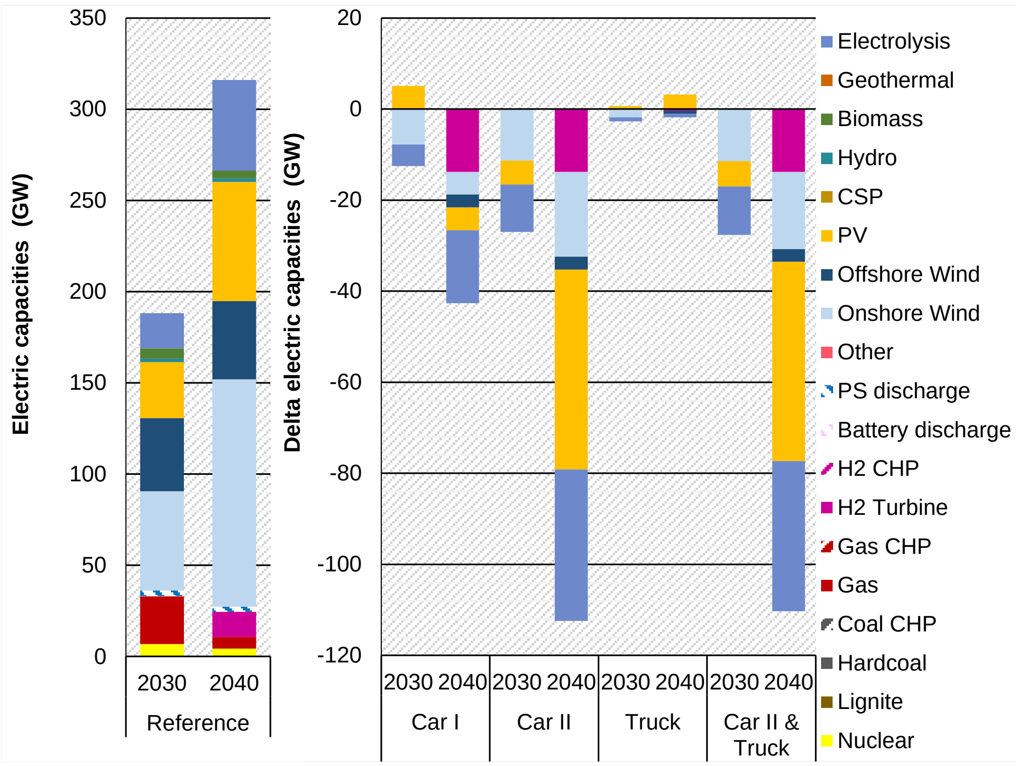


Figure 20: **Electric capacities and their changes in the scenario variants for the United Kingdom.**

3.3 Exemplary deep dive electricity dispatch in Germany 2040

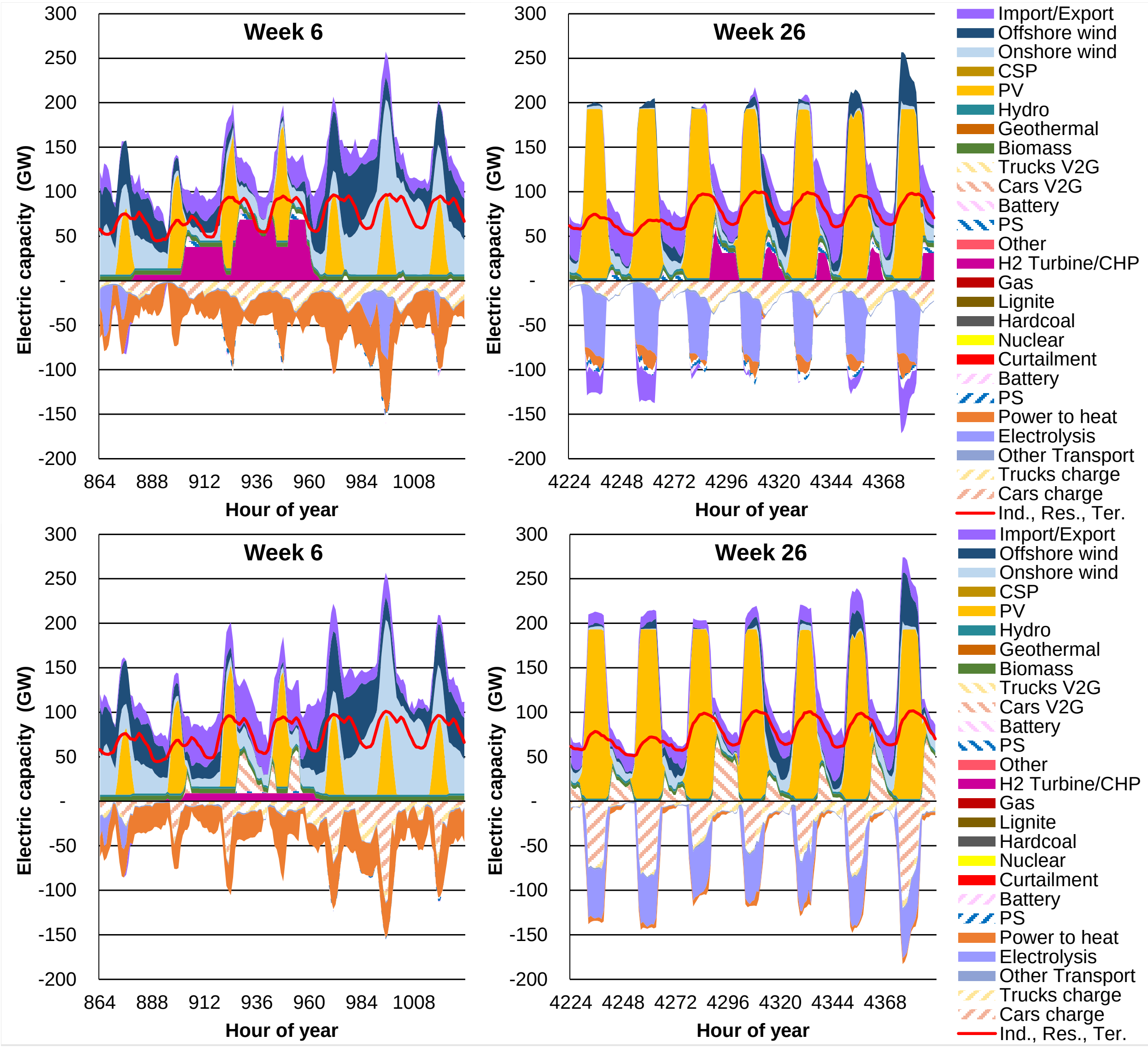


Figure 21: Comparison of dispatch results in the German electricity system in the reference scenario (top) and the Car II & Truck scenario (bottom) for a winter (left) and a summer (right) week in 2040.

Figure 21 shows the impact of car batteries on the dispatch in the German electricity system in 2040 for a characteristic summer and winter week. To this end, the reference scenario is compared to the Car II & Truck scenario.

The summer week is characterised by high and broad PV peaks with low wind feed-ins. In the reference scenario, these PV peaks are integrated, in particular, through the use of high electrolyser capacities, exports, the use of pumped storage power plants and electrical heat generation. In the Car II & Truck scenario, car batteries become the main user of PV power besides electrolysers. The vehicle batteries are used as system storage and shift the PV power to the evening and night. Compared to the Reference scenario, no hydrogen power plants need to run at night in this low-wind phase to cover the residual load, and imports from other European countries are reduced.

The winter week is characterised by small and narrow PV peaks, low wind feed-in in the middle of the week and increased electricity demand for heat generation. The comparison shows that the system-friendly charging behaviour of electric vehicles in the Car II & Truck scenario differs considerably from the uncontrolled charging in the reference scenario. Even if barely any electricity is fed back into the grid from the vehicle batteries during this week, the use of hydrogen power plants, in particular, can be considerably reduced in the middle of the week.

3.4 System costs and CO_2 emissions

Table 4 shows the absolute and relative changes in annual system cost for the different scenario variants compared to the reference scenario in 2030 resp. 2040. The costs include the fixed and variable annual costs of the installed and dispatched infrastructures for electricity, heat and hydrogen supply. When the installed capacity of a technology is increased—meaning investments are made in expanding this capacity—fixed costs arise. These include the annualized investment along with fixed operating and maintenance costs (fixed O&M). For the hourly operation of the technologies, which involves generating electricity and heat, variable costs are incurred. These consist of fuel costs, CO_2 costs and variable operating and maintenance costs (variable O&M). Further system cost elements are financing costs for investments in electricity and hydrogen infrastructure and storage. Investments are allocated to the simulation years using the annuity method and an interest rate of 2%. In the systemic analyses within the Enertile model, no additional costs are assumed for bidirectional charging compared to uncontrolled charging. The cost reductions of the overall system, therefore, provide an indication of how much cost savings bidirectional charging may cause.

The cost savings related to smart and bidirectional charging mainly arise due to reduced capital expenditures in flexible generation capacity. In the reference scenario investments in hydrogen turbines and stationary batteries are done that could be partly avoided with bidirectional charging. Fuel savings and related fuel costs are another main measure reducing overall system costs. Usage of hydrogen and natural gas can be reduced while at the same time less renewable energy must be curtailed. Both effects lead to cost savings for the system.

In both simulation years, the Car II & Truck scenario – with the highest flexibility potential from bidirectional charging of cars and trucks – achieves the greatest cost reductions. Compared to the Reference scenario, system costs decrease by EUR9.7b (5.5%) in 2030 and by EUR22.2b (12.6%) in 2040. In the applied modelling approach, the contribution of cars is greater than that of trucks. The Car II scenario, in which only cars can provide system flexibility, explains the majority of the cost reductions in the combined scenario with savings of EUR9.4b (5.3%) in 2030 and EUR21.3b (12.1%) in 2040. The Truck scenario, in which only trucks can charge bidirectionally, shows comparatively low-cost reductions of EUR0.7b (0.4%) in 2030 and EUR3.0b (1.7%) in 2040. The comparison of the Car I with the Car II scenario shows that higher car owner participation in bidirectional charging helps to support the system. The system costs in the Car II scenario are EUR5.8b lower in 2030 and EUR6.6b lower in 2040 than in the Car I scenario.

Table 4: Changes in annual system costs for the EU-27 (as covered by the energy system model Enertile) of the scenario variants compared to the Reference scenario.

Year	Scenario	Cost delta (EUR)	Cost delta (%)
2030	Car II & Truck	9.7b	-5.5%
	Car II	9.4b	-5.3%
	Car I	3.6b	-2.0%
	Truck	0.7b	-0.4%
2040	Car II & Truck	22.2b	-8.6%
	Car II	21.3b	-8.3%
	Car I	14.7b	-5.7%
	Truck	3.0b	-1.2%

The system costs savings on country level are estimated based on total system costs in each country. Highest savings are realised in Germany with EUR3.7b in the Car II & Truck scenario in 2030 and EUR8.4b in 2040 (see Table 5). The other countries have lower total system costs in the reference scenario and therefore also the system costs savings are lower with EUR1.9b savings in France and EUR0.9b savings in Spain.

Table 5: Changes in annual system costs in Germany, France, Spain, Italy, Poland and UK in 2030 and 2040 compared to the Reference scenario.

Year		Change in annual system costs in EUR					
	Scenario	Germany	France	Spain	Italy	Poland	UK
2030	Car II & Truck	3.7b	1.9b	0.9b	1.6b	1.0b	1.2b
	Car II	3.6b	1.9b	0.9b	1.5b	0.9b	1.2b
	Car I	1.3b	0.7b	0.3b	0.6b	0.4b	0.4b
	Truck	0.3b	0.1b	0.1b	0.1b	0.1b	0.1b
2040	Car II & Truck	8.4b	4.4b	2.1b	3.6b	2.2b	2.7b
	Car II	8.1b	4.2b	2.0b	3.5b	2.1b	2.6b
	Car I	5.6b	2.9b	1.4b	2.4b	1.5b	1.8b
	Truck	1.1b	0.6b	0.3b	0.5b	0.3b	0.4b

The absolute and specific emissions of power generation in the EU decrease substantially until 2030 and reach almost zero in 2040 (see Table 6). In 2030, the Reference and the Car I scenario have specific emissions of 19 g/kWh. The Car II scenario reduces emissions to 17 g/kWh. The Truck scenario maintains emissions at 19 g/kWh, and the combined Car II & Truck scenario has emissions at 17 g/kWh. By 2040, all scenarios converge to a specific emission level of 2 g/kWh.

Table 6: Absolute and specific emissions of power generation in the EU for 2030 and 2040

Year	Scenario	Specific emissions (g/kWh)	Absolute emissions (Mt)
2030	Reference	19	67
	Car I	19	65
	Car II	17	59
	Truck	19	67
	Car II & Truck	17	58
2040	Reference	2	12
	Car I	2	12
	Car II	2	10
	Truck	2	12
	Car II & Truck	2	10

The absolute emissions are highest in Germany with 18 Mt followed by Poland with 13 Mt in 2030 (see Table 7). Lowest absolute emissions occur in France with less than 1 Mt in 2030. Absolute emissions are reduced to less than 1 Mt in Germany and France until 2040. Highest emissions are in Italy with 8.5 Mt in the reference scenario and 6.1 Mt in the Car II & Truck scenario in 2040.

Table 7: Absolute emissions of power generation in Germany, France, Spain, Italy, Poland and UK for 2030 and 2040

Year		Absolute emissions (Mt)					
	Scenario	Germany	France	Spain	Italy	Poland	UK
2030	Reference	18	0.4	1	10.3	13.0	5.9
	Car I	18	0.3	1.1	10.1	12.6	5.3
	Car II	18	0.2	1.3	7.8	11.1	4.7
	Truck	18	0.3	1	10.4	12.9	5.9
	Car II & Truck	18	0.2	1.3	7.7	10.9	4.7
2040	Reference	0.1	0.2	0.75	8.5	0.1	1.3
	Car I	0.6	0.2	1.3	7.6	0.3	1.2
	Car II	0.3	0.1	1.4	6.4	0.2	1.2
	Truck	0.1	0.2	0.8	8.6	0.1	1.3
	Car II & Truck	0.3	0.1	1.3	6.1	0.1	1.1

Overall, the European electricity system is already largely decarbonised in the modelling results of the reference scenario. The option of improving the integration of fluctuating renewable electricity via vehicle batteries, therefore, has only minor positive impacts on the emissions balance of electricity generation. As shown above, the optimisation results tend to show cost reductions through the substitution of alternative flexibility options instead.

The results of the cost minimisation of the European energy supply system show that bidirectional car charging is an important flexibility and storage option for the electricity system. Utilising vehicle batteries can substantially reduce the expansion of stationary batteries and backup power plants. Additionally, less flexible electrolysis capacity is required to integrate renewable peak power generation. The vehicle storage system is beneficial for integrating PV power. The strong interaction between bidirectional charging and PV explains why cars have a higher impact on the electricity system than trucks: Due to cars' longer idle times during the day, cars' battery storage is more available at times of high PV generation than trucks. Neglecting higher costs for vehicle owners, the costs of the energy supply system can be reduced by up to 12.6% with the progressive use of bidirectional charging.

4 Grid system perspective: costs and savings from V2G

Relevant benefits of V2G can be realized on system level, especially to integrate PV generation and reduce the need for back-up capacity from hydrogen and gas driven power plants (see chapter 3). Additional impacts are expected to the power grids (see chapter 2) and the question arises what is needed from grid operators to realise the potential. This section looks at the impacts of V2G from the perspective of electricity grids and summarises current European network codes with regard to electric vehicles and V2G in section 4.1 to find beneficial obligations and framework conditions for V2G. It then analyses the effects of various operational management strategies for electric vehicles and V2G on the low-voltage grids and the necessary grid expansion in section 4.2. It also analyses the question what grid extension costs occur and if V2G can also be used to reduce grid extension costs with a grid-friendly charging behaviour.

4.1 V2G in European network codes

Grid operators are responsible for the connection of new consumers or generators and for the save operation of the grid. Main requirements and framework conditions for grid connections are defined in network codes to avoid that the grid is overloaded or destabilised. Consequently, network codes can hinder or foster the ramp-up of V2G in Europe. This section analyses how EV, including V2X, is considered within European network codes. Additionally, possible improvements of network codes to integrate EV and V2X are discussed. Initially, a more precise definition of grid connection and the purpose of establishing clear rules for grid connections is given:

“Grid connection refers to establishing and maintaining a physical connection between the transmission and/or distribution grids and the grid users.

Grid connection is a topic regulated by specific European network codes. These rules aim to develop a harmonised electricity grid connection regime, as well as efficient and secure operations. This is particularly important in view of the integration of an increasing share of sources of renewable energy in the system […]

Three European network codes on grid connection have been developed:

- The network code on requirements for grid connection of generators (RfG Regulation) establishes common standards that generators must respect to connect to the grid.
- The network code on demand connection (DCC Regulation) sets up harmonised requirements that demand facilities must respect to connect to the grid.
- The network code on requirements for grid connection of high voltage direct current systems (HVDC Regulation) covers the definition of harmonised standards for direct current (DC) connections.” [48]

In general, those European network codes are complementary. The first for generators, the second for loads and the last for HVDC connections. However, as loads and generators are complementary storages (EVs are considered within network codes as a special kind of storage) do not fit into that system. RfG Article 3 - Scope of application states:

> “2. This Regulation shall not apply to: …
>
> (d) storage devices except for pump-storage power-generating modules in accordance with Article 6(2)”

A similar formulation is found in DCC Art 3, 2b. Hence, storages and with them EVs are not covered by European network codes, currently. To bridge this gap, ACER established the Grid Connection European Stakeholder Committee (GC ESC). One of the working groups was tasked with the "Identification of storage devices". In their second phase, they focused more extensively on Electric Vehicles (EVs) [49]. Amongst others, the outcome of the second phase are seven policy recommendations of which two are relevant in the context of bidirectional charging:

> "6. Defining the list of the electrical charging parks under the scope of application of the DCC.
>
> So far as Electric Vehicles are concerned, a charging park (in particular V2G) would be treated as demand under DCC.
>
> 7. Removing barriers and limitations for the classification of small electrical charging parks concerning the RfG.
>
> Under RfG, the Expert Group considers electric vehicles (V2G) would be considered as a storage and hence treated in the same way as any other electricity storage module." [49]()

Taking that into account, ACER has published a policy paper [50] which describes three options of integrating EVs into the grid. The three options are shown in Figure 22.

