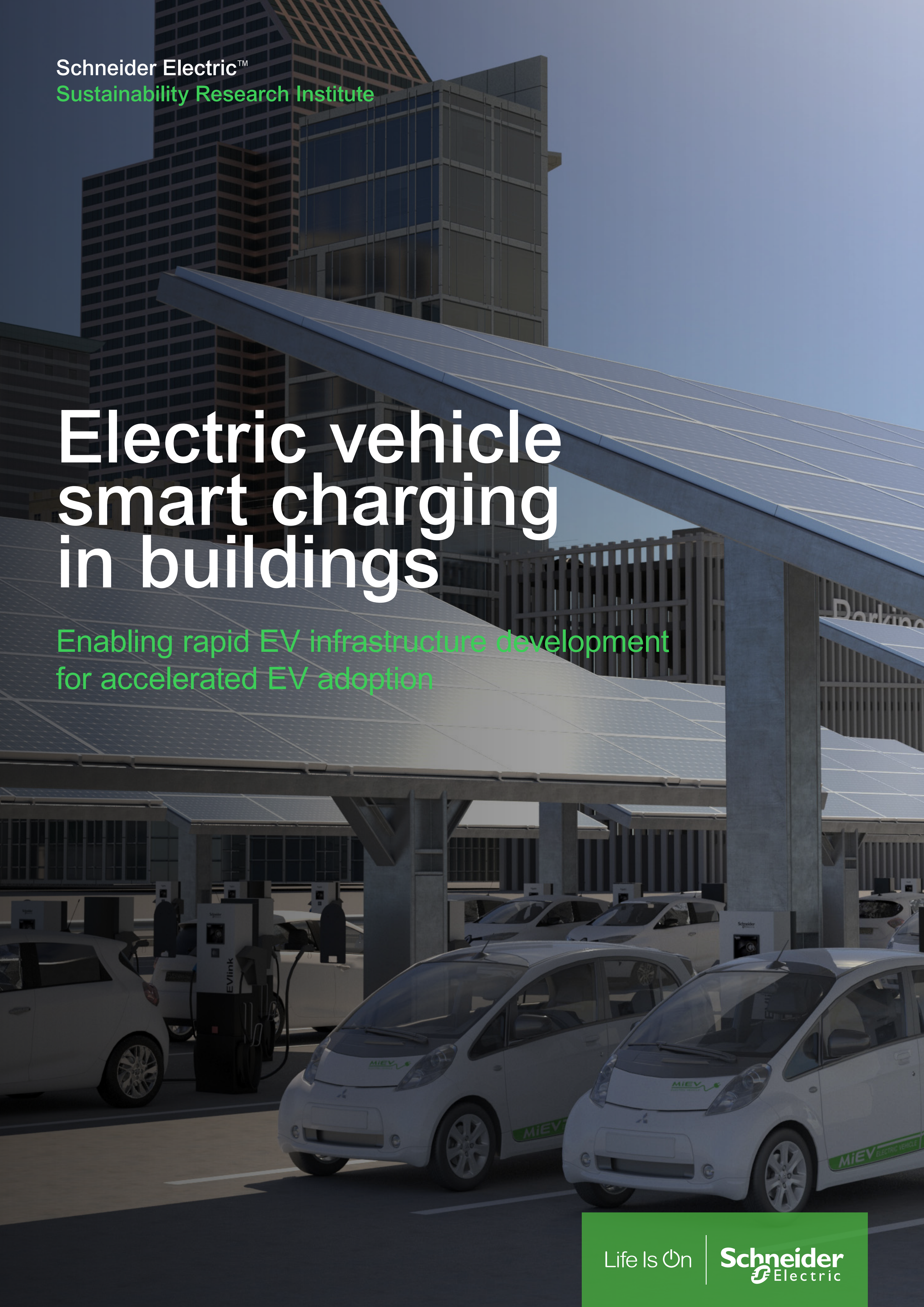
Schneider Electric™
Sustainability Research Institute

Electric vehicle smart charging in buildings

Enabling rapid EV infrastructure development for accelerated EV adoption



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It is our responsibility, as large organizations, to make a positive impact by reducing energy consumption and CO_2 emissions, contributing to societal progress, while being profitable.

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In this white paper, we demonstrate that electric vehicle smart charging will be a key enabler of a rapid infrastructure development leading to an accelerated electric vehicle adoption. Through a detailed cost-benefit analysis of local charging optimization, we show that both consumers and grid system operators can benefit from smart charging at a building level. We also recommend a thoughtful policy approach to make this happen.

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It is time to embrace sustainability as a business imperative, and to capture the momentum now, for the future.

Oliver Blum

Chief Strategy and
Sustainability Officer,
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SVP Strategy Prospective
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Glossary

EV Car and EV charging:

- **ICE**: Internal Combustion Engine
- **EV**: Electric Vehicle
- **LMS**: Load Management System
- **CSMS**: Charging stations management system
- **OCPP**: Open Charge Point Protocol
- **ESCO**: Energy Services Company
- **EMSP**: Electro Mobility Service Provider
- **CPO**: Charge Point Operator

Buildings:

- **Building**: through all of the paper, the term building encompasses any kind of real-estate construction, both residential, tertiary or industrial buildings
- **H**: Households
- **MD**: Multi-dwelling
- **C&I**: Commercial and Industrial
- **BEMS**: Building Energy Management System
- **DER**: Distributed Energy Resource
- **PV**: Photovoltaic
- **BESS**: Battery Energy Storage System

Grid:

- **Retail tariffs**: tariff scheme for an electricity consumer (consumption + power subscription + fixed costs + taxes)
- **DSO**: Distribution System Operator
- **TSO**: Transmission System Operator
- **BRP**: Balance Responsible Party

Economics:

- **TCO:** Total Cost of Ownership
- **TCC:** Total Cost of Charging
- **Energy costs:** refers to the energy consumption component of an electricity bill (€/kWh)
- **Power costs:** refers to the power component of an electricity bill (€/kW)
- **CAPEX:** Capital Expenditure
- **OPEX:** Operational Expenditure

Modelling:

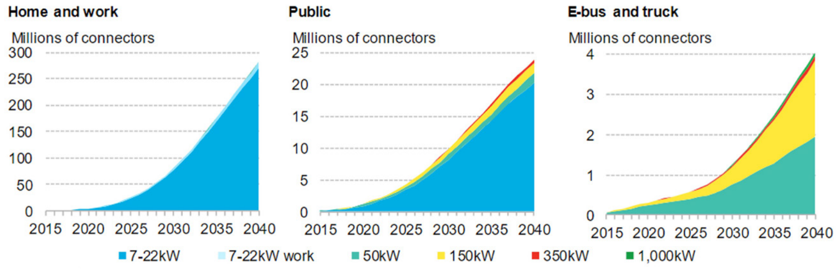
- **Optimization Lever (OL):** method of optimization allowing for potential customer-sided benefits
- **Customer side benefits:** value of smart charging benefiting the end-user (the charger user)
- **Grid side benefits:** value of smart charging benefiting grid and system operators
- **Customer-sided optimization:** Optimization of EV charging with the goal of benefiting the end-user first
- **Grid-sided optimization:** Utilization of EVs to optimize grid operations

Executive Summary

Decarbonizing road transportation thanks to Electric Vehicles (EVs) is already deeply transforming the mobility industry. This trend will accelerate in the decades to come at rapid pace. But for this major shift to play out with actual benefits to society, one of the major challenges to be tackled remains that of EV charging.

In fact, the lack of ubiquitous charging infrastructure could turn into a key bottleneck to a rapid transition to EVs. The cost of charging is also under intense scrutiny from the entire value chain, from consumers to system operators, and a key question is whether these costs can be optimized for rapid adoption.

At the same time, with 300 to 500 million connectors to be installed by 2040, the EV charging infrastructure is clearly becoming one of the essential building blocks of tomorrow's smart and decentralized energy system.

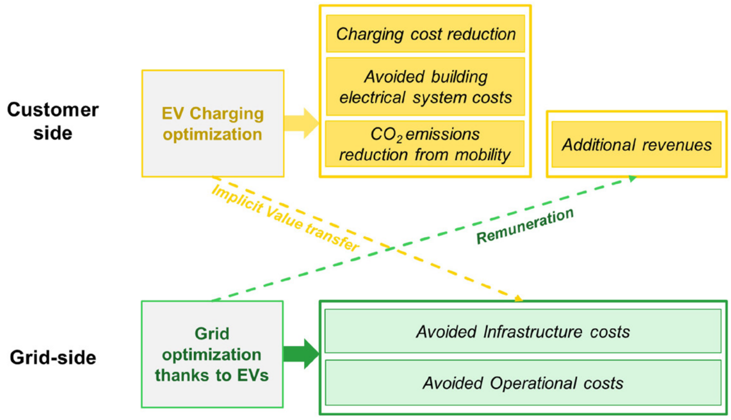


Source: BNEF. Note: Light commercial EVs are considered within home and public infrastructure.