	Description	Pros	Cons
Option 1	Ad hoc capacity threshold for electrical charging parks	Harmonised solution, reduced barriers to a greater electromobility at EU level	Need for a political compromise
Option 2	Two thresholds for exporting and importing capacities, matched with current thresholds at national level	Minor amendment to the RfG and partial solution to the issue	• Limitations to charging parks' flexibility • Interoperability issues/ reducing economies of scale
Option 3	Do nothing i.e., extend PGMs' current capacity thresholds to electrical charging parks	No changes to the regulation	• Problem unsolved • Expected large number of requests for derogations

Figure 22: Options to integrate electric vehicles into European network codes [50]

Since it offers most benefits, ACER favours Option 1 (highlighted with a red frame in Figure 22). Option 1 implies similar requirements for the grid connection of EV charging facilities all over Europe. Incorporating economies of scale could expedite the deployment of charging infrastructure, making it an effective strategy to promote the integration of electric vehicles (EVs) in Europe. However, this approach requires a political compromise, which might lead to a lengthy process. To facilitate the integration of EVs in Europe, it is crucial to accelerate this political process.

4.2 Assessment of low voltage distribution grid cost savings from V2G

In this section, the impact of V2G on grid expansion costs of low voltage distribution grids is assessed. It covers the methodology to calculate additional costs and savings for grid development, if V2G is implemented. The implementation is defined based on future projections for electricity demand and number of cars capable for V2G. Costs are derived by comparing different control strategies for charging EVs and for V2G.

4.2.1 Methodology

4.2.1.1 Selecting representative grid structures

Due to the similarities in the low voltage networks of different European countries and the availability of data for Germany, the representative networks for assessing grid cost savings with V2G were selected from synthetic grids based on the German low voltage network.

Based on the administrative boundaries of the VG250 database published by the German Federal Agency for Cartography and Geodesy [51], low-voltage grids were generated for all 11,110 German municipalities, totalling approximately 780,000 local grid stations and associated low-voltage grids. Since forecasting calculations for each grid would require significant time and computational resources, efforts were made to group the grids into representative clusters and to perform calculations only for these resulting grids.

In order to identify representative grids, eight key metrics (the line length of all cables in the grid, the installed transformer power, the number of connected loads, the number of inhabitants, the number of supplied buildings, the number of apartments, and the number of commercial units) were extracted from each individual low-voltage grid. These metrics were then clustered using a k-means algorithm.

The k-means algorithm partitions the data into K clusters based on similarity of characteristics, where K is arbitrarily chosen. First, K centroids, called points, were randomly selected from the dataset, and the remaining points were assigned to a cluster based on their proximity to the nearest centroids. A new centroid was calculated from the data points of each cluster using a mean value calculation, and the assignment process was repeated until the centroids stabilised, the clusters remained unchanged, or a predetermined maximum number of iterations was reached.

A higher number of cluster centres provides a better representation of the network population, but also increases the computational effort. The silhouette coefficient and the Calinski-Harabasz index (CHI) were used to determine the optimal number of cluster centres.

The silhouette coefficient measures the difference between the mean distance of all points to their nearest cluster and the mean distance of the clusters to which they are assigned. It is normalised based on the number of points and the larger value between inner and outer cluster distances, with a maximum value of 1 indicating optimal cluster selection.

The CHI calculates the ratio of dispersion between individual clusters and within a cluster. A higher CHI value indicates a well-chosen number of clusters. After analysing these metrics, the number of cluster centres was determined to be 35.

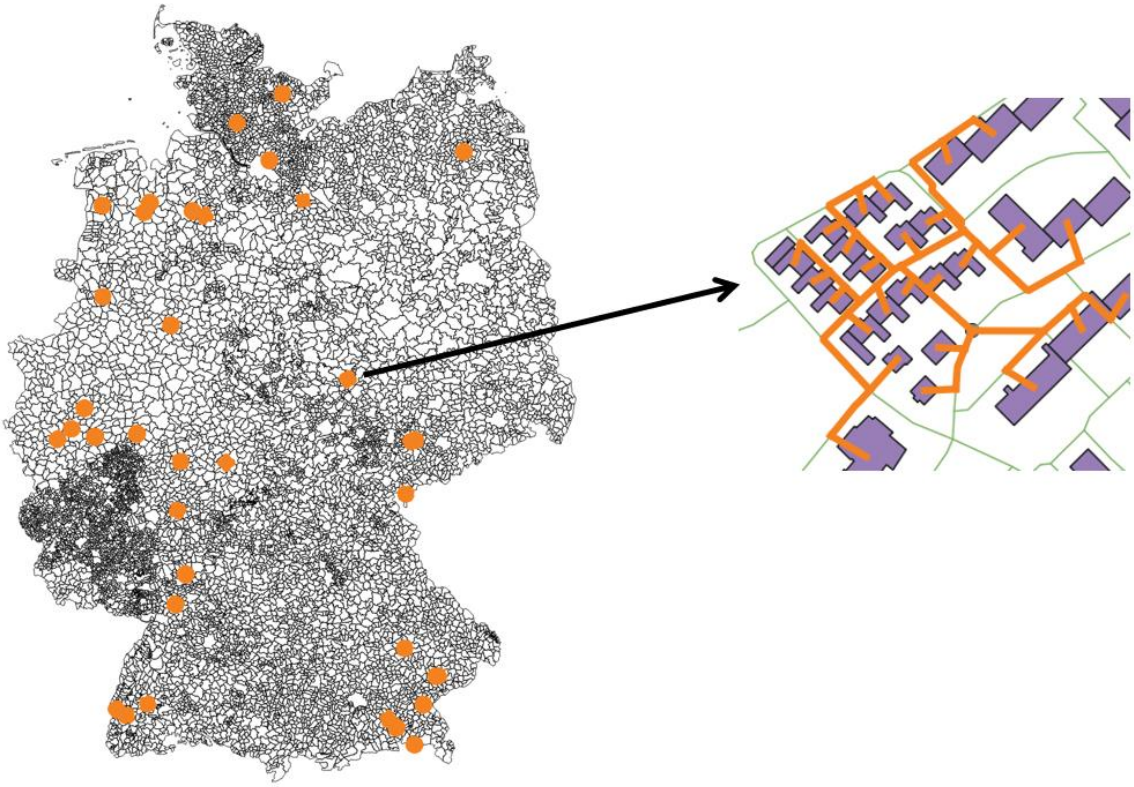


Figure 23: Representative grids for German low-voltage grids

Each cluster centre is assigned a weight based on the number of networks it represents. This weighting allows the newly calculated networks to be extrapolated to the entirety of Germany and facilitates the identification of expansion needs.

4.2.1.2 Calculation of grid reinforcement measures

For each cluster centre, after applying the scenario assumptions for future development of demand and supply (see section 4.2.2), the minimal expansion cost required to ensure a secure power supply are calculated. The model allows the following grid reinforcement measures:

- Reinforce transformers, by either replacing them with transformers with a higher rated power and/or transformers with an onload tap changer, to account for voltage issues.
- Reinforce cables by replacing them with a stronger type of cable.
- Install new cables.

The optimisation uses a genetic algorithm to find the best possible solution to meet the network planning principles. A special feature of all the grid calculations carried out is that annual time-series were used for all components instead of snap shots of critical situations, which is a common approach for network planning. In this common analysis worst case scenarios are considered, where two calculations are usually performed that consider demand side and generation side separately. For the demand side, it is calculated whether the grid can supply the expected load, for which simultaneity factors are used for all household loads and for all EV charging processes. No feed-in from PV systems is considered in this analysis. In the second calculation, only the supply side is considered to assess whether the grid is not overloaded with the expected feed-in of PV systems if loads are neglected.

The use of annual time-series overcomes this shortcoming of the common planning approach and allows an adequate investigation of the behaviour of different EV control strategies. With the worst-case assumptions typically used for grid expansion calculations in common grid planning, it is not possible to examine the interaction of all components, as the load and feed-in cases are examined individually. So, the classic planning uses worst-case assumptions, whereas the methodology used here always depicts a realistic interaction of all components. One effect of this holistic approach is that the grid load in the load case is lower than with classical simultaneity factors, so that the resulting grid expansion costs may also be lower. The other effect is that analyses are carried out that make the interaction of components over time comprehensible (see section 4.2.3.2).

4.2.1.3 Calculation of country results - Interpolation from German results

Each network is classified into one of three categories according to its respective degree of urbanisation. This value is based on data published by Eurostat in 2018. [52] The categories are densely populated, medium density and thinly populated. By assigning the population figures of individual communities to one of the three categories, it is possible to compare infrastructure between different countries. Through normalisation of the values for Germany, it is possible to project the calculated results to other countries. The grid expansion costs and the respective material savings for each country are then estimated based on the urbanisation categories and in relation to the results in the respective urbanisation category of Germany. In three countries (Spain, UK and France), most inhabitants live in dense urbanisation areas, in two countries (Germany and Italy) most inhabitants live in intermediate urbanisation areas and in one country (Poland) most people live in thinly urbanisation areas (see Table 10).

Table 8: Degree of urbanisation and total number of inhabitants for respective countries

Inhabitants	Germany	France	Italy	Poland	Spain	UK	EU28
Densely populated [M]	29.9	30.7	21.3	13.3	25.2	38.2	213.2
Medium density [M]	34.2	13.3	28.8	11.3	15.3	23.4	158.5
Thinly populated [M]	18.8	22.6	10.4	13.8	6.2	4.4	139.6
Sum	82.8	66.6	60.5	38.4	46.7	66.0	511.2

Based on the distribution of inhabitants, weight factors are derived to estimate results for the urbanisation areas for all countries based on the results for the urbanisation areas in Germany (see Table 9).

Table 9: Relative distribution of the population compared to Germany as a reference

Inhabitants relative to Germany	Germany	France	Italy	Poland	Spain	UK	EU 28
Densely populated [M]	100%	103%	71%	45%	84%	128%	714%
Medium density [M]	100%	39%	84%	33%	45%	69%	464%
Thinly populated [M]	100%	121%	55%	74%	33%	24%	744%
Sum	3.0	2.6	2.1	1.5	1.6	2.2	19.2

4.2.2 Scenarios

To draw up a forecast of grid expansion requirements, the synthetic grids must be generated with modified future time-series for load- and generation-curves. The profiles were generated with the synPRO Framework which is explained in section 5.1.1. The scenario assumptions follow the description in section 3.1. The Key technologies electric vehicles, heat pumps and rooftop PV that are relevant in low voltage grids increase their penetration substantially until 2030 and 2040, as shown in Table 10**.**

Table 10: Grid integration of key components in Germany for the years 2030 and 2040

	2030	2040
Mio. HP	**4,3**	**10**
Mio. EV	**14,1**	**30,7**
PV rooftop in GW	**129**	**240**

The assumptions were transferred to the grids described in Table 10. For this purpose, a heat requirement was determined for each building to which a heat pump was allocated, depending on the number of inhabitants, the size of the building and its age. If there was a heating network in a particular location, it was assumed that all heat was supplied by this network. The percentage of heat pumps was adjusted for locations without heat networks.

The distribution of EVs is based on [53]. In order to be able to transfer the assumption for rooftop PV to individual grids, the total relevant building area in Germany was used to determine the target penetration of PV systems. Within the grids, the systems were then randomly assigned to the roof areas.[54].

For the assessment of grid costs and savings from V2g, three different control strategies for EVs were implemented and analysed in the grid simulations:

- No control strategy: Unidirectional charging, depending only on user behaviour.
- Economically optimised bidirectional charging: If a car is plugged-in for charging, a controller optimises the cost to meet the required target SOC, while being able to benefit from a varying cost signal with bidirectional charging and discharging of the EV.
- Grid-friendly bidirectional charging: A control strategy that assumes a monitoring of transformer loads and the DSO requesting bidirectional flexibility of all plugged in EVs. No price signal is used here. The controller ensures that the original target SOC when unplugging the EV remains the same.

4.2.3 Grid reinforcement cost

This section shows the results of the grid reinforcement costs for Germany and Europe, which have been obtained with the described methodology (section 4.2.1) for the described scenarios and control strategies.

For Germany, the grid reinforcement costs for the low-voltage grids amount to a total of EUR10.75 billion for the 2030 scenario to reinforce the current grid structure. This applies to the uncontrolled case of EVs. Both economically optimised and grid-friendly operation reduce the costs slightly to EUR10.47 billion and 10.32 billion respectively. The costs increase overall with decreasing population density. In densely and moderately populated areas, purely economically optimised operation management can slightly reduce the necessary grid expansion costs. In sparsely populated areas, grid-friendly operational management based on transformer load monitoring reduces costs by 0.43 billion euros.

In the 2040 scenario, the costs for reinforcing the current grid structure in Germany rise to a total of EUR29 billion in the uncontrolled case. In general, the grid reinforcement increases more in densely populated and medium density regions compared to the 2030 scenario. Economically optimised EVs only slightly reduce costs in sparsely and densely populated areas, while costs increase in medium density regions. The grid friendly controlled EVs can slightly reduce the costs in all regions to a total of 27.27 billion euros: The reductions amount to 1.4% in densely populated areas, 7.5% in medium density regions and 6.6% in sparsely populated grids.

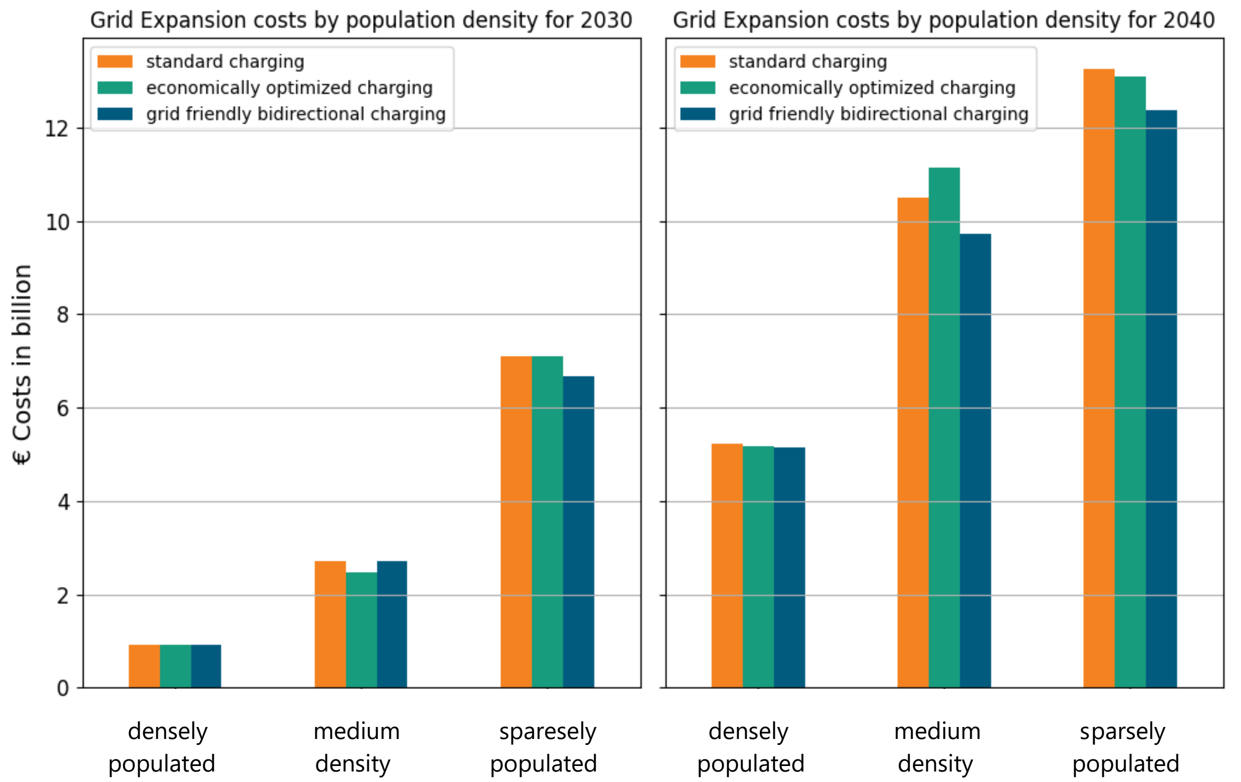


Figure 24: **Grid expansion costs for different control strategies, arranged by population density in Germany for the years 2030 and 2040**

The grid expansion costs are calculated for the entire system. This means that conventional household loads and commercial loads are considered together with all the new components added according to the scenarios. The additional systems are EVs and heat pumps on the one hand and PV systems on the other hand. Each component has a time-series for the entire year, and their combined impact for each time step is calculated in a power flow calculation. If an overload or an unacceptable voltage deviation occurs, an optimisation is performed to determine measures to reinforce the grid. The figure above shows the costs for all systems in the grids and shows that different control strategies for bidirectional EVs can have a beneficial impact on the required grid reinforcement. However, the figures do not show which components are responsible for the grid expansion. This is analysed in section 4.2.3.2. in more detail.

4.2.3.1 Interpolated saving potentials for France, Italy, Poland, Spain and UK

The sections above describe the development of the grid infrastructure in Germany. This section uses the German results on potential savings for the year 2040 and applies them to the EU respectively to France, Italy, Poland, Spain and the UK (see also the section 4.2.1.3). European results shown reduced grid expansion costs of EUR10m in 2040 due to gird friendly bidirectional charging (see Table 11 and Annex B for 2030 results).

Table 11: Savings of costs and material for grid expansion for EU 27 in 2040 due to grid friendly bidirectional charging

Population density	Reduced grid expansion /EUR	Savings steel/kt	Savings aluminium/kt	Savings PVC/kt	Reduced curtailment/GWh
Dense	432m	1	4	3	6
Intermediate	3,099m	12	33	20	2
Thinly	6,253m	155	48	9	18
Sum	**9,784m**	**169**	**85**	**31**	**26**

Figure 25 illustrates the benefits of grid-friendly operation of bidirectional V2X for the specified scenario in 2040 per country (see Annex B for results for 2030). The first row indicates a reduction in curtailment measured in GWh. This curtailment of PV feed-in was calculated as an alternative to grid expansion measures for uncontrolled EVs in grids that had originally been optimised for the case of grid-friendly EV control. The second row shows the potential reduction in PVC in kt. The third row highlights potential aluminium savings in kt. The fourth row details steel savings in kt. The fifth row presents an economic perspective, showing reduced investment in million EUR. In four out of the five rows, Germany exhibits the highest aggregate savings due to its larger population. France, however, shows a dominant reduction in curtailment, attributed to its significant proportion of thinly populated areas. Italy benefits particularly in the areas with medium population density, where grid-friendly operations prevent investment in cables, primarily made of aluminium and PVC, leading to significant material savings in these components. Poland's population is fairly evenly distributed across all sectors, making the sparsely populated areas the primary regions for potential savings due to the higher investment per inhabitant. The majority of Spain's population resides in densely populated areas, yet the principal cost-saving potential lies in areas with medium density. The UK has an even higher proportion of its population in densely populated areas compared to Spain, resulting in a lower percentage of inhabitants in sparsely populated regions. Nevertheless, due to its larger total population, the UK exhibits greater potential for cost savings.

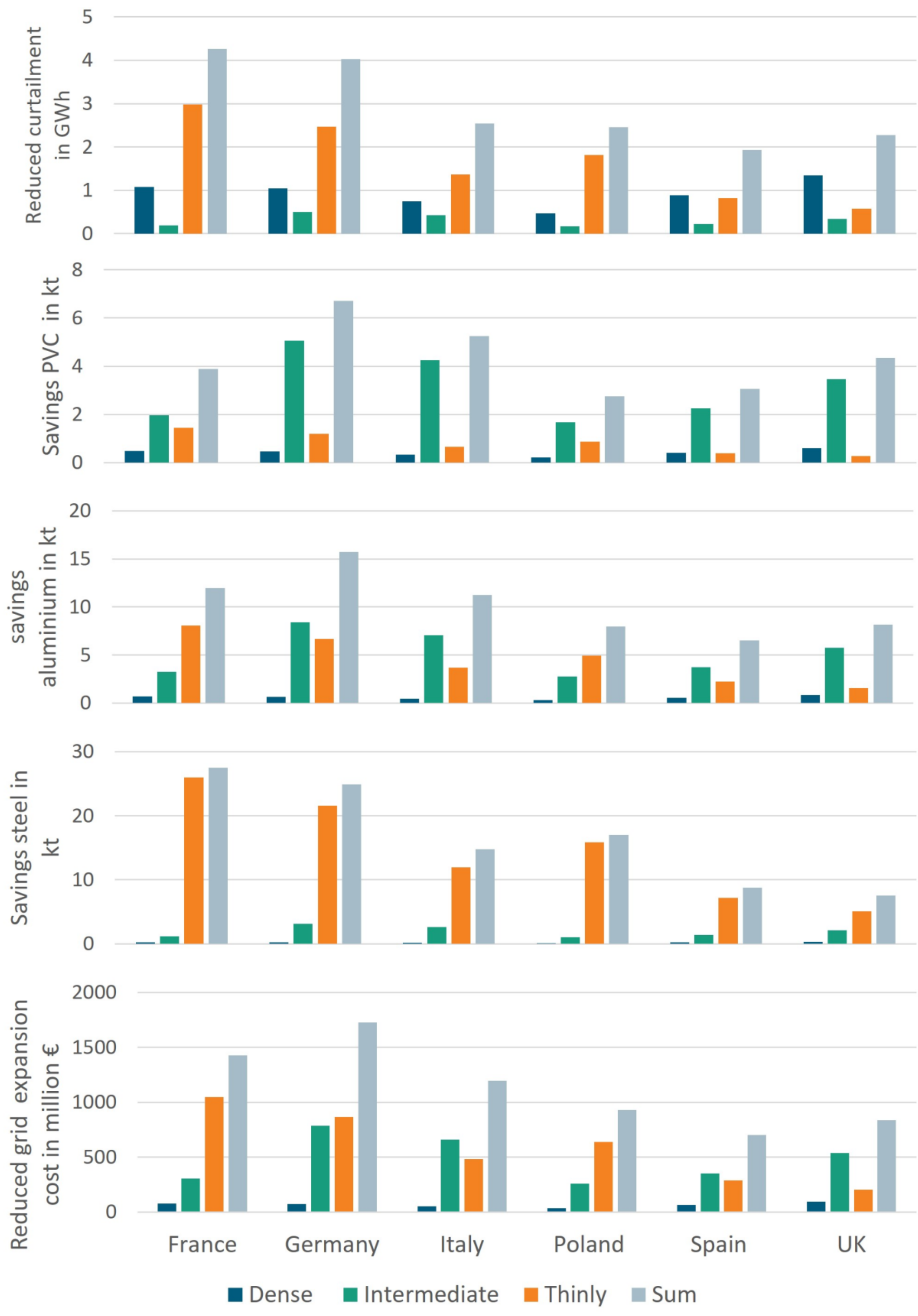


Figure 25: **Reduced curtailment, material savings and reduced grid costs from V2G for France, Germany, Italy, Poland, Spain and UK in 2040**

4.2.3.2 Analysis of time-series

To understand the causes of the grid reinforcement costs described in section 4.2.3, on the one hand, and the effect of the assessed control strategies, on the other hand, this section examines an exemplary day of one example grid.

Figure 26 shows the active power of all components in one grid in the upper part and the number of parked EVs in the lower part. This data is shown for a day in May in the 2040 scenario for default unidirectional charging.

Horizontal bars at the top indicate time windows in which the allowed limits were exceeded: The red bar marks a period in which the maximum permissible voltage is exceeded at one point in the grid or more. Cable overloads are shown in a green bar and transformer overloads due to PV feed-in are shown in a yellow bar.

The active power of PV systems is displayed as a positive time-series in grey, while the consumer side is negative. Profiles for households and commercial units are grouped as other loads in turquoise and the scenario drivers of heat pumps and EVs are shown separately. Heat pumps are shown in light blue, as they mainly heat during the night time. For EVs, the time-series for charging is displayed in dark blue with negative values, as it contributes to the load side, while discharging would be shown in orange, but as the uncontrolled charging does not provide an incentive for bidirectional use it is always zero here.

The lower part of the plot shows that the number of parked EVs is higher during the night time than during daytime and, especially, than during normal working hours. The transformer of the example grid supplies a total of 38 EVs.

It becomes evident that, in this case, grid reinforcement measures are required due to the high feed-in of PV systems. The maximum feed-in power on this partly cloudy day far exceeds the maximum power of the load side. This specific grid shows a dominant voltage penalty of excessive voltages, which is an effect of the PV systems. The overloading of lines and transformers is also caused by their feed-in.

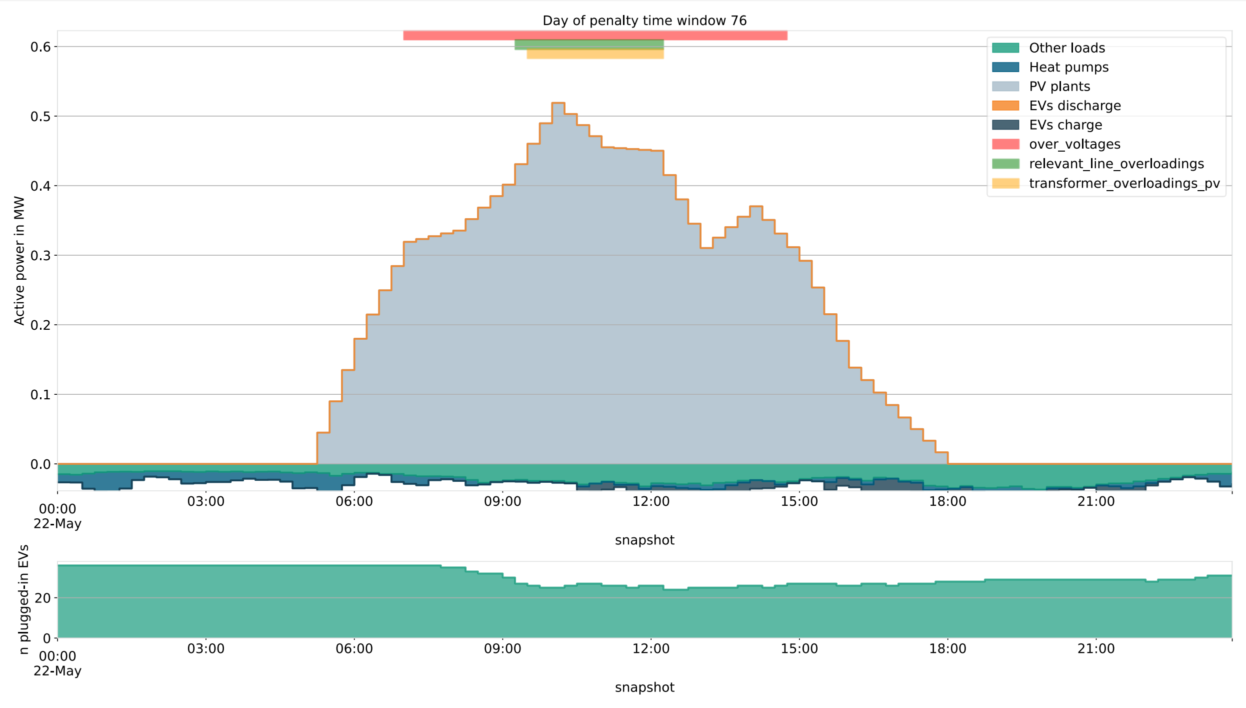


Figure 26: Exemplary day with over voltages, line overloading and transformer overloading in low voltage grid for uncontrolled charging

In comparison, Figure 27 shows the same day for the same grid with the analysed economically optimised EV charging. The profiles of PV feed-in and all loads except EVs are the same as in Figure 26. During nighttime, minimal discharging of EVs can be seen, while increased charging can be observed in the morning hours, when the PV feed-in ramps up. This behaviour slightly reduces the time penalty windows for over-voltages and line overloads. While these are clearly positive effects of the change in EV charging, the impact is rather small due to the dominant PV systems, so that the need for grid reinforcement is only slightly changed.

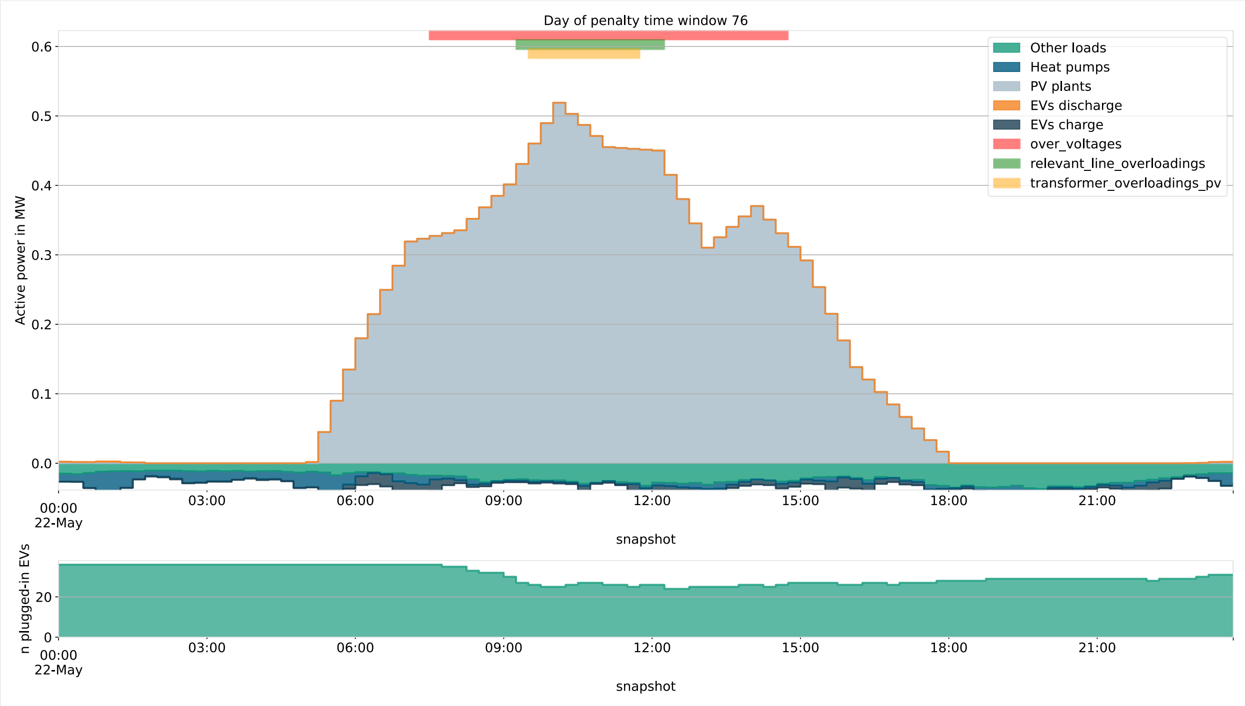


Figure 27: **Exemplary day with over voltages, line overloading and transformer overloading in low voltage grid for economically optimised bidirectional charging**

Finally, Figure 28 shows the same day with EVs explicitly controlled in a grid friendly manner. As described in section 4.2.1.1 the analysed control strategy is based on transformer load monitoring. The yellow horizontal bar indicating transformer overload can be reduced to one time step in this example: The required flexibility of the EVs is shown in orange for discharging in the early morning hours, which facilitates the EVs that are plugged in during the peak of the PV feed-in to charge significantly more. In this example, the control strategy can mitigate the transformer overload, but it does not prevent it entirely. Furthermore, the control strategy does not explicitly address excessive voltage or line overload, but only inherently. In this example, the required grid reinforcement measures can be decreased, but again, not entirely prevented.

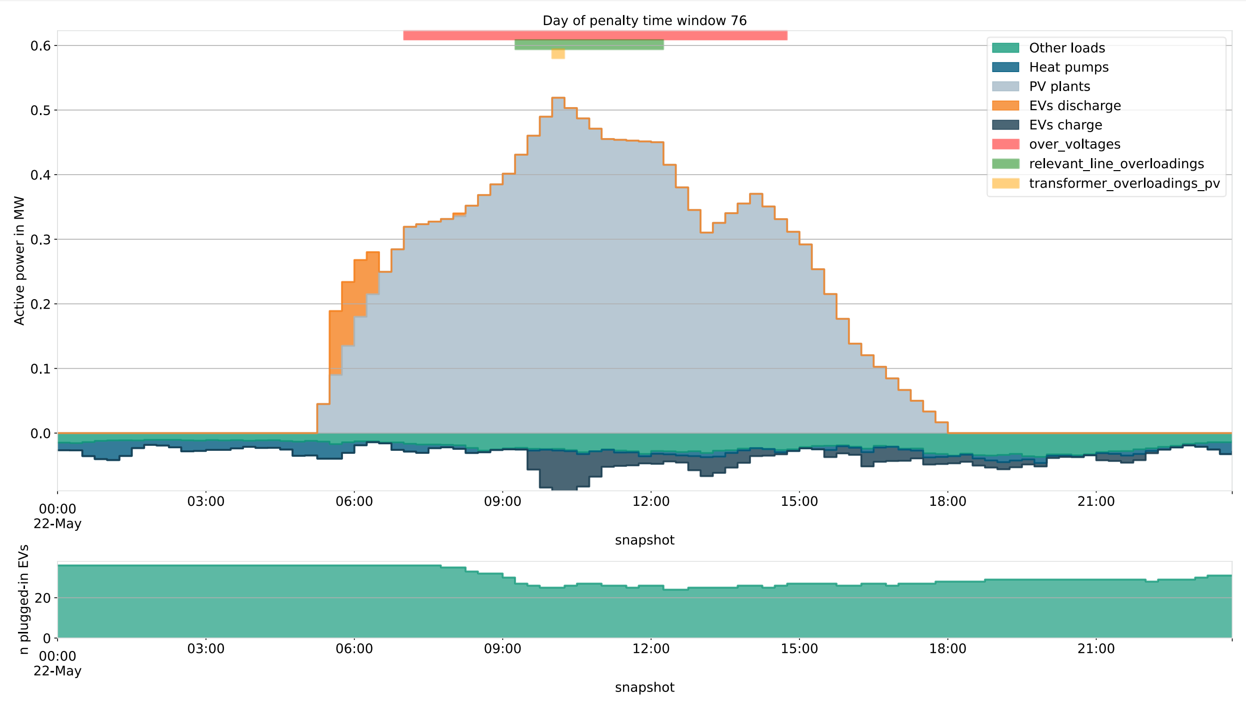


Figure 28: Exemplary day with over voltages, line overloading and transformer overloading in low voltage grid for grid friendly bidirectional charging

The effects described are highly dependent on the individual topology and distribution of scenario drivers in low voltage grids. In some grids, the assessed controllers alone are sufficient to avoid all penalties, while, in more grids, a positive effect can be observed that reduces the required reinforcement. For the solely economically optimised controller, the effect can be negative, but in the majority of cases it is positive or at least does no harm.