Tapping into the potential services provided by these chargers, smart charging will play a critical role into removing bottlenecks and accelerating adoption.

Yet, extensive analysis of the potential added value of smart charging remains scarce. Besides, most existing policies have so far focused on public charging infrastructure, even though about 90% of the chargers are expected to be installed in households and commercial buildings.

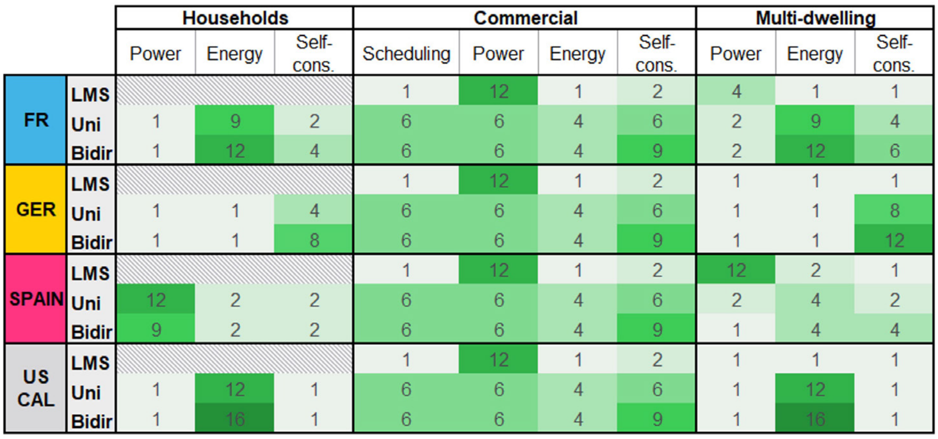
In this report, we demonstrate that both consumers and system operators can benefit from smart charging at a building level.



We deep dive into a detailed cost-benefit analysis of local charging optimization in households, multi-dwellings, and commercial buildings. We also explore the potential CO_2 reductions and grid & system services it can provide.

Key findings:

- Charging in buildings is vastly more affordable for consumers than public charging.
- Smart charging generates tremendous additional savings (up to 70% in some cases) to consumers, especially when time-of-use tariffs (Energy), demand charge (Power), and self-consumption develop. These savings improve depending on the features of the charging overall system (presence of a load management system to avoid demand charges, unidirectional or bidirectional charging from the chargers). The figure below provides a qualitative assessment of which driver is most relevant within each use case.



		Households			Commercial				Multi-dwelling		
		Power	Energy	Self-cons.	Scheduling	Power	Energy	Self-cons.	Power	Energy	Self-cons.
FR	**LMS**	▨	▨	▨	1	12	1	2	4	1	1
	Uni	1	9	2	6	6	4	6	2	9	4
	Bidir	1	12	4	6	6	4	9	2	12	6
GER	**LMS**	▨	▨	▨	1	12	1	2	1	1	1
	Uni	1	1	4	6	6	4	6	1	1	8
	Bidir	1	1	8	6	6	4	9	1	1	12
SPAIN	**LMS**	▨	▨	▨	1	12	1	2	12	2	1
	Uni	12	2	2	6	6	4	6	2	4	2
	Bidir	9	2	2	6	6	4	9	1	4	4
US CAL	**LMS**	▨	▨	▨	1	12	1	2	1	1	1
	Uni	1	12	1	6	6	4	6	1	12	1
	Bidir	1	16	1	6	6	4	9	1	16	1

Criticality of optimization levers depending on the country and segment (arbitrary scale).
The grade (from 1 to 16) for each optimization lever was given considering two criteria: the value of the savings imputable to the lever, and the share of the total value it represents amongst all other optimization levers.

- These benefits are also magnified with the provision of grid services, which reveal the true value of a fully smart and bidirectional charging strategy.
- Finally, smart charging also contributes to avoid large infrastructure investments while increasing the resilience of local and global grids, further strengthening the case for rapid rollout.

But to make this happen, a thoughtful policy approach is required. We show that a well-designed policy should ensure:

1. The promotion of charging at building site, removing all existing barriers
2. The promotion of smart charging, to optimize overall costs, notably with use of time-of-use tariffs and self-consumption
3. A better access to grid and system services for EVs to support the transformation of energy systems

This is further illustrated with concrete recommendations in the context of the recast of several key US and EU directives.

EV smart charging is a major enabler of the decarbonization of mobility, but also that of buildings and global energy systems. When coupled to EV smart charging, flexible sources and loads within buildings bring decarbonization and cost benefits, a generally more efficient and economically attractive proposition than centralized paradigms.

Chapter 1: the key challenge to mobility decarbonization is the charging infrastructure

1. The inevitable growth of the electric vehicle industry

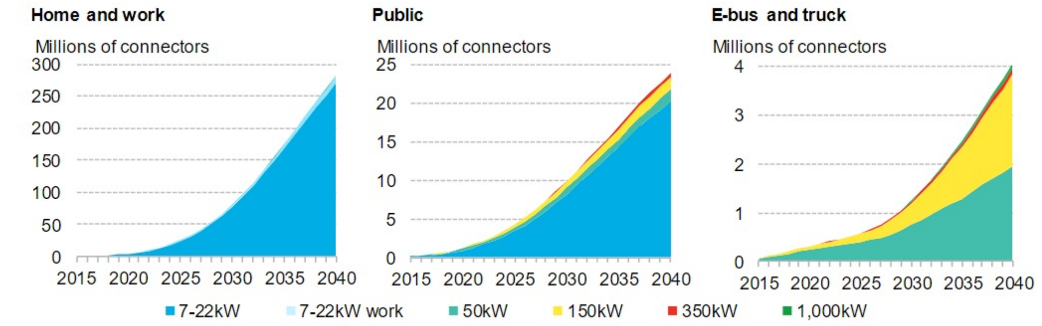
Electric vehicles (EVs) penetration is accelerating, with no sign of slowdown in the coming years. This represents a fundamental transformation of the automotive industry and the broader mobility ecosystem.

The EV market has experienced rapid growth over the last few years, especially in 2020 and 2021. After a slight slowdown in 2019, EVs came back stronger. As of June 2021, there are 12 million passenger EVs on the road and BloombergNEF expects this figure to rise to 54 million by 2025. Most international automakers already sell EVs and by 2022, there will be over 500 different EV models available globally [1]. High levels of investment are bolstering the restructuring of the industry as a result. According to McKinsey [2], the average annual investment in electrical vehicle and charging technologies has increased from $0.6 billion in 2010 – 2013 to $3 billion in 2014 – 2019. And this is only a beginning.

EV uptake can be attributed to several factors: driving experience, technology performance, cost decrease, and societal and environmental benefits- including reduction of air pollution and CO2 emissions.

From an end-user standpoint, EVs have significantly lower operating costs (fewer moving parts, regenerative breaking, lower maintenance costs, etc..) and their cost of acquisition will reach parity with current ICEs within this decade, making the case fully compelling [1].

Supporting the uptake of EVs will require significant expansion of charging infrastructure. According to BloombergNEF Net Zero scenario- describing a pathway towards carbon neutrality by 2050, approximately 500 million charging points will be needed globally by 2040 [1].Home and workplace charging are expected to account for the vast majority of EV charging (about 90%) as shown in Figure 1. This makes sense as even for a EV heavy driver, the daily average distance is about 60km only (see Annex 2).



Source: BNEF. Note: Light commercial EVs are considered within home and public infrastructure.

Figure 1: Cumulative global installed charging infrastructure by category: home and work, public, commercial in the BloombergNEF Energy Transition Scenario

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[1] By the end of 2020, there were only 1.36 million installed public charging connectors. Although this constitutes an increase of 48% from 2019, there is still significantly more work to be done in public charging.

2. Smart charging is key to fully electrified mobility and resilient energy systems

Despite these overwhelming advantages, there is still uncertainty as to how EV mobility will develop. This is essentially due to the availability of a resilient and ubiquitous charging infrastructure. Beyond immediate rollout hurdles, the key question is the potential toll from EV charging on the power infrastructure and the corresponding investments that would be required to upgrade it.