The supply task of low-voltage grids is changing due to the increasing number of EVs. However, these only account for part of the changes, as both the heat transition due to the increasing use of electrically powered heat pumps and the growing number of rooftop PV systems are having a major impact. Grid expansion costs are caused by all components in a grid. The interaction of the components was analysed using time-series based calculations. The grid expansion costs for Germany for 2030 amounted to EUR10.75 billion for uncontrolled EVs and to EUR29 billion for 2040.
The impact of a dynamic price on grid expansion measures was investigated for an economically optimised operating mode of bidirectional EVs. The effects depend heavily on the individual grids but are slightly positive overall. A grid-friendly controller that monitors the transformer load can reduce costs more significantly, although the individual topology and distribution of the systems also have a strong influence here.
The grid expansion costs and savings potential through modified EV operation strategies depend on the population density. For 2040, the grid-friendly control reduces the expansion costs by 1.4% in densely populated areas, by 7.5% in medium density regions and by 6.6% in sparsely populated grids. On the basis of the population and the distribution of population densities, the values calculated for Germany were interpolated to France, Italy, Poland, Spain and UK.

5 User perspective: Cost benefit of smart and bidirectional charging

After describing and quantifying the expected power system (Section 3) and the grid (Section 0) impacts from bidirectional charging, this section takes a closer look at potential gains for users when applying smart unidirectional or bidirectional charging at home. A quantification of bidirectional charging is done for the V2H use case (see Section 5.1). To quantify the earnings, energy system simulations are conducted using the Fraunhofer synPRO framework. Besides the economic gains, additional costs for bidirectional chargers are considered together with costs for advanced and interoperable communication systems and additional costs related to battery degradation (Section 5.2). Profitability is evaluated comparing costs and benefits for the V2H use case ((Section 5.3).

5.1 Benefits for consumers through smart and bidirectional charging

To quantify the economic benefits of bidirectional charging, various household load profiles and corresponding EV driving profiles were analysed for several European cities with individual PV generation and country-specific variable prices. We describe the modelling assumptions in the following section, followed by the simulation results.

5.1.1 Scenario definition, input data and simulation setup

Figure 29 shows the simulation setup. The central EV optimisation uses time-series data of EVs and household loads from the synPRO framework (upper part of Figure 29) together with price data (middle left part of the figure) and PV data (middle right part of Figure 29). Depending on the optimisation goal, the data is processed and optimised charging time-series are generated. In a post-processing step (lower part of Figure 29), an ageing model uses the optimised time-series to calculate battery ageing before the techno-economic evaluation is performed. The different models are described in the following sections.

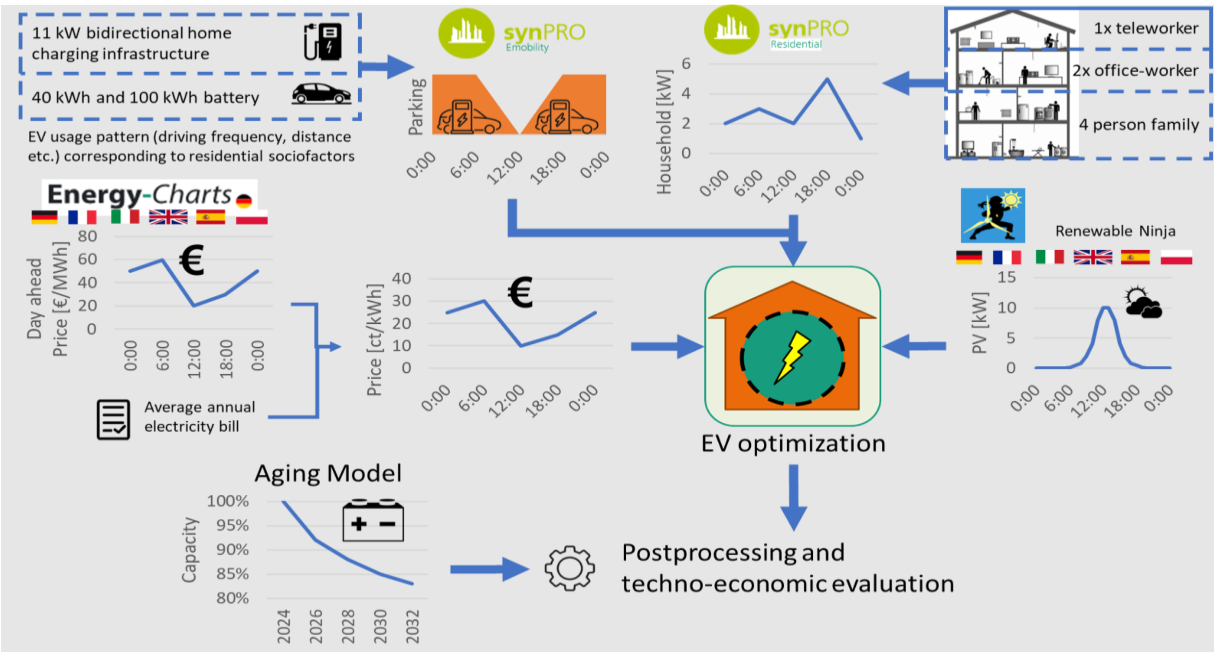


Figure 29: Simulation setup to assess user benefits

Residential load profile (synPRO)

Annual time-series data for the household loads are created by the synPRO residential module [55] for the following three different household categories:

1) Single teleworker
2) Two fulltime office workers
3) Family (with 2 adults and 2 children, one adult full time office worker)

Figure 30 shows the specific load patterns for the mean day (left) and the monthly energy demand (right). The mean day plot shows that the teleworker has the highest energy demand during the working hours, while the two fulltime workers have the highest demand in the afternoon. The pattern of the family is characterised by a lunchtime and evening peak. The total annual energy demand for the family is 3,970 kWh, followed by the two full-time workers with 2,150 kWh and the teleworker with 1,810 kWh.

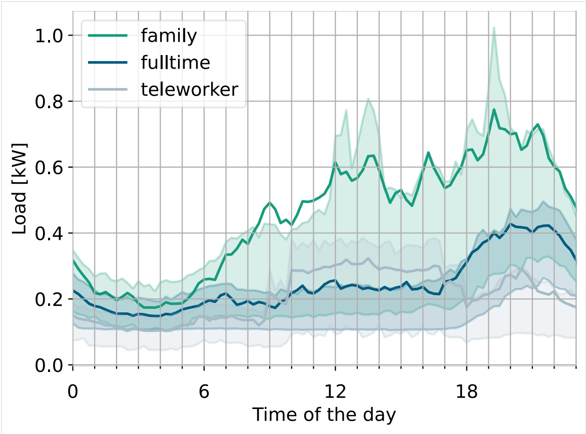
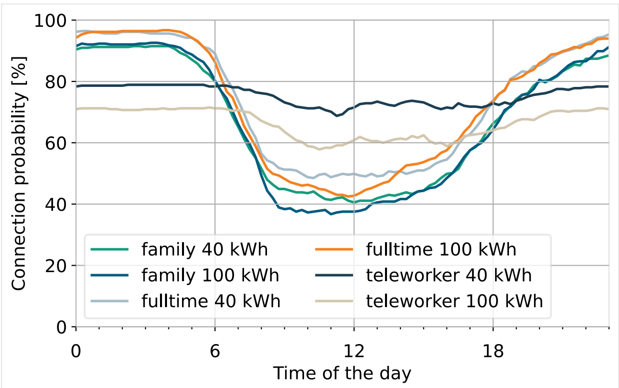


Figure 30: **Mean day household load (left), including the mean lines and 25% and 75% quantiles of the data (shading) and monthly household energy demand (right) for three household types.**

EV load profile (synPRO)

The synPRO EV module [56] generates time-series data for an uncontrolled charging of EVs, together with trip information data specifying when and where EVs are parked and connected. For this study, the focus is on residential parking locations. Two different types of EVs were generated for each household type. A small EV with a 40-kWh battery and a large EV with a 100-kWh battery are considered. The respective driving patterns are based on socio-economic factors, assuming that large EVs are used more frequently and for longer distances, and therefore, have a higher total energy demand. This means that for each socio-economic factor, a high and a low power consumption with a large and a small battery is analysed. Figure 31 (left) shows the connection probability of an EV during the different hours of the day for the different household categories. The probability for a teleworker is significantly higher at midday than for a fulltime office worker, and therefore the potential for PV harvesting is higher.



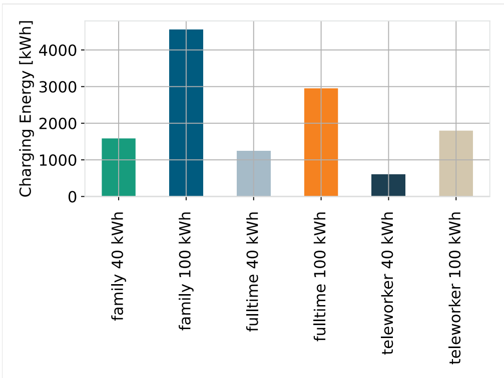


Figure 31: **Probability of EV connection (left) and annually charging demand (right) for the three household types for an EV with a 40 kWh and a 100-kWh battery.**

Variable household electricity prices

Based on the Fraunhofer energy charts, annual day ahead price data in their specific bidding zones have been obtained for the following 6 countries:

- Germany
- France
- Italy
- United Kingdom (UK)
- Spain
- Poland

The day ahead price for 2022 has been used via transferring the price pattern to the end user, while the total annual electricity bill in the specific country is not changed. Thus, a household with a constant load throughout the year would end up with the same bill using the variable price or a static price, while a household that consumes energy during low price windows would pay less. Figure 32 shows the price patterns for a random week in July and the mean day pattern. Only a part of the prices is variable, the static share of taxes and levies for the countries are as followed: France: 23%, Germany 36%, Italy 13%, Poland 38%, Spain 14% and UK 32%[16]. No sensitivity analysis on the prices is conducted, but higher taxes and levies would not affect the price optimization and the economic gains in this case. In the PV case, the economics would be positively influences. For the price optimization only the spread on the stock market is relevant. It will probably rise in the future with more fluctuating generation.

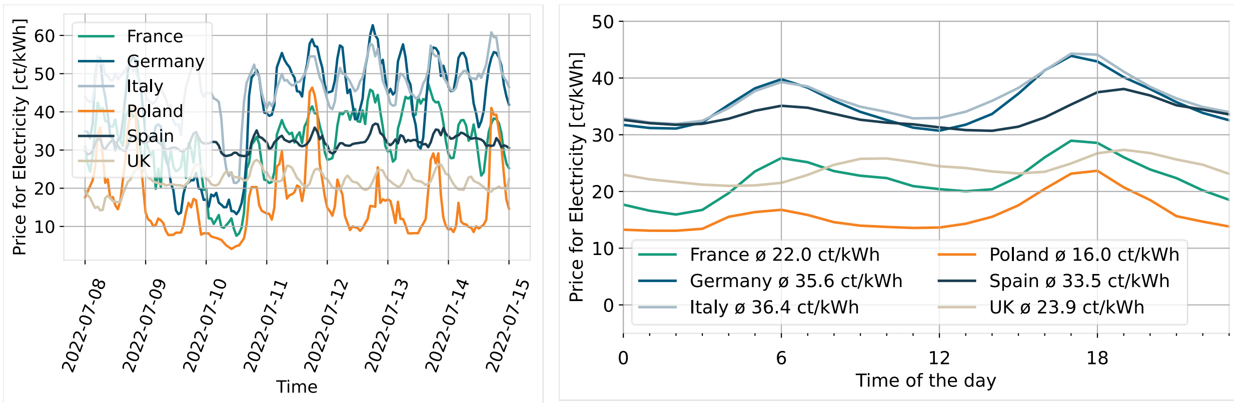


Figure 32: Exemplary week (left) and mean day (right) plot for fictional end user prices in different European countries[17].

[16] Calculated based on Eurostat data for 2022 (and 2019 for UK): https://ec.europa.eu/eurostat/databrowser/view/nrg_pc_204/default/table?lang=en

[17] The day ahead price characteristics in the national bidding zones was mapped on the average national residential electricity prices including fiscal charges.

PV input data

PV input data for each country was taken from Renewable.ninja, using the capitals of the six countries considered to determine radiation data. We also used the year 2022 for the price data. The installed PV capacity was set to 8 kWp for the family, 6 kWp for the two fulltime workers and 4 kWp for the teleworker. Figure 33 shows the mean day plots: the different PV potentials for different installed capacities (left) and different solar radiation (right). All data have been transformed to UTC time. The load curves in the right figure are used as a reference. Only one pair of aggregated loads has been inserted, belonging to the Berlin PV curve. However, in the simulation, the same load characteristics are converted to regional time so that the PV and load patterns match.

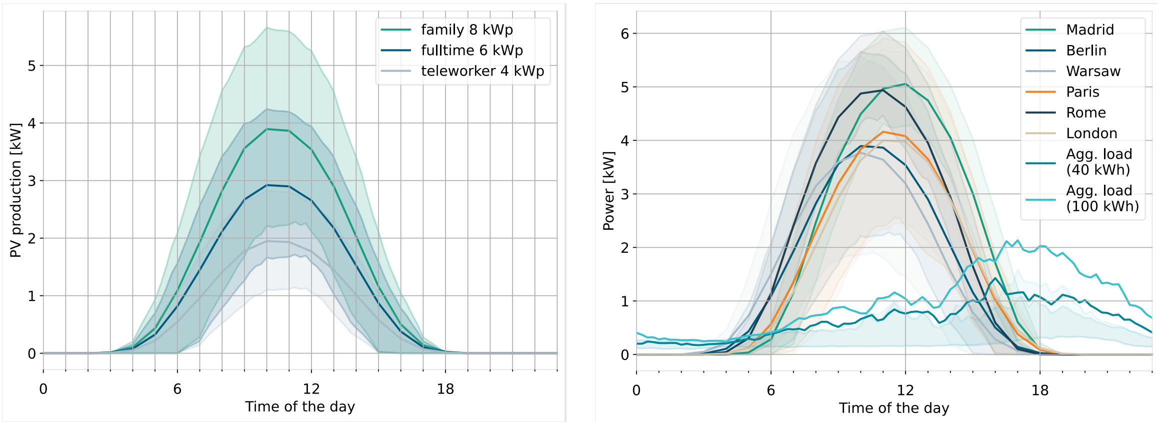


Figure 33: Mean day PV production for Berlin with the household types (left). Mean day production for an 8 kWp PV plant in different regions, together with the aggregated load (household appliances + uncontrolled EV) of the family (right)[18].

Optimisation Scenarios

Within the optimisation, the following V2H scenarios were simulated:

- **Baseline:** Upon arrival, the EV is charged with maximum power until the target SOC is reached.
- **PV optimised:**
  - **Unidirectional:** The EV is preferably charged with the available PV power. If the PV power is not sufficient to achieve the target SOC, the remaining energy is charged from the grid.
  - **Bidirectional:** The EV is charged with as much PV power as possible whenever available and is discharged to supply household appliances, when possible, while still ensuring the target SOC upon departure with the highest possible solar energy mix within the battery.
- **Price optimised:**
  - **Unidirectional:** The EV is charged when household electricity prices are lowest.
  - **Bidirectional:** The EV is used to charge electricity during low price periods to later supply household appliances if the price spread is high enough to compensate for the charging/discharging losses. Otherwise, the EV is charged during the low-price periods to meet the target SOC. Trading back to the market is not considered.
- **PV and Price optimised (uni- & bidirectional):** A mixture of the scenarios PV and Price optimised, PV is considered to have zero cost.

[18] Shaded areas represent the 25 % and 75 % data quantile. (All data in UTC time)

Battery Ageing model

In a post-processing step, the resulting EV charging time-series are used as input data for an ageing model that determines the battery lifetime based on both cycling and calendar ageing.

Cycling and calendar ageing models are used to analyse ageing of LFP (Lithium Iron Phosphate) battery chemistry. Key parameters affecting ageing, such as average SOC, standard deviation of SOC and total energy throughput, are considered. The assumption of constant temperature over time facilitates the calculation of ageing values for each scenario. A detailed description can be found in the annex

5.1.2 Electricity cost savings from V2H applications for EV users

In this section, we show the simulation results for the three household types in the selected countries with specific PV production and country-specific price data. The results are shown for a price and a PV-optimised case and consider a uni- and a bidirectional charging controller. The combination of price and PV-optimisation is also analysed, and all cases are compared against the baseline without optimising the charging process.

Charging behaviour of different control strategies

Figure 34 shows the load profiles of the EV, the PV power plant and the residence (i.e. house), as well as the electricity price, in the baseline and three exemplary bidirectional charging schedules for the family scenario. While the baseline charging initiates immediately upon arrival, the remaining three bidirectional charging schedules are outcomes derived from their respective optimisation problems. It is noticeable that, in the “PV optimised” case, only a small fraction of the residual load can be met by the EV. This limitation arises because the end of the parking time coincides closely with a surge in PV production. In the “price optimised” case, a significant fraction of the residual load is covered by the EV, as it leverages the ensuing price drop by charging at maximum power. The combined case “PV and price optimised” exploits both the price drop and the brief period of PV production occurring at the end of the parking period. Additionally, the PV production at the beginning of the parking time is harnessed, resulting in a reduction of the charging power adjusted to the PV production compared to the pure “price optimised” case. This can be explained by the existence of low prices during this period. The energy generated from PV is assumed to be used at zero cost.