The charging of millions of EVs in an uncontrollable way could indeed increase the risk of grid failure and/or high costs. As an example, the French transmission system operator RTE estimates that if more than 60% of charging was not controllable in 2035, the winter peak load could grow by 6 to 8 GW [3]. EVs could also soon have impacts on local distribution grids[2], EV chargers being power intensive installations. In a neighborhood with a high penetration rate of EVs, residential transformers and distribution cables could quickly be overloaded, threatening power supply quality and reliability. [4]

Dealing with such issues in a traditional way will require massive infrastructure investments and come at the expense of consumers. The alternative (and complementary solution) is smart charging. Yet, smart charging is not widely deployed today due to higher upfront costs (compared to basic charging).

The question however is that of the value it could bring. In fact, smart charging provides increased flexibility of charging, thereby helping smooth grid demand. This potential is magnified when combined with distributed generation resources and flexibility strategies within a building (flexible loads, local energy storage, both electric and thermal), opportunities which cannot materialize in public charging setups. In theory, there is thus untapped potential for more optimized charging strategies.

Yet, there are only few existing studies exploring in detail this potential. This report is another and critical contribution to this discussion. It explores the issue by running a cost competitiveness benchmark following different smart charging strategies, and across a range of use cases (households, multi-dwellings, commercial buildings, and public charging). The report also analyzes impacts in terms of carbon emissions optimization and the impacts on the grid infrastructure.

3. How smart charging creates value

While smart charging can benefit multiple stakeholders[3], we focus our approach on two categories driving the uptake:

- the end user, broadly defined as the category which incurs costs (charging Capex and charging bill), and thus has the most direct interest in opting for the cheapest charging solution. In residential dwellings, the end-user is usually the house owner. In other cases, the end-user may be the building owner, the tenant or a mobility service provider.
- the Distributed System Operator (DSO), the Transmission System Operator (TSO), and in a European context the Balance Responsible Parties (BRP). Smart charging shall reduce whole system costs by lowering infrastructure needs and optimizing operations. Namely, lowering peak power demand would have material impact on expensive and carbon-intensive peak units (often gas and coal-fired power plants). It would also reduce the need for expensive and material-intensive grid upgrades.

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[2] The situation varies widely across geographies

[3] See Appendix 1

Figure 2 summarizes key values for each category and how they must ultimately coordinate to realize those benefits.

The first area to focus on is end-user economics, as the primary decision maker and investor. Customer side charging optimization focuses on the management of energy resources inside the building energy system. It is essentially based on retail tariff data and management of local loads and resources. But these optimization levers also generate some implicit/benefits to system operators.

Then, the system operator can also leverage EVs for grid side optimization. It focuses on the response of the EV to a real-time signal from the grid or electricity market (explicit flexibility). The primary beneficiaries of this optimization are the grid and system operators, even though the end-user is ultimately compensated for the service.

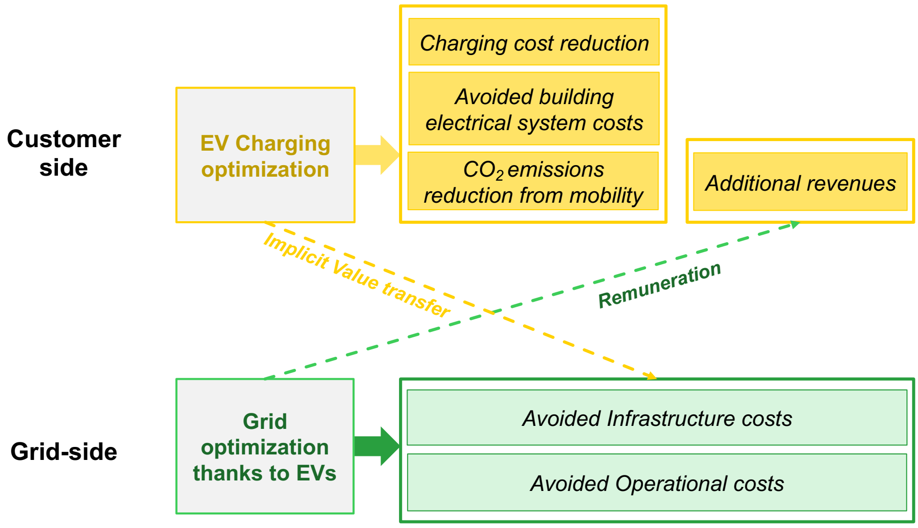

Figure 2: Sources of customer and grid benefits from smart charging under study[4]

The core focus of this report is to clarify benefits of smart charging at end user level, thru a detailed modelling exercise to quantify those in different contexts (chapter 2). Grid optimization is also reviewed, leveraging current literature on the topic, and feedbacks from existing projects in operations (chapter 3).

4. Modelling of EV smart charging benefits at end-user level

The key instrument we use to quantify these benefits is the Total Cost of Charging (TCC). It is derived from the cost of electricity used for charging, as well as upfront costs (Capex) and other operational expenses (Opex) of the charging system. **Around 120 charging use cases were modeled.**

The general idea driving our use case building methodology is to get as close as possible to real-life conditions in any given context. The constraints and opportunities stemming from these different situations help define the relevant smart charging strategy which is then modelled thru a specific algorithm.

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[4] Implicit Value is also referred as Incentive based value

Key parameters are regrouped in three blocks (Figure 3), with each block being influenced by the choices made in the previous one[5].

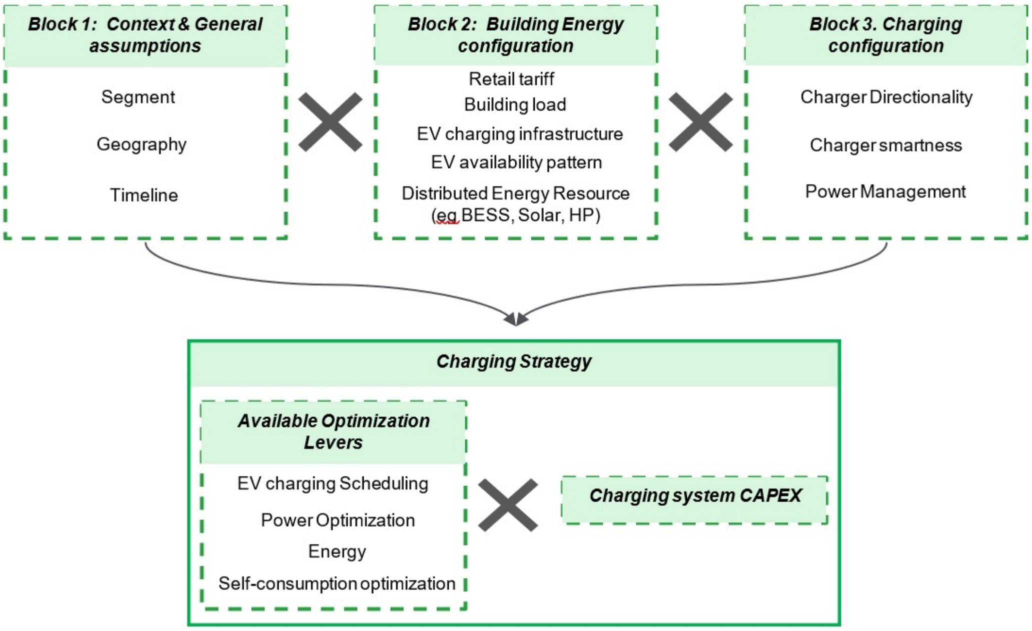

Figure 3: Method for use case modelling and charging strategy design

Our model focuses on 3 building types which represent the bulk of end-user charging opportunities: Households (H), Multi-dwelling (MD) residential and Commercial and Industrial buildings (C&I)[6]. Four different geographies are selected to understand how local rules and specificities impact the value of smart charging: France, Germany, Spain, and California state. For each geography, public charging costs are retrieved[7]. This cost is the first element of comparison for our modeling results.

The exact site configuration can then be retrieved (Block 2): retail electricity tariffs depend on the local retailer offers, building size and electric loads depend on climate and local behaviors, the number of chargers and their size differ in each segment (and are derived from market forecasts). Distributed Energy Resources (PV, BESS) are sized following optimization prior to any charger installation, and their Capex is not taken into account in our economic analysis. Finally, EV presence patterns are designed to reflect driver's behaviors in each segment[8].

In block 3, the level of control (or smartness) of charging is defined. Beyond uncontrolled charging, a load management systems (LMS) is a first step towards smart charging, limiting the power drawn from a set of multiple chargers. Then comes smart charging, which can be unidirectional or bidirectional. This is defined from the charger standpoint, not the building. Where public charging relies on charging optimization that can be done directly with the grid (V-to-G), in buildings, optimization is done with the building loads (V-to-B), or with both, in sequence (V-to-B-to-G)(Figure 4).

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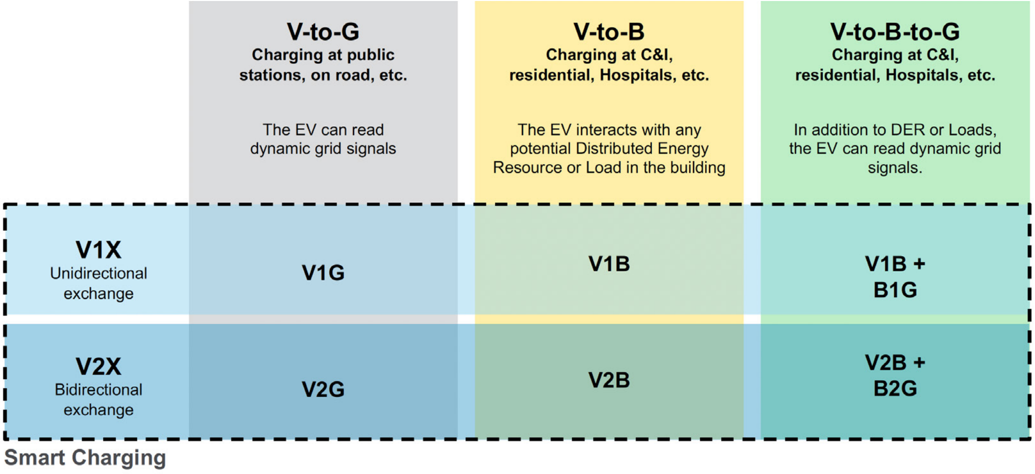
[5] Further details are given in Annex 2

[6] In fleet depot buildings, energy for mobility is by far the main component of the energy bill, which makes the relation between EV charging and the building less interesting.

[7] As these costs vary significantly today, they have generally been aggregated to a mean value. See Annex 2 for details on this.

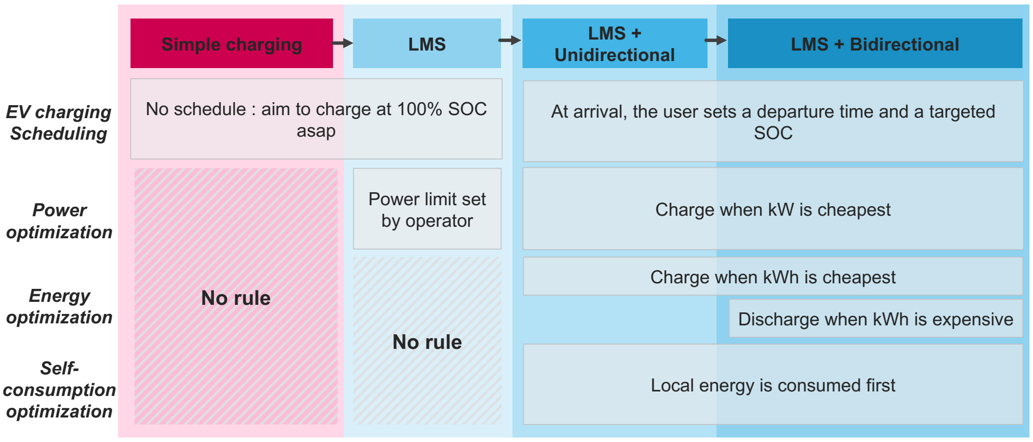
[8] Further detail for each segment is available in Annex 2.



	V-to-G **Charging at public stations, on road, etc.** The EV can read dynamic grid signals	**V-to-B** **Charging at C&I, residential, Hospitals, etc.** The EV interacts with any potential Distributed Energy Resource or Load in the building	**V-to-B-to-G** **Charging at C&I, residential, Hospitals, etc.** In addition to DER or Loads, the EV can read dynamic grid signals.
V1X Unidirectional exchange	**V1G**	**V1B**	**V1B + B1G**
V2X Bidirectional exchange	**V2G**	**V2B**	**V2B + B2G**

Figure 4: Smart charging framework description

Finally, the charging strategy is defined (Figure 5). It is a balance between the extent of optimization possible (across different paradigms: scheduling, power, energy, self-consumption) and the actual upfront cost of the solution (capex of solution: LMS, unidirectional, bidirectional, etc.).



	Simple charging	**LMS**	**LMS + Unidirectional**	**LMS + Bidirectional**
EV charging Scheduling	No schedule : aim to charge at 100% SOC asap		At arrival, the user sets a departure time and a targeted SOC	
Power optimization	**No rule**	Power limit set by operator	Charge when kW is cheapest	
Energy optimization		**No rule**	Charge when kWh is cheapest	Discharge when kWh is expensive
Self-consumption optimization			Local energy is consumed first	

Figure 5: Smart charging strategy

The simulations were run using the Schneider Electric proprietary Micro-Grid Design Tool (MGDT). This tool is designed to size components of a Micro-Grid (PV, Battery, Genset, etc.) depending on a real-life building or site configuration. It takes into account retail and grid injection tariffs, solar irradiance, and economic data to derive the Micro-Grid's behavior and economic benefits. [5] A specific module models EV presence patterns which in turn helps determine charging loads[9].

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[9] Further details are given in Annex 3. The model assumes that the EV end-user always complies to set departure times, and that PV outputs, grid retail tariffs and building loads are perfectly predictable for the whole charging period. Such assumptions yield a slight overestimation of the savings reachable in real-life. However, these issues are found to be irrelevant compared to the intrinsic sensitivity of the results to initial assumptions.

Chapter 2: Smart charging at building level provides significant economic benefits

Massive savings if done right

The Total Cost of Charging provides a consolidated perspective of benefits from an end-user standpoint. The net present cost is here annualized to provide a simpler perspective of benefits for end-users[10] (Euros per year). It is expressed as a percentage of public charging costs (Figure 6).

The smart charging outcomes detailed below account for all 4 optimization levers discussed above (scheduling, power/demand charge optimization, energy optimization, self-consumption optimization). These are indeed combined when applicable and differently used across different sectors in different geographies depending on the type of smart charging solution, local constraints, local building profiles, and regulation. The smart charging system optimizes for all this, within each case[11].

		Households 4,9 MWh 1 charger				**Commercial** 291 MWH (180 MWh after scheduling) 30 chargers		**Multi-dwelling** 15,5 MWh 4 chargers			
		Flat		ToU		ToU		Flat		ToU	
		No PV	PV	No PV	PV	No PV	PV	No PV	PV	No PV	PV
FR	**Uncontr.**	-17%	-35%	-22%	-25%	-28%	-38%			-16%	-20%
	LMS					-45%	-56%			-18%	-24%
	Uni	-15%	-36%	-37%	-40%	-64%	-74%			-33%	-37%
	Bidir	-8%	-31%	-46%	-48%	-60%	-70%			-29%	-37%
GER	**Uncontr.**	-17%	-26%			-11%	-24%	-23%	-25%		
	LMS					-34%	-48%	-21%	-23%		
	Uni	-17%	-30%			-59%	-71%	-20%	-31%		
	Bidir	-12%	-28%			-57%	-69%	-14%	-34%		
SP	**Uncontr.**			-3%	-5%	-5%	-19%			10%	17%
	LMS					-28%	-43%			-36%	-33%
	Uni			-49%	-51%	-54%	-67%			-38%	-35%
	Bidir			-48%	-49%	-50%	-63%			-32%	-28%
US CAL	**Uncontr.**			-23%	-23%	-40%	-48%			-4%	-4%
	LMS					-55%	-64%			-21%	-21%
	Uni			-53%	-53%	-71%	-79%			-65%	-65%
	Bidir			-130%	-130%	-68%	-76%			-142%	-90%

Figure 6: Reduction of Total Costs of charging in different Segments, Countries and Cases in 2025 (in % compared to public charging)

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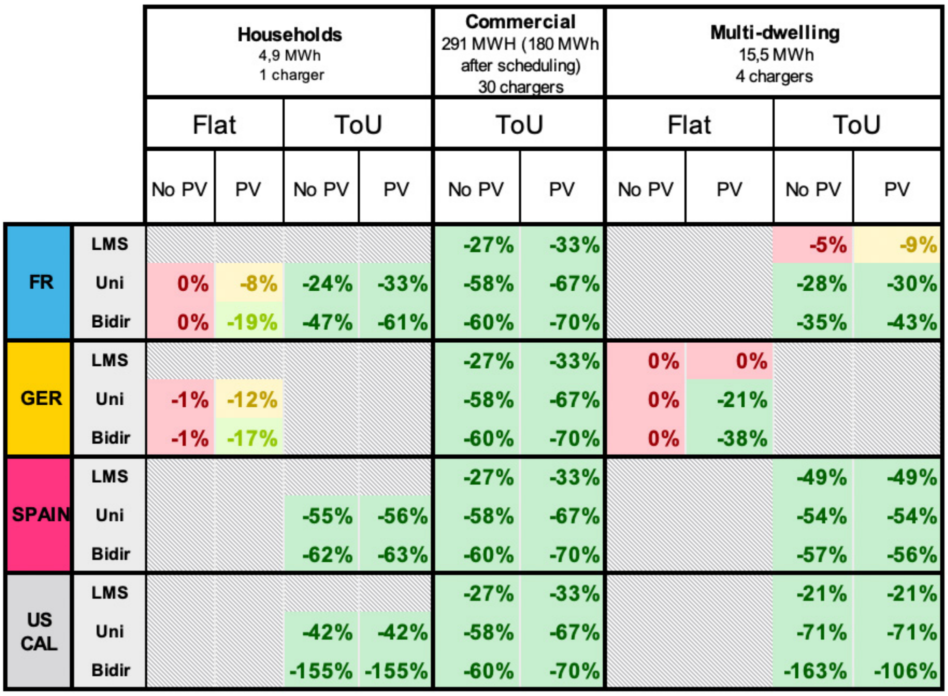
[10] WACC 7%, lifespan 15 years.