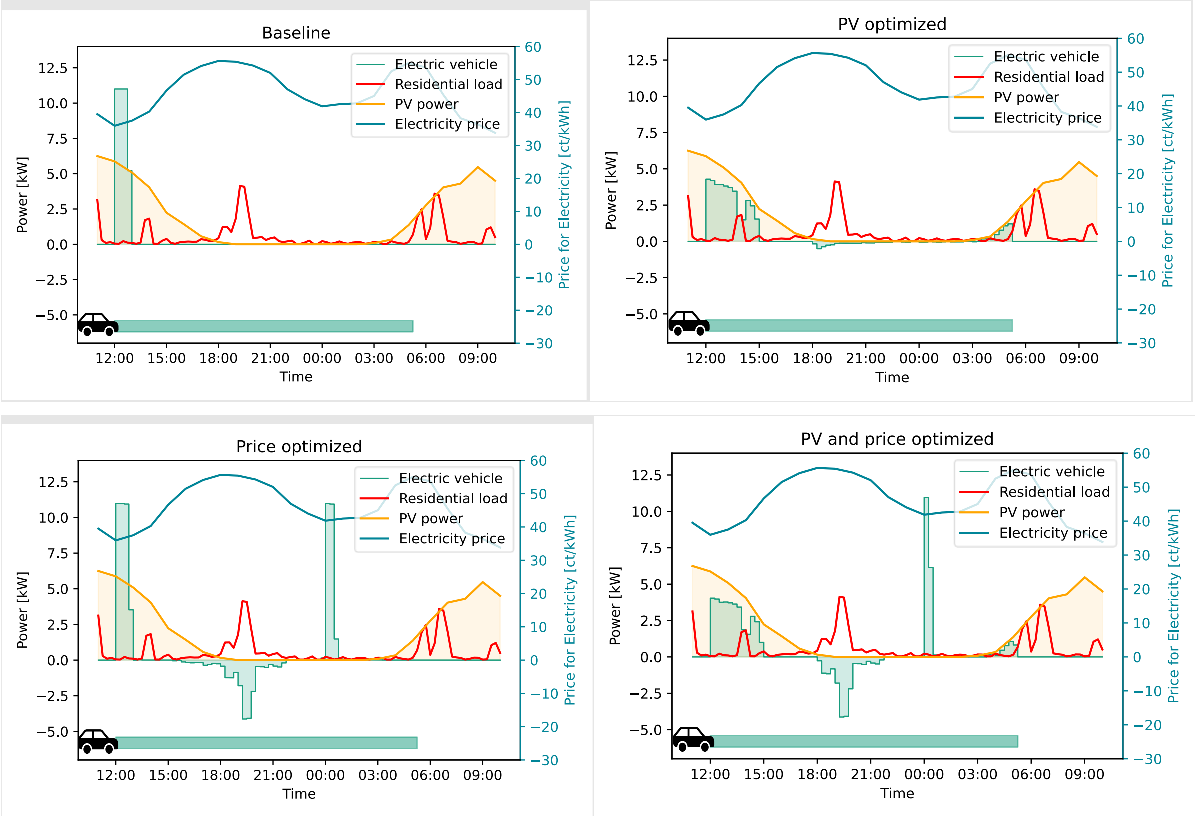


Figure 34: Exemplary bidirectional charging profile of the “family” scenario for the “baseline” and the three optimisation cases “PV optimised”, “price optimised” and “PV and price optimised” for the 14th-15th July[19].

Cost savings due to self-consumption and variable electricity prices

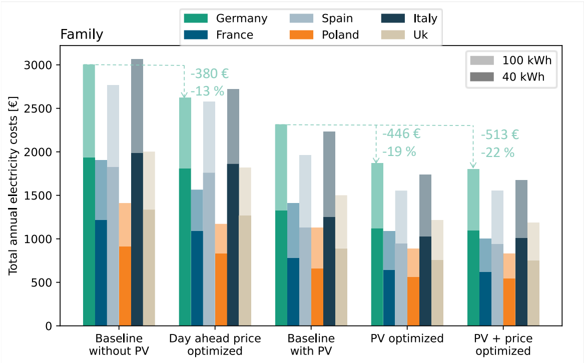
Figure 35 visualizes the economic benefit[20] of **unidirectional** charging for different household types in different countries. Benefits are shown as total electricity costs but exclude PV and EV costs. Additional costs of BEVs with and without bidi charging capacities, together with the costs for EMS, is part of the cost-benefit analysis chapter (see 5.3).

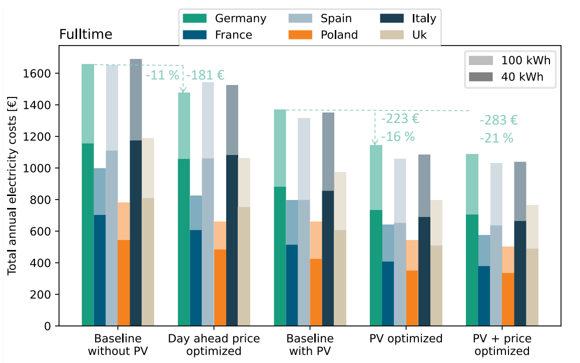
The highest electricity bill reduction can be achieved with a mixed PV- and price-optimised controller for a single teleworker in Italy with 41% reduced costs (=EUR300). The impact of PV-optimised charging is the main source of cost reduction. For the PV-optimised scenario in Germany, the reduction achieved for a single teleworker is 31%, while an optimisation based on day-ahead prices only achieves a cost reduction of 12%. The combined scenario achieves a cost reduction of 36%. As on-site PV energy is assumed to be consumed at zero cost, while the day-ahead price is almost always above zero, PV consumption is always prioritised. In addition, there is a strong correlation between high PV generation and low day-ahead prices, which means that the lowest day-ahead prices reflected in the variable end-user tariff are unlikely to be exploited by the combined controller. However, as there are no additional costs, apart from the development of a more sophisticated controller, this control method should be the method of choice in case of variable prices. When comparing the influence of the household type,

[19] The green bar below the x-axis represents the parking time of the EV.

[20] Note that only cost reductions are displayed. Economic gains from PV fed into the grid are subject to national legislation and chosen sales channels and are not considered in this evaluation. In Germany, a feed-in tariff would lead to smaller benefits from a controlled scenario since a gain in self-consumed energy leads to less compensation for feed-in PV. V2H is still beneficial but instead of a price spread of 35.6 ct/kWh the gains from self-consumption shrink to 27.5 ct/kWh (assuming 8.1 ct/kWh feed in remuneration as of March 2024).

it can be seen that teleworkers benefit the most, even though they have lower charging demand than families and fulltime workers. The German family profits with a maximum cost reduction of 22%, while the two fulltime workers save 21%. Having a closer look at the fulltime workers, the difference between PV-optimised and day-ahead optimised becomes smaller. This can be explained by EVs that are mostly not present during the sunny working hours. The PV-optimisation generates cost saving of 31% for one teleworker compared to only 16% for two fulltime workers, even though the installed PV capacity is higher for the two full-time office workers. Cost savings due to day-ahead price optimisation are almost identical between teleworkers and full-time office workers with 12% resp. 11%.





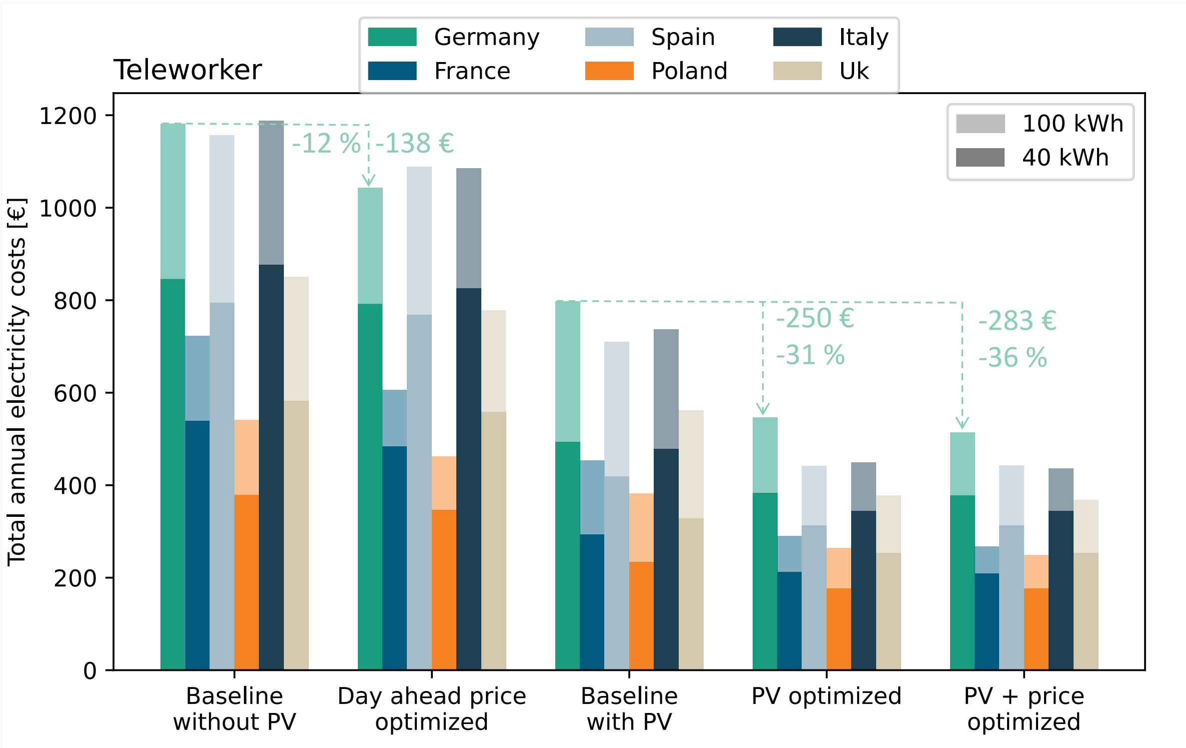


Figure 35: **Total electricity bill for various scenarios for unidirectional charging. Upper left for a family, upper right for two fulltime workers and bottom for a teleworker.** [21]

[21] The different colours represent different countries, the opacity the two different battery sizes and the four different groups on the x-axis represent the different control targets. The numbers show the absolute and relative bill reduction of the different controls compared to the baseline scenario for the German case.

Figure 36 shows the annual electricity costs and cost savings for a **bidirectional** setup. The qualitative relationship of the bars is similar to the unidirectional scenarios (Figure 35). For the German use cases, a family can reduce its annual bill by 31% with a PV- and price-optimised control approach, saving EUR726, while two office workers save EUR363 (-26%), and a teleworker saves up to EUR365, a cost reduction of 45%. The savings are higher compared to the uni-directional charging setup by 5% to 9%. When considering bidirectional charging, it must be considered that, although the self-consumption of PV power can be increased on a larger scale, additional losses due to the charging/discharging cycles lower the economic gains. In addition, these cycles are naturally performed with lower power levels, especially for the discharging process, since household loads are mostly in the power range of some 100 W to a few kW. In this power range, the efficiency of the charging equipment is quite low, assuming that it can supply such low power levels at all[22]. Therefore, in particular when considering variable electricity prices, the price spread needs to be high enough to compensate for additional energy losses. With an exemplary full-cycle efficiency of 70%, a price spread of at least 30% is required to break even, leaving only small periods in the daily day-ahead price curve. The cost savings from bidirectional charging quantified within this study go in line with numbers found in literature that range from EUR150 to EUR400 in the V2H use case (see Section 2.2). Note that this only considers the V2H applications. Additional savings could be realised if electricity is used for arbitrage trading back in the grid, but this use case could not be analysed in detail with an energy system model. Estimations of savings from arbitrage can be found in literature (see Section 2.2). The arbitrage use cases may be utilized by aggregators with pools of private electric vehicles and are not likely to be followed by single individuals.

[22] We considered the charging infrastructure to be able to operate continuously in between -11 kW and 11 kW. However, many chargers have a minimum power value of a few kW. In this case, charging processes would likely use additional grid energy in times with low PV surplus and almost never discharge, or if so, discharging into the grid would be a consequence.

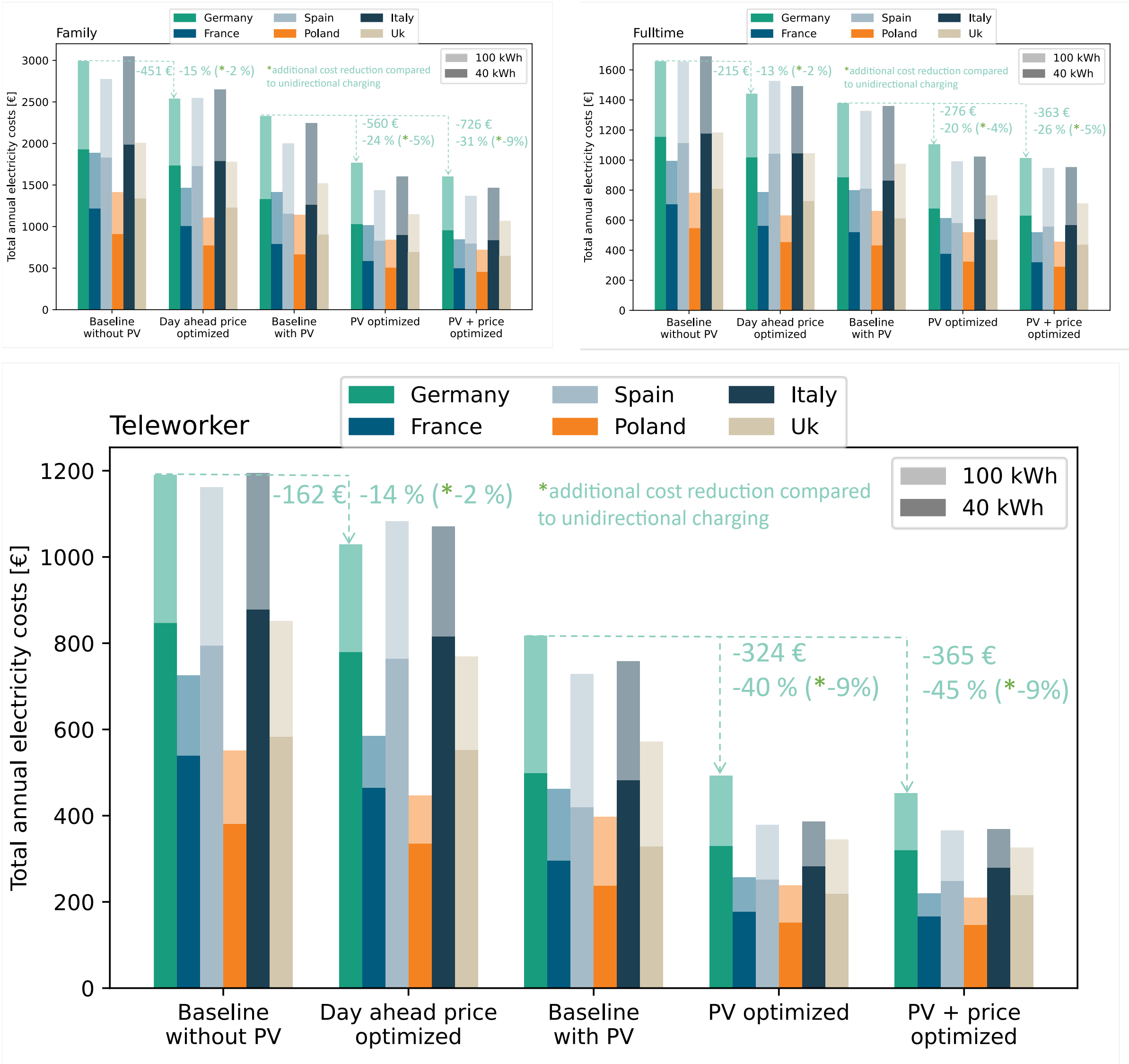


Figure 36: Total electricity bill for various scenarios for bidirectional charging. Upper left for a family, upper right for two fulltime workers and bottom for a teleworker[23].

Cost savings due to increased battery lifetime

Apart from the energy bill reduction due to a higher self-consumption rate and exploited variable electricity prices, another cost-saving factor may result from extended battery lifetime by applying bidirectional charging. The main source for extended lifetime is the reduced calendrical ageing resulting from more beneficial charging states. A shorter lifetime and more cyclic ageing can occur if the battery has considerably more charging cycles. Therefore, the benefit or drawback from bidirectional charging is highly dependent on the charging scenario and the baseline.

In general, bidirectional charging results in a negligible decrease in lifetime compared to the unidirectional charging in the simulation. A significant effect on battery degradation can be observed, when

[23] The different colours represent different countries, the opacity the two different battery sizes and the four different groups on the x-axis represent the different control targets. The numbers show the absolute and elative bill reduction of the different controls compared to the baseline scenario for the German case. The cost reduction compared to unidirectional charging in % is marked with a "*".

the required SOC is changed to 100%. Such a SOC level results in an increased battery degradation of approximately 40%. Figure 37 shows the results of applying the ageing model described earlier. In the upper part of Figure 37, a target SOC of at least 80% was assumed. In the baseline scenario, this means that the battery is charged to exactly 80% on departure whenever subsequent trips do not require more than 80% SOC (>95% of all trips). In the other scenarios, the controller can still utilise the full battery capacity with the constraint that at least 80% SOC is guaranteed at departure. In the lower part, 100% target SOC is required. Unidirectional charging is shown on the left and bidirectional charging on the right side. Green dots represent results from the non-linear ageing model, blue dots from the linear model 66. It shows that PV-optimised charging increases battery lifetime in all cases. For price-optimised behaviour, unidirectional charging also increases the lifetime, while bidirectional charging, following the linear model, has a wide range of lifetime effects with some scenarios also with higher battery degradation.