[11] Note that for residential bidirectional cases in California, savings go above 100%, meaning that the EV user actually earns some money. This is due to a net-metering policy, in which one's remuneration for injection is higher than the one from the grid. If no control is done, an EV battery can be used to buy energy at a cheap price and resell it at peak price to the grid. Such scheme should soon become obsolete.

Figure 7 provides a complementary perspective with a focus on the electricity bill, without upfront costs (Capex) of charging. This enables a more direct understanding of the impact to the consumer.



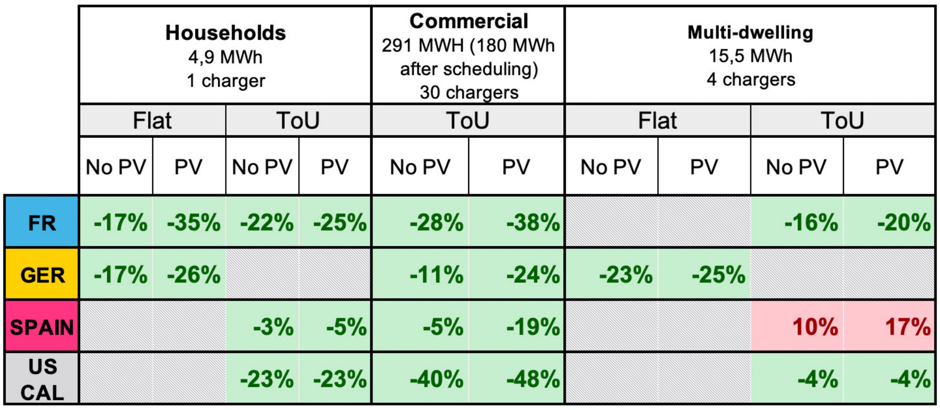
		Households 4,9 MWh 1 charger				**Commercial** 291 MWH (180 MWh after scheduling) 30 chargers		**Multi-dwelling** 15,5 MWh 4 chargers			
		Flat		ToU		ToU		Flat		ToU	
		No PV	PV	No PV	PV	No PV	PV	No PV	PV	No PV	PV
FR	**LMS**					-27%	-33%			-5%	-9%
	Uni	0%	-8%	-24%	-33%	-58%	-67%			-28%	-30%
	Bidir	0%	-19%	-47%	-61%	-60%	-70%			-35%	-43%
GER	**LMS**					-27%	-33%	0%	0%		
	Uni	-1%	-12%			-58%	-67%	0%	-21%		
	Bidir	-1%	-17%			-60%	-70%	0%	-38%		
SPAIN	**LMS**					-27%	-33%			-49%	-49%
	Uni			-55%	-56%	-58%	-67%			-54%	-54%
	Bidir			-62%	-63%	-60%	-70%			-57%	-56%
US CAL	**LMS**					-27%	-33%			-21%	-21%
	Uni			-42%	-42%	-58%	-67%			-71%	-71%
	Bidir			-155%	-155%	-60%	-70%			-163%	-106%

Figure 7: Reductions in Electricity Costs of charging in different Segments, Countries and Cases in 2025 (in % vs. uncontrolled charging in the building)

5 key takeaways can be drawn from the above analysis and are further expanded below:

1. Charging at a building level provides cost benefits compared to public charging across most cases
2. Smart charging adds further value, through strategies that are adapted to each context
3. Distributed generation coupled with smart charging contributes significantly to further savings
4. Smart charging helps save on electrical system costs within buildings
5. Smart charging helps abate carbon emissions

Takeaway #1: Charging at a building level provides cost benefits compared to public charging across most cases



	Households 4,9 MWh 1 charger				**Commercial** 291 MWH (180 MWh after scheduling) 30 chargers		**Multi-dwelling** 15,5 MWh 4 chargers			
	Flat		ToU		ToU		Flat		ToU	
	No PV	PV	No PV	PV	No PV	PV	No PV	PV	No PV	PV
FR	**-17%**	**-35%**	**-22%**	**-25%**	**-28%**	**-38%**			**-16%**	**-20%**
GER	**-17%**	**-26%**			**-11%**	**-24%**	**-23%**	**-25%**		
SPAIN			**-3%**	**-5%**	**-5%**	**-19%**			**10%**	**17%**
US CAL			**-23%**	**-23%**	**-40%**	**-48%**			**-4%**	**-4%**

In the **Total Cost of Charging table**, look at the first top lines of each country to spot the cost gaps. In green all the situations where uncontrolled charging at building is cheaper, in red situations where it is not.

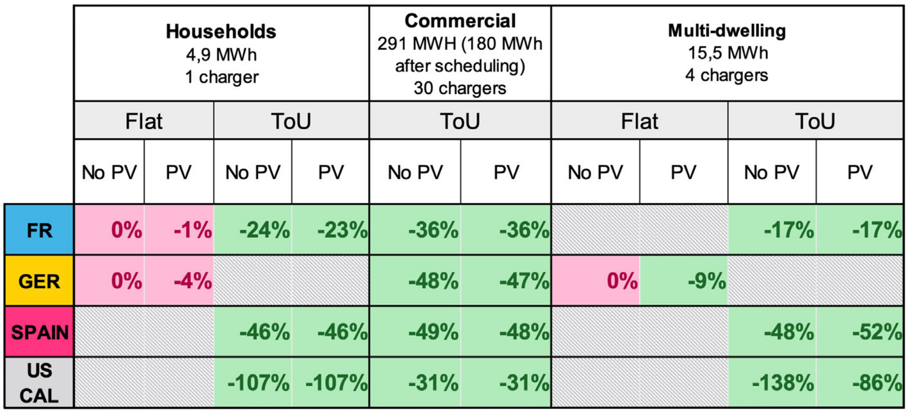
Figure 8: Annualized cost reductions with uncontrolled charging

Uncontrolled charging is in average 18% cheaper within building premises compared to public (Figure 8). In households, it is 20 %. There are five reasons to this:

- Public charger cost is higher than a building one as it must be more robust (weatherproof, vandalism proof).
- Public charging cost also accounts for the cost of parking (in the street).
- Mobility Service Provider margins must be integrated.
- There is possibly (zero-marginal cost) rooftop PV energy available within buildings.
- Part of the necessary electrical infrastructure already exists in buildings.

Takeaway #2: Smart charging adds further value, through strategies that are adapted to each context

#2.1 Time of Use (TOU) tariffs are a key incentive to smart charging



	Households 4,9 MWh 1 charger				**Commercial** 291 MWH (180 MWh after scheduling) 30 chargers		**Multi-dwelling** 15,5 MWh 4 chargers			
	Flat		ToU		ToU		Flat		ToU	
	No PV	PV	No PV	PV	No PV	PV	No PV	PV	No PV	PV
FR	**0%**	**-1%**	**-24%**	**-23%**	**-36%**	**-36%**			**-17%**	**-17%**
GER	**0%**	**-4%**			**-48%**	**-47%**	**0%**	**-9%**		
SPAIN			**-46%**	**-46%**	**-49%**	**-48%**			**-48%**	**-52%**
US CAL			**-107%**	**-107%**	**-31%**	**-31%**			**-138%**	**-86%**

Additional Total Cost of Charging reduction through smart charging vs uncontrolled charging. These savings add to savings from charging at building vs public charging. For instance, in the Californian C&I case, uncontrolled charging saves 40% of costs compared to public charging, and smart charging brings a further 31 %. In total, costs can be reduced by 71% in green all the situations where smart charging is cheaper than uncontrolled charging, in red situations where it is not (or barely).

Figure 9: Annualized cost reductions with smart charging

Figure 9 shows that for almost all configurations, the most efficient smart charging system brings additional value compared to uncontrolled charging. This mostly depends on the existence of Time-of-Use (ToU) tariffs. For instance, in the Californian C&I case, uncontrolled charging saves 40% of costs compared to public charging, and smart unidirectional charging brings a further 31 %. In total, costs can be reduced by 71%

In the future, EVs will also represent a larger share of a building's total electricity bill. This is due to the growing penetration of charging infrastructure as well as more efficient use of other loads within buildings. Smart charging will then become even more relevant. Figure 10 compares a low efficient building with 15 chargers (typical use case today) with a highly efficient building equipped with 30 chargers (typical future case). While EV represents already a sizeable share of the electricity bill in the first case, this share will increase significantly with further penetration. Smart charging helps strongly mitigate this pattern.

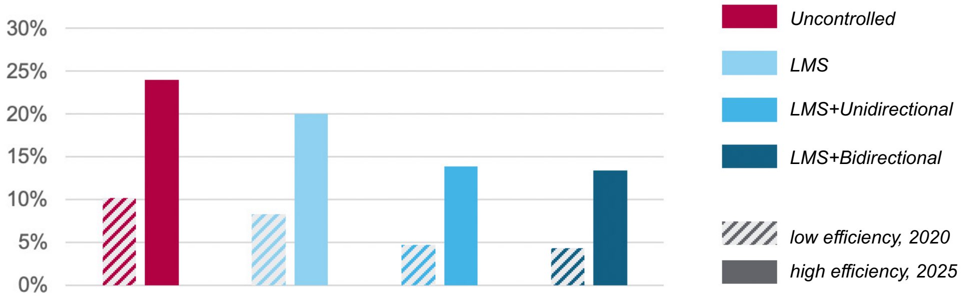
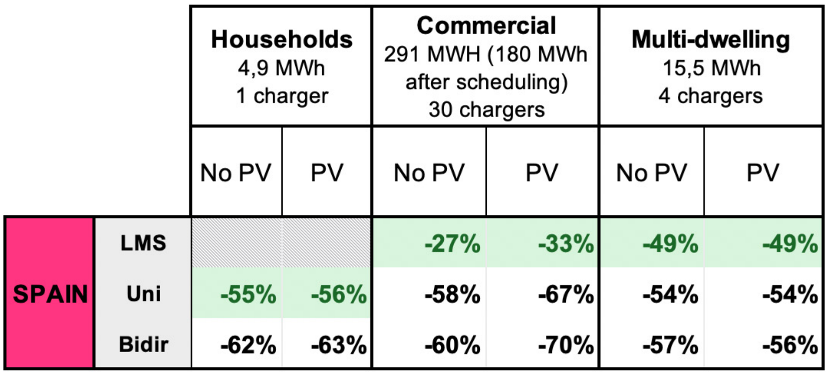


Figure 10: Share of EV charging in the building's total electricity costs in the 2020s and in the 2025s in C&I Buildings

#2.2 Demand charges are also a key driver of smart charging adoption



		Households 4,9 MWh 1 charger		**Commercial** 291 MWH (180 MWh after scheduling) 30 chargers		**Multi-dwelling** 15,5 MWh 4 chargers	
		No PV	PV	No PV	PV	No PV	PV
SPAIN	**LMS**	▨	▨	**-27%**	**-33%**	**-49%**	**-49%**
	Uni	**-55%**	**-56%**	**-58%**	**-67%**	**-54%**	**-54%**
	Bidir	**-62%**	**-63%**	**-60%**	**-70%**	**-57%**	**-56%**

In the **Electricity Cost Table**: in all segments in Spain, Power is heavily priced. Gaps between uncontrolled charging and LMS (or Unidirectional in Households) are substantial (from 27% to 49%).

Figure 11: Impact of power optimization on the electricity bill

The implementation of Load Management Systems in commercial building is a great option to mitigate demand charges from high EV penetration within buildings (Figure 11). Unidirectional smart charging coupled to Power ToU tariffs[12] (in commercial buildings and in Spain for instance) further reduces costs.

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[12] Different demand charge levels (€/kW) for different times of the day

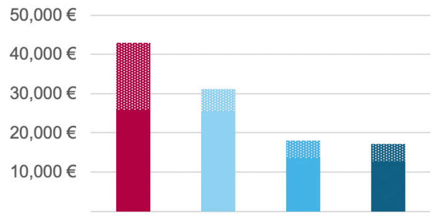

Figure 12: Annual Electricity costs decomposition in Commercial Buildings in Spain (2025 w/o PV)

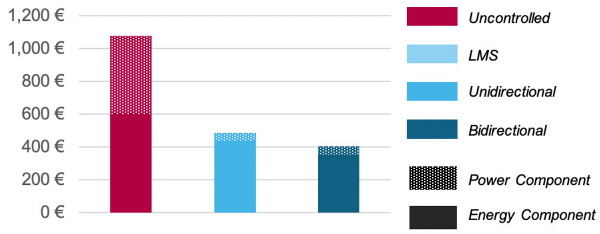

Figure 13: Annual Electricity costs decomposition in Households in Spain (2025 w/o PV)

A key takeaway however is the balance between Energy ToU tariffs and demand charge optimization strategies. In the commercial buildings segment (Figure 12, Spain example), the cost associated with the power component is reduced almost threefold when having a LMS and even 20% further with unidirectional charging. Even greater benefits on the power component can be observed in households (Figure 13, Spain).

#2.3 Balance between ToU and demand charge strategies

However, putting a high price on Power limits the benefits of other optimization levers such as Energy ToU tariffs. Indeed, by greatly limiting the power input of the charger, charging times are spread, and less room is available for choosing at what time charging is optimal.

In fact, the right arbitrage between power limitation and energy ToU will depend on the grid configuration in each geography and each segment. By fixing adequate price signals, system operators can implicitly fine-tune charging optimization strategies to their flexibility needs.

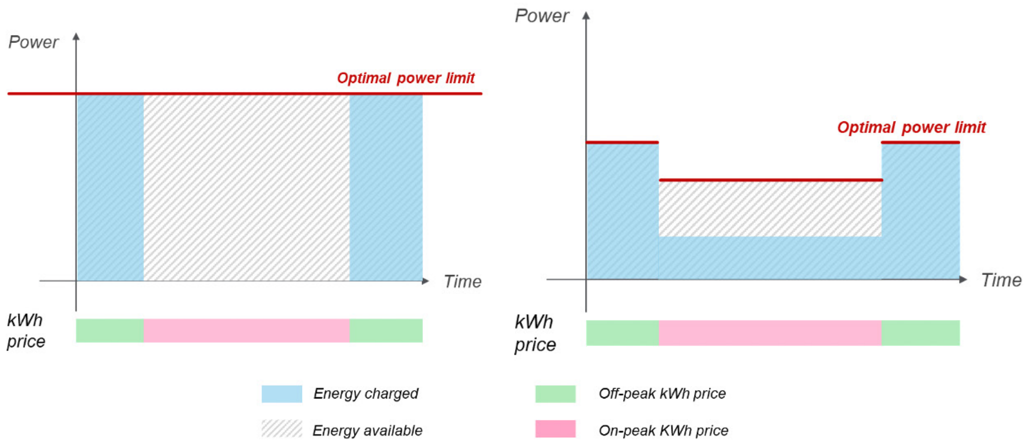

Figure 14 shows this type of theoretical arbitrage. The blue area corresponds to charging demand. On the right side, demand charges (limiting power demand) drive charging during times of peak electricity prices, a strategy which enables lower power demand, but higher charging expenses.

Takeaway #3: Distributed generation coupled with smart charging contributes significantly to further savings

PV self-consumption provides additional benefits across all use cases, albeit at different levels[13] (Figure 15).

		Households 4,9 MWh 1 charger		**Commercial** 291 MWH (180 MWh after scheduling) 30 chargers	
		NoPV	PV	NoPV	PV
FR	**LMS**	▨	▨	**-27%**	**-33%**
	Uni	**0%**	**-8%**	**-58%**	**-67%**
	Bidir	**0%**	**-19%**	**-60%**	**-70%**

In the **Electricity Cost Table**: For the C&I and Households segments, comparing costs between the cases with or without PV.

Figure 15: C&I and Household segments electricity costs

For both C&I buildings and Households, self-consumption optimization can bring further reduction in electricity cost (from 8 to 70% in the case for France).

Takeaway #4: Smart charging helps save on electrical installation costs within buildings

In addition to electricity bill savings, reducing power needs thru smart charging can avoid electrical system costs inside the building.