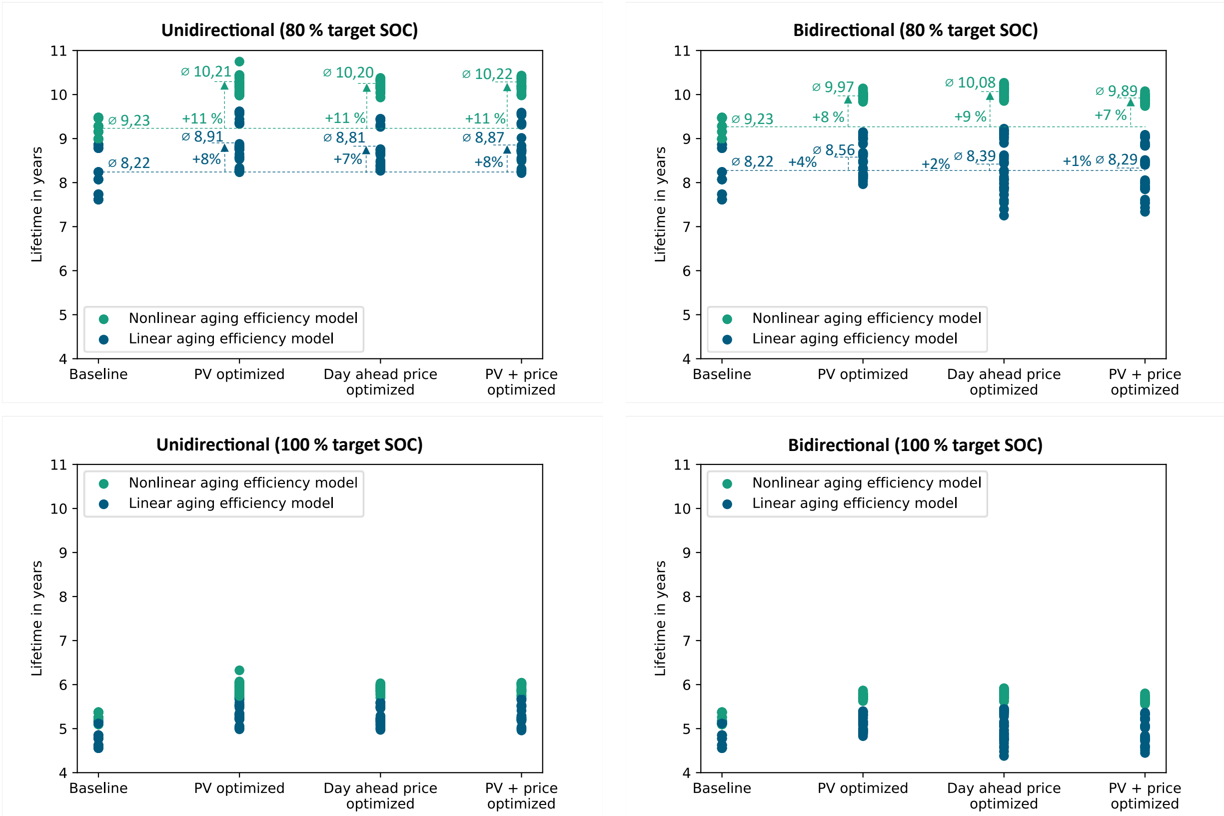


Figure 37: Battery lifetime for the uni- (left) and bidirectional (right) use cases with an 80% target SOC (top) and 100% target SOC (bottom). For the 80% scenario, the mean values and the percentage increase compared to the baseline scenario are included.

In general, there are various ageing models in literature. We have chosen two different approaches which already show different results in terms of absolute offset (non-linear always has longer lifetimes than linear) and the relative comparison with the baseline scenario (the spread of the scenarios including day-ahead prices is larger than in the non-linear model). Long-term results for battery ageing derived from field data with different charging conditions are still lacking, and the battery research is developing new designs in rapid succession. Hence, the assessment of ageing is subject to high uncertainties. However, previous studies come to similar conclusions stating that bidirectional charging does not necessarily decrease battery lifetimes [29, 57]. Derived from [57], strong V2X usage has similar ageing effects in the "nominal case", performs better than the "charge when you can" scenario (which is the baseline in the simulation conducted in this study), but worse than the "just-in-time charging" (see Figure 38).

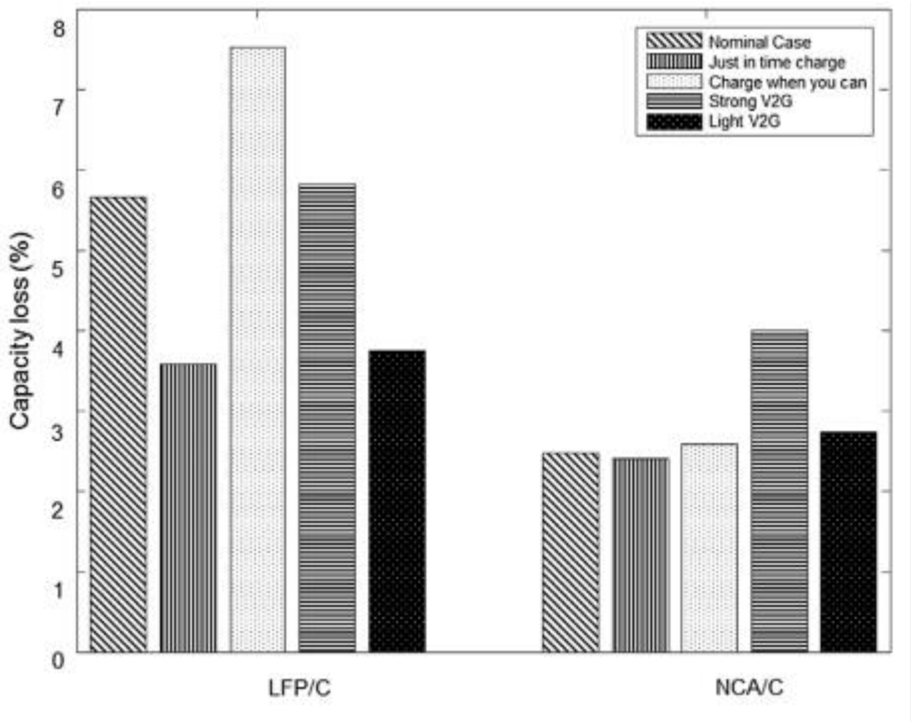


Figure 38: Capacity loss for LFP/C and NCA/C battery technologies after 1 year according to different use cases24.

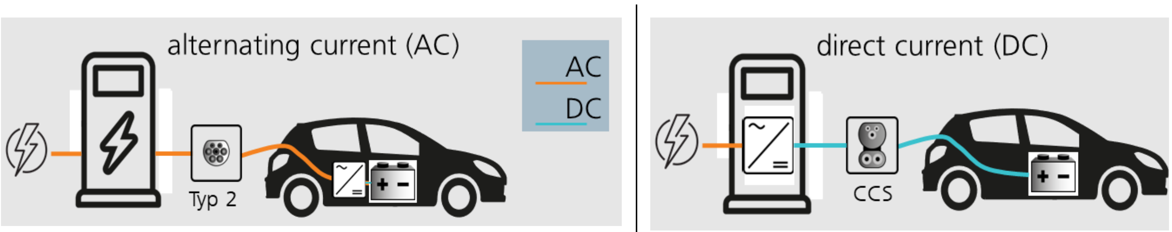
The simulation results show large **cost saving potentials** for controlled uni- and bidirectional charging. In Germany, for example, two fulltime workers can reduce costs by 21%, a family by 22% and a teleworker by 36% when following a combined control approach for PV- and price optimisation. The highest benefits come from the increase of self-consumption, while variable electricity prices offer less potential. Similar findings apply to the other countries observed, with different absolute values of cost savings. The use of bidirectional charging can further increase the cost savings by up to 9% (in Germany for teleworkers). The additional potential of bidirectional energy is subject to additional losses for charging/discharging cycles with low part load efficiency and the major PV excess already being exploited during EV charging.
The **lifetime of the battery** can be substantially extended by changing the target SOC upon departure from 100% to 80% instead. This increases the lifetime by an average of 40%. Controlled unidirectional charging increases the battery lifetime by a further 5-10% on average, compared to uncontrolled charging, with bidirectional performance slightly better than unidirectional charging.

[24] The "charge when you can" mode is comparable with the "baseline" mode in this study

5.2 AC and DC charging equipment costs for V2G

The user costs for V2G are mainly defined by the charging concept. Bidirectional charging can be realised with AC and DC chargers, but technical implementation is different. As the most important starting point to enable V2G, the EV manufacturer has to adapt the battery management system (BMS) and EV charge controller (EVCC) through the functionality of discharging to the vehicle´s plug. This is independent of AC and DC charging. The main difference is that, for DC charging, the converter[25] moves from the EV to the EV charging equipment (EVSE).

A schematic set-up of the AC and DC charging equipment is shown in Figure 39 with an onboard charger (OBC) for AC charging located in the car. It also shows the main advantages and disadvantage of both solutions. AC connection requires a type 2 plug, and DC connection requires a CCS (Combined Charging System) plug that can be used for AC charging as well. Many European EVs already have a CCS connection and are, therefore, prepared for both.



- ↗ In Europe, almost all EVs are equipped with OBC
- ↗ Almost all residential chargers are AC
- → Technical effort for bidirectional OBC is low
- ↘ Adaptations required in EV BMS & EVSE
- ↘ High level communication (ISO 15118-20) between EVSE and EV necessary (in standardisation)
- ↘ Network codes need to be met by OBC

- ↗ OBC not relevant
- ↘ Additional converter required in EVSE
- ↘ Adaptations required in EV BMS & EVCC
- ↗ High level communication ISO15118-20 is already a standard for DC

Figure 39: Comparison between infrastructure for alternating (AC) and direct (DC) current charging concepts for V2X applications and main advantages (green arrows) and disadvantages (red arrows).

In Europe, almost all EVs are equipped with an on-board charger (OBC) and almost all residential chargers are AC chargers. AC charging is, therefore, the default charging setup for residential applications. So far, DC charging is only used for fast charging. To make residential chargers bidirectional, OEMs would need to make their OBC bidirectional, which is relatively easy from a technical point of view. Bidirectional converters are well known from battery systems and can be implemented with a cost increase of around 10%.

Feeding electricity back from the EV to the household/grid requires more sophisticated higher-level communication between EV and EVSE. This communication will be based on the ISO15118-20 standard, which has been released for DC charging, and is currently in the standardisation process for AC charging. The main challenge is that, in the bidirectional case, the network codes must be fulfilled by the OBC and transferred by the EVSE. It is expected that EVs will need to fulfil the same network codes

[25] Converter includes inverter and rectifier

as residential storage, as they are at a similar power level. However, network codes vary between grid operators and countries, and regulation here is challenging.

As a requirement for V2G charging, the EVSE needs to be upgraded for higher-level communication. This upgrade requires new controller hardware that can handle the additional IP-based communication via the control pilot (CP) contact modulated with power line communication. Older EVSE must be replaced by a new one. As there is no difference in the content of the charger, the authors expect prices to be similar to those for unidirectional EVSE. Last year, many manufacturers claimed to be ready for bidirectional charging. For new models, this could mean that higher-level communication can be achieved with an update or upgrade.

While, in the AC case, the converter is located in the car, in the DC case, however, the converter for generating DC electricity for the battery is located in the EVSE. Hence, the EVSE must be replaced with a new one containing more electronics – an AC EVSE is more or less a controlled contactor. The DC EVSE also needs a converter. So far, DC-charging is almost exclusively used for fast charging, which makes DC charging prices a bad indicator. But the prices of hybrid converters for residential storage are in the same order of power and give a good indication. A 10-kW hybrid converter[26] costs around EUR2,400.00.

Costs for energy management systems must be considered as well to implement V2G. Figure 40 shows how V2G charging infrastructure is integrated into the energy system via an energy management system (EMS). The EVSE is the communication interface between the EMS and the EV. Ensuring interoperability requires the application of well-defined standards. According to the current market, OCPP 2.0.1 or OCPP 2.1 (open charge point protocol) is the most promising standard for the EMS. For EVs ISO 15118-20 should be requested for either DC or (when released) AC.

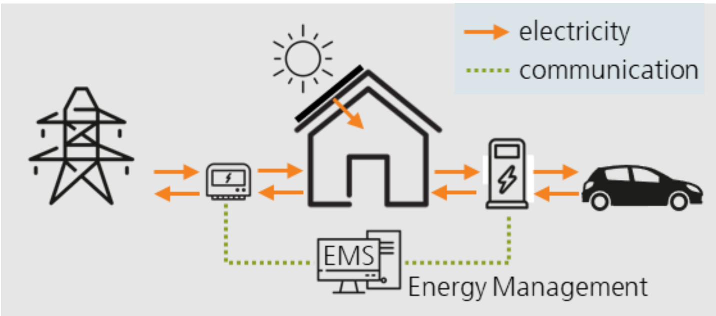


Figure 40: Integration of V2G into the home energy management system

The assessment of future prospects for bidirectional charging infrastructure in households seems to be diverging between AC and DC technologies. DC-based systems are expected to be implemented more rapidly due to their higher charging speeds and increasing adoption in commercial and industrial applications.

However, AC-based systems remain fundamentally more cost-effective and simpler to implement. Consequently, despite the faster progression of DC technology, AC systems are likely to dominate household applications due to their technical simplicity and lower costs. Thus, while DC technology may advance quicker, AC will likely be the more economical and practical choice for residential use. Table 12 shows prices that we expect in a developed market for V2G applications. If car manufacturers change the current approach to equip all cars with on-board chargers, the economic advantage of AC systems could be reduced.

[26] converter price example here: https://www.photovoltaik4all.de/fronius-symo-gen24-10.0-plus

Table 12: Summary of expected price for bidirectional charging equipment

	Unidirectional		Target Bidirectional
	Simple control	EMS included	EMS included
AC charging	**EUR1,000**	**EUR1,250**	**EUR1,350**
EVSE	EUR1,000	EUR1,000	EUR1,100
Energy Management	-	EUR250	EUR250
DC charging	**EUR3,000**	**EUR3250**	**EUR3,250**
EVSE (10 kW)	EUR3,000	EUR3,000	EUR3,000
Energy Management	-	EUR250	EUR250

Source: Own assumptions

5.3 Cost benefit analysis for V2H and V2G applications

Cost benefit analysis for V2H

The cost-benefit assessment of V2H systems takes into account the price of bidirectional charging equipment and the annual savings.

The one-time cost of unidirectional charging equipment is estimated as EUR1,000 for AC charging and EUR3,000 for DC charging. Applying an advanced energy management system for controlled uni- or bidirectional charging, additional EUR250 are needed. For bidirectional charging the DC cost stay identical, while AC cost increase by about EUR100.

The annual savings for unidirectional charging in the German use cases range between EUR130 and EUR510, which shows that, after only two years, costs for an energy management system are compensated. In the bidirectional AC case, only small additional costs of EUR100 apply, while additional annual savings of EUR60 to EUR200 are possible.

This shows that, if charging infrastructure and a PV-System are already in place, implementing an energy management system is always the economic choice. Even if no PV-System is installed, variable tariffs offer annual cost saving incentives of at least EUR130 to follow a controlled charging approach.

Since bidirectional charging does not decrease battery lifetimes and only comes with about EUR100 additional cost for AC infrastructure (and no additional cost for DC), considering the additional annual savings of EUR16 to EUR200, a V2H EMS is always the economic choice. However, the effect is less pronounced than for the simple decision of controlled unidirectional charging.

While the economic benefit of bidirectional charging always covers the costs for additional hard- and software, for a fulltime worker in Poland, the economic gain is the smallest, while a family in Italy can profit the most.

Cost benefit analysis for providing V2G services instead of following V2H incentives

An analysis of V2G services in Europe indicates potential cost savings. Germany leads with reductions of 1.4% in grid reinforcement costs in densely populated areas and significant savings in less populated regions. France sees large reductions, benefiting from its sparsely populated areas. Italy avoids significant investment in power lines, especially in intermediate regions. Poland saves mainly in less populated areas, while Spain, despite its dense population, concentrates savings in intermediate regions. The UK benefits from savings due to its large urban population (as shown in section 3.2).

These savings depend on network topology and distribution. While some regions can avoid penalties altogether with V2G controllers, most benefit from the reduced need for grid reinforcement. Although optimised controllers may have drawbacks in some cases, overall, they offer positive or neutral effects.

In Germany, the introduction of V2G services for EVs is expected to result in savings in grid expansion costs by 2030 and 2040. In the 2030 scenario, the estimated German savings amount to EUR430 million, with 14.1 million EVs expected to be in operation. This translates into savings of around EUR30.50 per EV. By 2040, these savings are projected to increase to EUR1.73 billion, driven by an expected 30.7 million EVs, resulting in approximately EUR56.35 saved per EV.

Cost comparison of V2G and V2H services

Assuming that the cost of implementing V2G and V2H services is the same, it is clear that the financial incentives for V2H are significantly higher than the avoided grid reinforcement costs of V2G. While V2H could save a family in Germany owning a PV-plant up to EUR726 per year (only utilizing variable tariffs with no PV-plant saves EUR451), an EV could save only EUR56.35 of grid costs over the period to 2040.

Conclusion

V2H systems can often contribute to the stability of the electricity grid and do not necessarily preclude the implementation of V2G services, as the need for V2G is less frequent. It is possible that V2H will also lead to a reduction in the expansion of the electricity grid, an aspect not considered in this study. This could lead to additional savings. When V2H systems are market-driven, many charging and discharging cycles are expected to be grid-supportive. This typically occurs when grid load is low and electricity prices are correspondingly low. This dual approach can optimise grid management by effectively addressing both consumer incentives and grid operator needs.

6 Conclusions & Recommendations

Effects on the power system level

On the power system level, the transformation of the mobility sector necessitates an increase in electricity demand supported by more renewable generation and backup capacities but also leads to a stronger dependency on electricity exchange between countries. Based on the power system model results, smart charging and Vehicle-to-Grid (V2G) technologies can play a crucial role in alleviating the pressures of this transformation across all mentioned areas; they can help to decrease curtailment and reduce the need for electricity grid expansion. Additionally, smart charging and V2G enable better integration of photovoltaic (PV) capacity, allowing for more capacity to be installed. This reduces the need for other alternative flexibility resources within the system, in particular less reliance on stationary battery storage. Furthermore, a more effective integration of PV through electric vehicles is achievable if the vehicles are connected during daytime. With large numbers of electric vehicles, the market can become saturated. The additional value of flexibility from truck charging is limited in this case.

Another effect of smart charging and V2G is a reduction of generation capacity in electrolysis and the electrification of hydrogen as well as the reduction of electricity generation capacity from natural gas. This effect further increases, and a stronger reduction of these capacities can be seen, if V2G is applied. This includes a stronger decrease in the required backup capacities of gas and hydrogen power plants, as well as lower utilization of power generation from these plants. If the number of electric vehicles increases and a large number of vehicles is already equipped with bidirectional charging technologies, the marginal additional value of flexibility becomes smaller.

Effects on the distribution grid level

Regarding the grid implications of bidirectional charging, our analysis focused on two distinct use cases: economically optimized charging and grid-friendly charging. Economically optimised charging involves using dynamic retail tariffs for electric vehicle (EV) users, commonly referred to as vehicle-to-home (V2H). This method has shown only marginally positive effects on peak loadings. While the integration of photovoltaic (PV) generation can decrease grid load, the impact is highly dependent on specific grid characteristics. Overall, no strong negative effects can be observed due to economically optimized charging.

Grid-friendly charging involves monitoring transformer loading to adapt charging activities. During periods of potential grid overload caused by high demand, charging processes are postponed as much as possible without compromising the target state of charge (SOC). Conversely, if overload occurs due to high electricity feed-in, plugged-in cars are charged wherever feasible. This approach helps to reduce overloads but does not eliminate them entirely.

Several grid-specific conditions, including the presence of EVs but also the integration of other technologies such heat pumps and PV installations, determine the need for grid extensions. Therefore, the contribution of Vehicle-to-Grid (V2G) technologies is limited under these circumstances. Despite these limitations, grid-friendly charging typically results in a slight reduction in grid extension costs on average. This showcases the potential of adaptive charging strategies to mitigate some grid challenges while recognizing the complexity and variability of grid systems.

Effects on the user level

In addition to these systemic benefits, individual benefits for electric vehicle users also occur and increase with higher price variability, incentivising the adoption of smart charging and V2G technologies. The financial savings from bidirectional charging vary significantly depending on the size of the EV and the typical driving profile of the user. Smaller EVs can expect savings ranging from EUR30 to

EUR430 per year (4 – 34 % cost savings), while larger EVs can benefit from savings between EUR78 and EUR780 per year (7 – 35 % cost savings), if V2H is considered and compared to unmanaged charging. This is in line with recent studies that identified substantial economic potential for car and truck users. Revenues found in literature are ranging between approximately EUR300-1,500[27] per car and year and between approximately EUR3,000-10,000 per truck and year in the case of depot charging.

The integration of photovoltaic (PV) systems and the utilization of dynamic pricing structures can substantially increase these potential savings. Bidirectional charging increases savings by 5 % compared to smart charging alone. From the household categories perspective, the analysis of EV charging at home shows larger cost saving potentials for teleworkers compared to families and fulltime workers. For example, two German fulltime workers can reduce their electricity costs by 26% (EUR360), a family by 31% (EUR730) and a teleworker by 45% (EUR370) when following a combined control approach for PV- and price optimisation. The highest benefit results from the increased self-consumption of PV power, while a variable electricity price offers significantly smaller potentials. The savings vary depending on price levels and price spreads of electricity costs. In countries with lower electricity costs, such as Poland and France, lower cost reductions in absolute terms can be realised. Consequently, vehicle-to-home (V2H) technologies also generate cost savings in these countries, but profitability is lower when the same level of investment is considered.

Implementation barriers

V2X is currently in a testing phase in many countries in Europe, and first commercial trials can be seen. In recent years, industry has increasingly recognised the potential and started to develop cars and charging infrastructure capable of bidirectional charging. Yet, many of the (announced) car models focus on V2L/V2H use cases, and the availability of cars that are capable of V2G is still scarce. Similarly, many of the announced bidirectional wall boxes are not available yet.

In addition to technical barriers and potential acceptance issues, the current regulatory, policy and market environment defers or impedes V2X deployment. However, regulation on EU-level has increasingly considered V2X, and recent regulatory revisions are conducive to V2X (e.g. the internal electricity market directive, the AFIR, the RED III, the EPBD and the ETD—once agreed upon). Yet, national law still needs to be adapted accordingly in many cases. EU countries differ in their V2X-friendliness with regard to regulatory, policy and market considerations.

In the realm of technological development for electric vehicle charging, both AC (alternating current) and DC (direct current) technologies are functional and supported by most vehicle manufacturers. Vehicles that are V2X-ready (vehicle-to-everything) do not incur significant additional costs, making both technologies viable. However, for a broad diffusion of bidirectional charging infrastructure, a uniform standard is essential to avoid proprietary solutions and ensure the interoperability of different vehicles with the charging infrastructure. AC charging systems require less hardware, making them more suitable for residential use and slow charging applications. In contrast, DC charging systems, due to their additional hardware costs, remain more expensive and are primarily used for fast charging, while the business case for bidirectional charging is less clear. An economic analysis in Germany, considering full electrification of single-family homes, reveals that a DC-dominated world, compared to an AC dominated one, would lead to an approximate economic disadvantage of EUR30 billion, assuming there are 12 million single-family homes. Moreover, a scenario where passenger vehicles rely solely on DC charging without onboard chargers is viewed as unlikely. Currently, DC technology holds a developmental lead, both in terms of hardware and communication software. For ex-

[27] Note that EUR1,500 in literature also includes arbitrage trading of a private car, which was not part of the study at hand.

ample, the ISO 15118-20 standard for DC is already available, whereas for AC, it is still under development and presents more complexity due to grid code compliance aspects. In the long run, AC technology is considered to be more cost-effective and promising due to its lower hardware requirements and adaptability for residential and slow charging purposes. This positions AC as a favourable option for future technological investments and infrastructure development in electric vehicle charging.

The lifetime of the battery should be no barrier for the implementation of V2G, as the analysis based on an ageing model for the battery life indicated. If V2G is combined with controlled charging battery lifetime is increased by 5 - 10 %. Even stronger impacts on the battery lifetime result from target SOC upon departure.

7 List of figures

8 List of tables

9 References

[1] P. Jochem, S. Babrowski, and W. Fichtner, "Assessing CO 2 emissions of electric vehicles in Germany in 2030," Transportation Research Part A: Policy and Practice, vol. 78, pp. 68–83, 2015, doi: 10.1016/j.tra.2015.05.007.

[2] M. Kühnbach, J. Stute, T. Gnann, M. Wietschel, S. Marwitz, and M. Klobasa, "Impact of electric vehicles: Will German households pay less for electricity?," Energy Strategy Reviews, vol. 32, p. 100568, 2020. doi: 10.1016/j.esr.2020.100568. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2211467X20301218

[3] C. Gschwendtner, S. R. Sinsel, and A. Stephan, "Vehicle-to-X (V2X) implementation: An overview of predominate trial configurations and technical, social and regulatory challenges," Renewable and Sustainable Energy Reviews, vol. 145, p. 110977, 2021. doi: 10.1016/j.rser.2021.110977. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1364032121002690

[4] W. Kempton and S. E. Letendre, "Electric vehicles as a new power source for electric utilities," Transportation Research Part D: Transport and Environment, vol. 2, no. 3, pp. 157–175, 1997. doi: 10.1016/S1361-9209(97)00001-1. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1361920997000011

[5] INNOVATION outlook : Smart charging for electric vehicles. Abu Dhabi: IRENA, 2019.

[6] V2G Hub. "V2G Around the world." Accessed: May 23, 2024. [Online]. Available: https://www.v2g-hub.com/insights/

[7] R. Loisel, G. Pasaoglu, and C. Thiel, "Large-scale deployment of electric vehicles in Germany by 2030: An analysis of grid-to-vehicle and vehicle-to-grid concepts," Energy Policy, vol. 65, pp. 432–443, 2014, doi: 10.1016/j.enpol.2013.10.029.

[8] T. Gnann, A.-L. Klingler, and M. Kühnbach, "The load shift potential of plug-in electric vehicles with different amounts of charging infrastructure," Journal of Power Sources, vol. 390, pp. 20–29, 2018. doi: 10.1016/j.jpowsour.2018.04.029. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0378775318303720

[9] Vehicle to Grid Hub. "Insights: Status." Accessed: May 24, 2024. [Online]. Available: https://www.v2g-hub.com/insights/status/#graphs

[10] Vehicle to Grid Hub. "Insights: Map." Accessed: May 24, 2024. [Online]. Available: https://www.v2g-hub.com/insights/

[11] J. Dow. "Tesla releases Powershare bidirectional charging – on Cybertruck only, so far." Accessed: Aug. 1, 2024. [Online]. Available: https://electrek.co/2023/11/30/tesla-releases-powershare-bidirectional-charging-on-cybertruck-only-so-far/

[12] smartEn, "Assessment of the regulatory framework of bidirectional EV charging in Europe," 2023. Accessed: May 24, 2024. [Online]. Available: https://smarten.eu/wp-content/uploads/2023/12/V2X-Enables-abd-Barriers-Study_11-2023_DIGITAL.pdf

[13] ADAC, "Das Elektroauto als Stromspeicher fürs Haus: So funktioniert bidirektionales Laden," 2024. Accessed: May 24, 2024. [Online]. Available: https://www.adac.de/rund-ums-fahrzeug/elektromobilitaet/laden/bidirektionales-laden/

[14] Electric Vehicle Database. "Current and Upcoming Electric Vehicles." Accessed: Jun. 11, 2024. [Online]. Available: https://ev-database.org/

[15] PV Magazine. "Produktdatenbank Elektroauto-Ladelösungen: Wallboxen und Ladesäulen 2023." Accessed: Jun. 11, 2024. [Online]. Available: https://www.pv-magazine.de/marktuebersichten/marktuebersicht-elektroauto-ladeloesungen/produktdatenbank-elektroauto-ladeloesungen-wallboxen-und-ladesaeulen-2023/

[16] e-mobileo. "Wallboxen für bidirektionales Laden (V2H, V2G,...)." Accessed: Jun. 11, 2024. [Online]. Available: https://www.e-mobileo.de/v2g-und-v2h-wallboxen-fuer-bidirektionales-laden/

[17] Nationale Leitstelle Ladeinfrastruktur, "Bidirektionales Laden diskriminierungsfrei ermöglichen," 2024. Accessed: Jun. 11, 2024. [Online]. Available: https://nationale-leitstelle.de/wp-content/uploads/2024/03/Bidirektionales-Laden_final_240306.pdf

[18] M. B. Anwar et al., "Assessing the value of electric vehicle managed charging: a review of methodologies and results," vol. 15, no. 2, pp. 466–498, 2022, doi: 10.1039/D1EE02206G.

[19] C. Gschwendtner, C. Knoeri, and A. Stephan, "Mind the goal: Trade-offs between flexibility goals for controlled electric vehicle charging strategies," early access. doi: 10.1016/j.isci.2023.105937.

[20] FfE, "BDL - Bidiretkionales Lademanagement Abschlussbericht der FfE," 2023. Accessed: May 24, 2024. [Online]. Available: https://www.ffe.de/wp-content/uploads/2023/03/BDL-Abschlussbericht.pdf

[21] J. Stute, S. Pelka, M. Kühnbach, and M. Klobasa, "Assessing the conditions for economic viability of dynamic electricity retail tariffs for households," Advances in Applied Energy, vol. 14, p. 100174, 2024, doi: 10.1016/j.adapen.2024.100174.

[22] A. Stephan and C. Gschwendtner, "Enabling Flexible Electric Vehicle Grid Integration - ErVIn," 2021. Accessed: Jun. 11, 2024. [Online]. Available: https://www.aramis.admin.ch/Default?DocumentID=68837&Load=true

[23] M. Mueller and Y. Schulze, Eds., Future grid load with bidirectional electric vehicles at home. Berlin: VDE VERLAG GMBH, 2021.

[24] cenex, "Project Scirius Trial Insights: Findings from 300 Domestic V2G Units in 2020," 2021. Accessed: May 24, 2024. [Online]. Available: https://www.cenex.co.uk/app/uploads/2021/05/Sciurus-Trial-Insights.pdf

[25] Daimler Truck and Tennet, "Flexibility marketing options for charging processes of electric medium-duty and heavy-duty commercial vehicles," 2022. Accessed: May 24, 2024. [Online]. Available: https://tennet-drupal.s3.eu-central-1.amazonaws.com/default/2022-11/Daimler%20Truck%20TenneT%20Feasibility%20Study.pdf

[26] F. Biedenbach and K. Strunz, "Multi-Use Optimization of a Depot for Battery-Electric Heavy-Duty Trucks," WEVJ, vol. 15, no. 3, p. 84, 2024, doi: 10.3390/wevj15030084.

[27] D. Wang, J. Coignard, T. Zeng, C. Zhang, and S. Saxena, "Quantifying electric vehicle battery degradation from driving vs. vehicle-to-grid services," Journal of Power Sources, vol. 332, pp. 193–203, 2016, doi: 10.1016/j.jpowsour.2016.09.116.

[28] P. B. Andersen, S. Hashemi Toghroljerdi, T. M. Sørensen, B. E. Christensen, Høj, Jens Christian Morell Lodberg, and A. Zecchino, "The Parker Project: Final Report," 2019. Accessed: Jun. 11, 2024. [Online]. Available: https://backend.orbit.dtu.dk/ws/portalfiles/portal/201164295/Parker_Final_report_v1.1_2019.pdf

[29] J. Gong et al., "Quantifying the impact of V2X operation on electric vehicle battery degradation: An experimental evaluation," eTransportation, vol. 20, p. 100316, 2024, doi: 10.1016/j.etran.2024.100316.

[30] B. K. Sovacool, L. Noel, J. Axsen, and W. Kempton, "The neglected social dimensions to a vehicle-to-grid (V2G) transition: a critical and systematic review," Environ. Res. Lett., vol. 13, no. 1, p. 13001, 2018, doi: 10.1088/1748-9326/aa9c6d.

[31] L. Schmidt, N. Waxmann, D. Reichert, and K. V. Boesche, "Bidirektionales Laden in Deutschland - Marktentwicklung und Potenziale," 2023. Accessed: May 24, 2024. [Online]. Available: https://www.energy4climate.nrw/fileadmin/Service/Publikationen/mobilitaet/Potenzialanalyse-bidirektionales-Laden.pdf

[32] M. Kubli, "EV drivers' willingness to accept smart charging: Measuring preferences of potential adopters," Transportation Research Part D: Transport and Environment, vol. 109, p. 103396, 2022. doi: 10.1016/j.trd.2022.103396. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1361920922002231

[33] M. Helferich, J. Tröger, and A. Stephan, "Smart Charging in Germany: Acceptance and Tariff Design," 2023, doi: 10.24406/publica-1634.

[34] European Parliament, Union´s electricity market design: Regulation, 2023. Accessed: Jun. 11, 2024. [Online]. Available: https://www.europarl.europa.eu/doceo/document/TA-9-2024-0284_EN.html

[35] European Parliament, Revision of the Renewable Energy Directive: Fit for 55 package, 2023. Accessed: Jun. 11, 2024. [Online]. Available: https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/698781/EPRS_BRI(2021)698781_EN.pdf

[36] European Commission, Directive (EU) 2024/1275 of the European Parliament and of the Council of 24 April 2024 on the energy performance of buildings (recast) (Text with EEA relevance), 2024. [Online]. Available: http://data.europa.eu/eli/dir/2024/1275/oj

[37] Council of the European Union, "Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the energy performance of buildings (recast)," Dec. 2023. Accessed: Jan. 12, 2024. [Online]. Available: https://www.consilium.europa.eu/de/press/press-releases/2023/12/07/fit-for-55-council-and-parliament-reach-deal-on-proposal-to-revise-energy-performance-of-buildings-directive/

[38] European Parliament, "Revision of the Energy Taxation Directive: Fit for 55 package," 2021. Accessed: Jun. 11, 2024. [Online]. Available: https://www.europarl.europa.eu/RegData/etudes/BRIE/2022/698883/EPRS_BRI(2022)698883_EN.pdf

[39] ACER, "Report on Electricity Transmission and Distribution Tariff Methodologies in Europe," Slovenia, 2023.