Our model shows that for commercial buildings a LMS could reduce peak demand for charging by up to 30% without altering the charging success rate. To find this result, the power limit fixed in the LMS was gradually lowered until this limit was too low to charge EVs on time[14]. This translates into optimization of the electrical installation. Yet, an exact quantification of Capex optimization remains complex, due to inherent differences across different building types and load profiles.

- the electrical connection (breakers, cables, switches) of the charging system to the building can be downsized. This part is well documented. Schneider Electric research suggests that around 100 €/charger can be saved thanks to demand charge optimization[14] .
- Yet, most of the opportunity resides in the optimization of the overall capacity of the electrical system (designed for peak demand), i.e. transformers and power switchboards. The Load Management System helps prevent such expensive upgrades.

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[13] We consider in this analysis that PV electricity is at zero-marginal cost (see Chap. 1.4).

[14] This 30% result assumes no tolerance for charging failure. It could be possible to compute a power limit allowing for some charging sessions to be uncomplete. The more charging is tolerated to remain incomplete, the more the peak reduction.

[14] See Appendix 2

Box: Showcasing the key role of Load Management Systems at Schneider Electric Paris HQ

At Schneider Electric Paris HQ, 50 EV charging stations were installed, covering 7,5% of parking lots in the building. With a total installed capacity of 1,100 kW with charger maximum power ranging from 3,5 to 55kW, power demand could have overloaded the building's electrical system easily. Thanks to the deployment of 5 Load Management Systems, the maximum charging load has been optimized, to the extent no additional investment on the electrical system was required.

Takeaway #5: Smart charging helps abate carbon emissions

Electricity wholesale prices are generally positively correlated with carbon intensity[15], and utility retailers tend to mimic these in their retail tariffs. Hence, smart charging – by the nature of its optimization – helps lower the carbon intensity of charging (tapping into low-carbon available electricity demand, which is the most affordable) [6].

This is all the more true when distributed generation (by nature zero carbon) is present and integrated in the overall smart charging optimization strategy. Figure 16 shows the carbon intensity of EV charging for the Spanish Household cases.

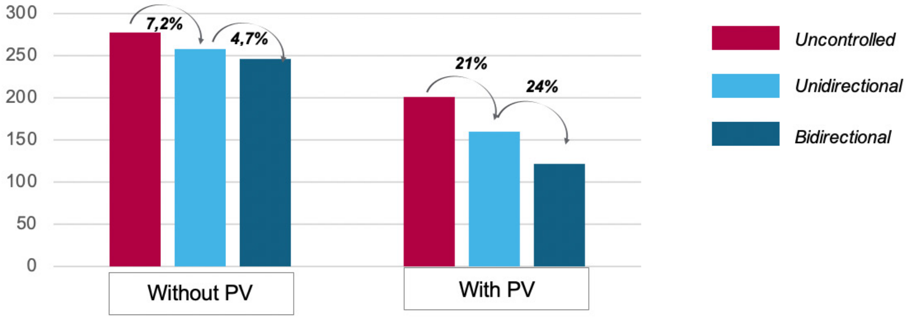

Figure 16: Carbon content (gCO2/kWh) of electricity in Households cases in Spain

Conclusion

Smart charging enables significant optimization of Total Cost of Charging and ultimately electricity bills for adopters. This is because smart charging algorithms tap in the 4 levers of optimization available (scheduling, power, energy, self-consumption).

The availability of each of these 4 levers however varies greatly across use cases (building type, regions, etc.). Figure 17 provides a qualitative assessment of which driver is most relevant within each use case[16].

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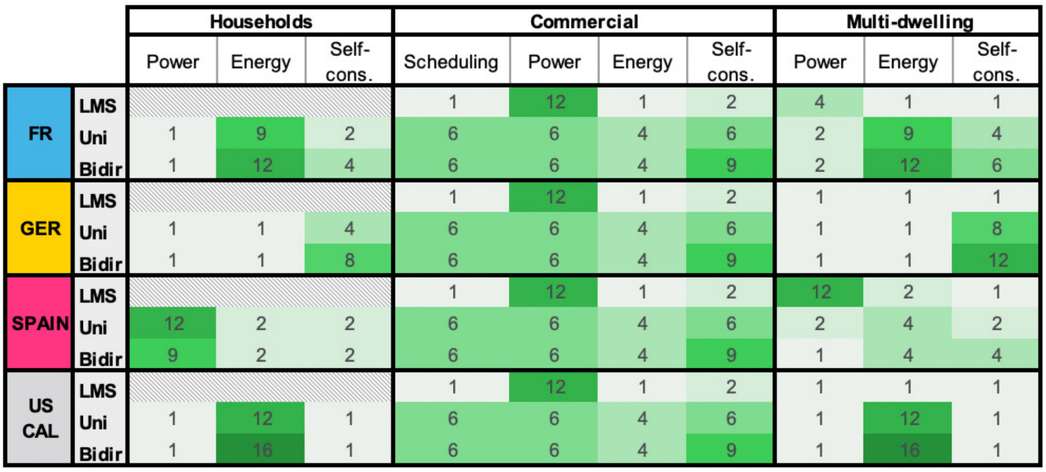
[15] This is especially true in a system with a merit order ranking energy sources taking pollution into account

[16] For a given optimization lever, the grade level (from 1 to 16) integrates both the amplitude of savings it generates alone, and the relative share of savings it provides with respect to other levers into consideration.



		Households			Commercial				Multi-dwelling		
		Power	Energy	Self-cons.	Scheduling	Power	Energy	Self-cons.	Power	Energy	Self-cons.
FR	**LMS**				1	12	1	2	4	1	1
	Uni	1	9	2	6	6	4	6	2	9	4
	Bidir	1	12	4	6	6	4	9	2	12	6
GER	**LMS**				1	12	1	2	1	1	1
	Uni	1	1	4	6	6	4	6	1	1	8
	Bidir	1	1	8	6	6	4	9	1	1	12
SPAIN	**LMS**				1	12	1	2	12	2	1
	Uni	12	2	2	6	6	4	6	2	4	2
	Bidir	9	2	2	6	6	4	9	1	4	4
US CAL	**LMS**				1	12	1	2	1	1	1
	Uni	1	12	1	6	6	4	6	1	12	1
	Bidir	1	16	1	6	6	4	9	1	16	1

Figure 17: Criticality of optimization levers depending on the country and segment (arbitrary scale)

We can draw critical insights from this analysis on the impact of regulations on different building types in different geographies, and the weight of each lever on smart charging optimization.

- In the residential market (households and multi-dwelling), favored smart charging strategies vary significantly across regions with 3 main regional groups
    - — France and California favor energy optimization approaches (ToU).
    - — Spain optimization strategies are heavily influenced by demand charge tariffs.
    - — Germany is more reliant on self-consumption potential.
- In the commercial sector however, scheduling and demand charges both contribute significantly, while self-consumption plays also a non-negligible role. Energy optimization is however of much less importance. This is due to the specific load demand, with EV charging happening at time of maximum operational load of the building.

While smart charging strategies in the commercial sector clearly revolve around overall demand management, due to specific load profiles and EV charging patterns, the case for residential is more dependent on opportunities stemming from regulations in place and therefore varies significantly across regions.

Chapter 3: Smart charging contributes to optimize necessary grid infrastructure upgrades, a key enabler to rapid adoption

In chapter 2, we demonstrated significant benefits accessible from smart charging at end-user level. Beyond these, smart charging in buildings is also helping reduce stress on grid infrastructure.

We can draw 2 key takeaways from our analysis:

- Smart charging focused on end user benefits also infrastructure costs, hence facilitates EV uptake.
- Grid-side optimization has a clear value today, which will increase with further EV penetration.

Takeaway #6: Smart charging focused on the end user helps reduce transmission and distribution grid costs, hence facilitate EV uptake

As seen earlier, Load Management Systems help reduce the peak power needed for charging EVs by up to 30%, with positive impacts on the electrical system within buildings. This also translates into optimization at the grid level.

Yet, expensive and lengthy infrastructure upgrades may ultimately become a clear bottleneck to EV adoption. As a consequence, more and more regulators, utilities and DSOs opt for retail tariffs in which power subscription represents a larger part of the bill. [7] Time-of-Use demand charge is another opportunity for smart charging. Such non-wire alternative is clear (and complementary) alternative to increased infrastructure investments with higher returns on investment.

The research literature remains scarce today on the exact potential, due to inherent disparities across geographies and local situations.