[40] Bundesministerium für Digitales und Verkehr (BMDV), "Masterplan Ladeinfrastruktur II der Bundesregierung," 2023. Accessed: Jun. 11, 2024. [Online]. Available: https://bmdv.bund.de/SharedDocs/DE/Anlage/G/masterplan-ladeinfrastruktur-2.pdf?__blob=publicationFile

[41] NOW-GmbH, "Facilitating bidirectional charging nationwide," NOW-GmbH, 2024. Accessed: Jun. 11, 2024. [Online]. Available: https://www.now-gmbh.de/en/news/pressreleases/facilitating-bidirectional-charging-nationwide/

[42] Bundesministerium für Digitales und Verkehr (BMDV), "Smart-Meter-Gesetz final beschlossen: Flächendeckender Einsatz intelligenter Stromzähler kommt," 2023. Accessed:

Jun. 11, 2024. [Online]. Available: https://www.bmwk.de/Redaktion/DE/Pressemitteilungen/2023/05/20230512-smart-meter-gesetz-final-beschlossen.html

[43] V2G Hub, "Insights," 2024. Accessed: Jun. 11, 2024. [Online]. Available: https://www.v2g-hub.com/insights/

[44] Department for Business, Energy & Industrial Strategy and ofgem, "Electric Vehicle Smart Charging Action Plan," 2023. Accessed: Jun. 11, 2024. [Online]. Available: https://assets.publishing.service.gov.uk/media/655dfabf046ed400148b9e0a/electric-vehicle-ev-smart-charging-action-plan.pdf

[45] electrive, "British government boosts bidirectional charging," 2023. Accessed: Jun. 11, 2024. [Online]. Available: https://www.electrive.com/2023/12/21/british-government-boosts-bidirectional-charging/

[46] S. Alibas et al., "European Hydrogen Infrastructure Planning," 2024, doi: 10.24406/publica-2733.

[47] D. Speth and P. Plötz, "Depot slow charging is sufficient for most electric trucks in Germany," Transportation Research Part D: Transport and Environment, vol. 128, p. 104078, 2024, doi: 10.1016/j.trd.2024.104078.

[48] ACER, "Connection Codes," 2023. Accessed: Jun. 11, 2024. [Online]. Available: https://www.acer.europa.eu/electricity/connection-codes

[49] Storage Expert Group, "Phase II Final Report," 2020.

[50] ACER, "ACER POLICY PAPER on the revision of the network code requirements for grid connection of generators and the network code on demand connection," 2022. Accessed: Jun. 11, 2024. [Online]. Available: https://acer.europa.eu/sites/default/files/documents/Position%20Papers/260908%20ACER%20GCNCs%20Policy%20Paper_final.pdf

[51] Bundesamt für Kartographie und Geodäsie, "Verwaltungsgebiete 1:2500000 Stand 01.01. (VG250 01.01)," 2024. Accessed: Jun. 11, 2024. [Online]. Available: https://gdz.bkg.bund.de/index.php/default/digitale-geodaten/verwaltungsgebiete/verwaltungsgebiete-1-250-000-stand-01-01-vg250-01-01.html

[52] European Commission, "Geoportal of the european comission (EUROSTAT)," 2018. Accessed: Nov. 6, 2023. [Online]. Available: https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/population-distribution-demography/degurba

[53] M. Kühnbach et al., "Potentziale von Stellplätzen an Wohn- und Nichtwohngebäuden zur Bereitstellung privater Ladeinfrastruktur," 2024.

[54] J. Kähler, "Netzausbaubedarf für die Transformation des Energiesystems anhand repräsentativer Verteilnetze (Grid expansion requirements for the transformation of the energy system based on representative distribution grids). presented at the 39-PV-Symposium/BIPV-Forum, Bad Staffelstein, Germany, 27.-28. Februray 2024,"

[55] D. Fischer, A. Härtl, and B. Wille-Haussmann, "Model for electric load profiles with high time resolution for German households," Energy and Buildings, vol. 92, pp. 170–179, 2015, doi: 10.1016/j.enbuild.2015.01.058.

[56] D. Fischer, A. Harbrecht, A. Surmann, and R. McKenna, "Electric vehicles' impacts on residential electric local profiles – A stochastic modelling approach considering socio-economic, behavioural and spatial factors," Applied Energy, vol. 233-234, pp. 644–658, 2019. doi: 10.1016/j.apenergy.2018.10.010. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0306261918315666

[57] M. Petit, E. Prada, and V. Sauvant-Moynot, "Development of an empirical aging model for Li-ion batteries and application to assess the impact of Vehicle-to-Grid strategies on battery lifetime," Applied Energy, vol. 172, pp. 398–407, 2016, doi: 10.1016/j.apenergy.2016.03.119.

[58] B. Lux et al., "The role of hydrogen in a greenhouse gas-neutral energy supply system in Germany," Energy Conversion and Management, vol. 270, p. 116188, 2022, doi: 10.1016/j.enconman.2022.116188.

[59] L. Lam and P. Bauer, "Practical Capacity Fading Model for Li-Ion Battery Cells in Electric Vehicles," IEEE Trans. Power Electron., vol. 28, no. 12, pp. 5910–5918, 2013, doi: 10.1109/TPEL.2012.2235083.

[60] J. Nájera, J. R. Arribas, R. M. de Castro, and C. S. Núñez, "Semi-empirical ageing model for LFP and NMC Li-ion battery chemistries," Journal of Energy Storage, vol. 72, p. 108016, 2023, doi: 10.1016/j.est.2023.108016.

Annex A - Modell description

Enertile

Enertile is an energy system optimisation model developed at the Fraunhofer Institute for System and Innovation Research ISI. The model focuses on the power sector, but also covers the interdependencies with other sectors, especially heating/cooling and the transport sector. It is used for long-term scenario studies and is designed to depict the challenges and opportunities of increasing shares of renewable energies.

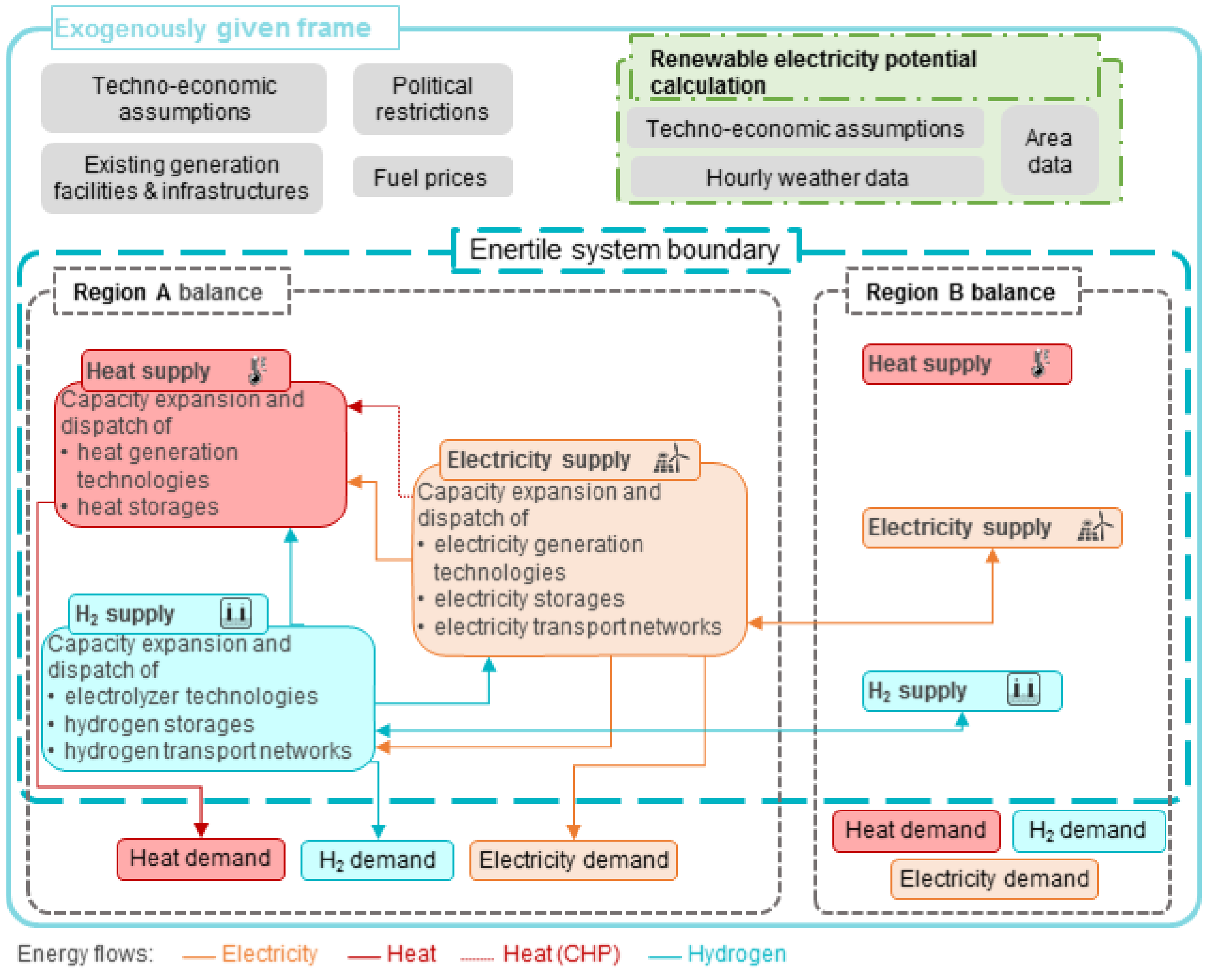


Figure 41: **Schematic representation of the system boundaries, inputs and interactions of the energy supply model Enertile [58].**

Renewable power generation technologies are central for the transition to a greenhouse-gas neutral energy system. Their availability, however, fluctuates spatially and temporally due to weather conditions. In order to optimize the energy supply in Enertile, the potential of renewable energies is, therefore, determined in advance, featuring high technological, spatial and temporal resolutions. Techno-economic data for the technologies onshore wind, offshore wind, PV (rooftop and ground mounted) and CSP are combined with land use data and real weather data from 2010 on a grid of edge lengths of 6.5 x 6.5 km. The result of this preliminary analysis includes the installable capacity, electricity yield and generation profiles of the individual technologies and serves as the basis for Enertile's expansion and dispatch decisions.

The weather-induced fluctuating availability of renewable energies challenges the hourly balancing of electricity supply and demand and increases the need for flexibility options. In addition to stationary storage technologies, cross-regional balancing via transmission networks and flexible demands, Enertile, therefore, considers the flexibility potential of an electrified transport sector. Cost minimisation can use the aggregations of car and truck batteries in a model region for system balancing as long as the underlying driving profiles of the electric vehicles can be met. The maximum power for the charging and discharging of these mobile storages is also limited by the driving profiles or the dwell times of the vehicles.

Battery Ageing model

For cycling ageing, the model proposed by L. Lam et al. [59] is utilised, while for calendar ageing, the model developed by J. Nájera et al. [60] is employed. These models incorporate the experimental observation that higher state of charge (SOC) and greater throughput into the battery result in accelerated ageing. This means that, when the battery is operating at high SOC levels and experiencing high throughput, its ageing rate tends to increase accordingly. The total battery Q_{tot} can be modelled for calendar and cycling ageing functions. The mathematical models for calendar ageing, denoted Q_{cal} and cycling ageing, denoted Q_{cyc}, are presented below:

$$Q_{tot} = Q_{cyc} + Q_{cal}$$

$$Q_{cal} = f.\exp\left(g.\,\overline{SOC}\right).\ \exp\left(\frac{h}{T}\right).\ t^{0.5}.\ Q_{nom}$$

$$Q_{cyc} = k_{s1}.\ SOC_{dev}\,.\exp\left(k_{s2}.\overline{SOC}\right) + k_{s3}.\exp\left(k_{s4}.SOC_{dev}\right).\exp\left(-\frac{Ea}{R}\left(\frac{1}{Ti}-\frac{1}{T_{ref}}\right)\right)Ah$$

Where $\overline{SOC}$ is average and SOC_{dev} is the standard deviation of the state of charge, T is the temperature, t is the time, Ah is the total throughput, other parameters and constants are provided in the reference (REF).

We simulate one year of ageing to estimate the lifetime of the battery, assuming that the battery reaches the end of its life, when 80% of its active capacity remains. The amount of time to this point is calculated using both linear and nonlinear models. This naming is based on the time model dependency of cycling ageing. The model incorporates coefficients for both annual cycling and calendar ageing. When the total loss reaches 20% of the nominal battery capacity, the battery is considered to have reached the end of its life. The models can be described as follows:

$$Q_{cal}^{an}\,t^{0.5} + Q_{cyc}^{an}t = 0.2Q_{nom} \text{ (linear)}$$

$$Q_{cal}^{an}\,t^{0.5} + Q_{cyc}^{an}t^{0.5} = 0.2Q_{nom} \text{ (non-linear)}$$

To estimate the lifetime of the battery, t (time) simulations were performed for one year and Q_{cal}^{an} and Q_{cyc}^{an} values were calculated. The estimated lifetime of the battery is then determined based on the results obtained from solving these models for t (time).

Annex B – Interpolation of grid reinforcement for 2030

The grid expansion costs for 2030 in densely populated and intermediate populated areas are identical for standard charging and the grid-friendly bidirectional charging approach. Therefore, the reduced grid expansion costs in these areas are zero in 2030 (see Table 13). Reduced grid expansion costs in thinly populated areas reach EUR3,204m in the EU 27 in 2030. Figure 42 shows the reduction of required grid expansion costs for 2030 per country when the grid-friendly bidirectional charging approach (described in 4.2.2) is applied. In cases of transformer overloads, the DSO requests bidirectional flexibility from all plugged-in EVs.

Table 13: Savings of costs and material for grid expansion for EU 27 in 2030 due to grid friendly bidirectional charging

Population density	Reduced grid expansion /EUR	Savings steel/kt	Savings aluminium/kt	Savings PVC/kt	Reduced curtailment/GWh
Dense	0	0	0	0	0
Intermediate	0	0	0	0	0
Thinly	3,204m	99	23	0	0
Sum	**3,204m**	**99**	**23**	**0**	**0**

Source: Own assumptions

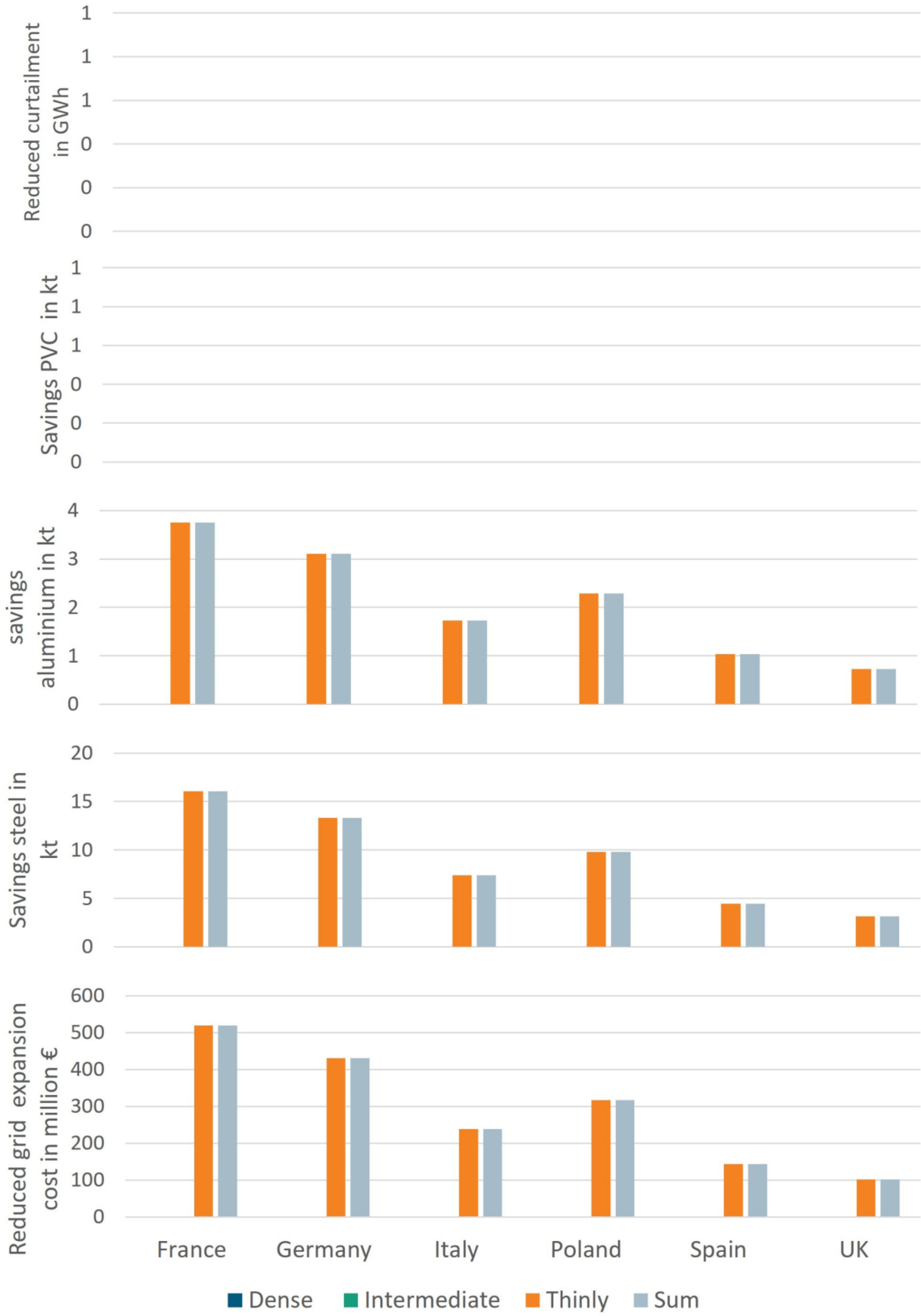


Figure 42: **Reduced curtailment, material savings and reduced grid costs from V2G for France, Germany, Italy, Poland, Spain and UK (2030)**