- The French DSO ENEDIS estimated that avoided infrastructure costs from smart charging would translate into infrastructure savings worth 10 to 100 euros per year and per EV. [8]
- The INVADE project (Netherlands) concluded that EV smart charging could eliminate virtually any need for infrastructure investment in several geographies. [9]

Takeaway #7: Grid-side optimization has a clear value today, which will increase with further EV penetration

Aside from implicit value generated by charging optimization, smart charging can also provide explicit services to the grid by acting as backup storage system. These services include ancillary services, capacity mechanisms, wholesale market optimization, as well as local power backup, power quality management and congestion avoidance[17].

Figure 18 provides a detailed account of several ongoing experimentations in Europe, alongside existing prospective studies. In average, grid services are found to generate annually between a few tens to several hundred of euros of potential additional benefits to end-users.

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[17] See Appendix 6 for detailed definitions of grid services

Project	Country	Year	Segment	Grid services explored	Value estimation	Comment
Transmission and energy markets level grid services						
Parker Project [10]	Netherlands	2019	Commercial Buildings	Ancillary services (primary and secondary reserve frequency regulation)	~500€/ EV/year remuneration for customer	Value estimation made by testing a remuneration model on a concrete case. High variability of results.
Jedlix-Renault ZOE [11]	Netherlands	2017	Households & Public charging	Wholesale market arbitrage	60-180 €/ EV/year remuneration	
HAVEN [12]	UK	2019	Households	Balancing and Frequency regulation	80-140 €/EV/ year remuneration	Paper in which grid services are quantified on top of V2B.
OVO Energy-Sciurus [13]	UK	2020	Households	Ancillary services	205 €/EV/year remuneration	Paper in which grid services are quantified on top of V2B. High levels of uncertainty. Overestimation of value due to COVID 19.
				Dynamic Containment	448 €/EV/year remuneration	
Octopus Energy [14]	UK	2021	Households	Wholesale market (other services unclear)	350 €/EV/year savings or remuneration	V1G
RTE [3]	France	2019	Households	Unclear	250 €/EV/year remuneration	RTE mentions this value is a high estimation based on the hypothesis that grid service markets are not saturated
Distribution level grid services						
ENEDIS [8]	France	2020	All segments	Backup local supply in case of incident or maintenance works	35- 200 €/ charger/ incident	All the numbers reported correspond to a global value across all the value chain of charging, except for congestion avoidance. Only a fraction of this value s accessible to the charger user through remuneration.
				Congestion avoidance	50-70 €/ charger/year for 10 years	
				Local Renewables surplus absorption	5 €/charger/ year	
Both Distribution and Transmission level grid services						
Fully Costed System [15]	UK	2021	Commercial Buildings/ Depot	Capacity adequacy	65€/EV/year	EV is part of a logistics fleet. Numbers reported correspond to a global value across all the value chain of charging.
				Wholesale market	32€/EV/year	
				Distribution grid services	490€/EV/year	

Figure 18: Value estimation of grid services in various studies

Each specific experimentation above however focuses on the valuation of one or a part of the whole accessible set of grid services only. Stacking of these services will depend on the regulatory landscape. In the case of V-to-B-to-G, it is unclear what share of grid services and local services can be stacked, but it is important to note that there will be no less opportunities for grid services than in the V-to-G case.

Box: Bidirectional charging and Battery State of Health

Bidirectional smart charging is often considered to have a negative impact on the lifetime of batteries, as it increases the number of cycles of use. While clear from a pure physical standpoint, battery degradation models can also be included in smart charging optimization strategies [16]. Such integration could in fact have a positive impact on battery lifetime. It is well known that Lithium-ion batteries perform better at a state of charge of around 50%. Smart charging could thus contribute to battery lifetime by preventing extreme state of charge. [17].

While this study was focused on residential and commercial buildings, it is worth mentioning the case of large vehicle fleet depots here. In this case, energy demand will mostly be driven by EV charging, and so will costs. These depots offer a significant opportunity as well for grid services

- EVs are having well-defined schedules (especially buses) allowing to sell adequacy services.
- Their storage/backup capacity is substantially larger than other building types thus easier to monetize.
- Multi-site aggregation is possible, enabling Virtual Power Plant schemes to emerge.

The key takeaway is that, despite scarce existing literature and obvious differences across regions and building types, smart charging at building level can be further expanded to cope with new grid services while providing relief on existing infrastructure. Although more research is required, which goes beyond the scope of this report, we find that the conclusion remains robust, provided the right incentives, signals, and rules of engagement are put in place, in addition to tariff schemes discussed in chapter 2.

Chapter 4: Embrace modern issues with modern policy solutions

EV policy and charging infrastructure policies have taken center stage in the EU and US legislative agendas recently. The above research provides key insights to the debates at hand.

The key goal is to enable rapid deployment of EV charging infrastructure to enable EV adoption, at the lowest possible expense for the consumer, while mitigating very large grid infrastructure upgrades, traditionally longer to materialize.

The above research concludes with no ambiguity that smart charging at building level offers significant opportunity for rapid adoption (without discarding the others). This should therefore be a key priority for policymakers.

Smart charging enables to optimize charging costs for consumers, while reducing stress on grids, thus expensive and lengthy infrastructure upgrades: a modern solution to crack a modern issue.

Foster EV charging deployment in households and buildings, and make it smart right from the start

As a complement to ambitious public charging programs, the potential of private deployment should be bolstered thru clear mandates, both for new buildings (thru codes) and existing ones (regulations and mandates). California, which currently prepares provisions to its Energy code for EV charging [18] [19], and the European Union, which is in the process of re-designing the European Building Performance Directive (EPBD) [20] [21], are promising examples.

Such policies should notably address:

- Deployment targets (eg number of charging points and timeline).
- Evolutive penetration rate of charging points at building level (to ensure deployment of future-proof electrical charging infrastructure).
- Power capacity requirements (to ensure deployment of future-proof electrical distribution systems).
- EV charger functionalities, from plug-type and metering functionalities to integration capabilities
- Charging connectivity, cybersecurity, and interoperability standards enabling secure local supervision from local Load and Energy management systems.

Beyond regulations, it is worth mentioning other certifications/labels such as the EU “Smart Readiness Indicator” [22] or the “Ready 2 Service 4 Mobility” [23] which can support the uptake of electromobility services offered by buildings through performance levels associated with key capabilities to make EV future-proof buildings: pre-equipment and sizing, charging functionalities, interoperability and scalability, quality and compliance standards and metrics.

Prioritize smart charging to avoid large grid investments and unleash end user benefits through deployment of dynamic tariffs and self-consumption favorable policies

As seen before, smart charging delivers maximum value with well-designed dynamic retail tariffs and when distributed generation is available. Therefore, they should be promoted together. It would also be valuable to set deployment targets which combine total installed smart charging power capacity with distributed generation available.

For commercial buildings or multi-dwellings, the installation of a load management system should be compulsory. Bringing value to both the end user and the grid, the installation of such systems could condition access to subsidies.

Retail tariff schemes should continue to evolve to better reflect real-cost dynamics and incentivize smarter demand controls.

- Time of Use (ToU) tariffs provide significant incentives to end users (and EV owners) to optimize demand.
- Demand charges or variable power prices help integrate infrastructure constraints into real-time power capacity optimization.
- Grid services could be further integrated into advanced retail schemes, as penetration of EVs increases.

Standards for smart charging solutions should include the ability to interact with local distributed generation. They must be able to receive/send information in real-time, communicate with Energy management systems, and be remotely monitored and controlled. As far as unidirectional charging is concerned, electrical and installation standards are usually well defined already. Data interoperability requires more attention in the current policy making context.

Finally, it is key to ensure interoperability of protocols and data between these actors, as well as fostering open, secured, and scalable systems.

In the EU, the (AFID) Alternative Fuel Directive, aiming at tackling these challenges, shall be considered as a promising practice. [24]

Prepare for bidirectional charging and seize opportunities for grid services

Going a step further, additional value will be captured with bi-directional charging (V2B2G). However, many vital communication and electrical standards are still missing today to support the deployment at scale of such services, a clear focus point for the industry.

Key points of attention should notably cover:

- Equipment and installation rules required for bi-directional charging deployment
- Data interoperability

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Annex

Annex 1: Stakeholders of the smart charging value chain

Stakeholders getting value from smart charging as a service:

- **The Charger User:** Entity paying for the charging of the EVs
- **The Distributed System Operator (DSO),** responsible for the planning, operation, maintenance, and development of the distribution network (low and medium voltage). This actor, last in the chain before the final consumer, is also responsible for the quality of the electricity delivered, the stability of the distribution network and metering.
- **The Transmission System Operator (TSO),** responsible for the planning, operation, maintenance and development of the electric transmission system and its interconnections. It is responsible for the stability of the system and the connection of customers and DSOs to the transmission network.
- **The Balance Responsible Parties (BRP) in most European countries,** financially responsible for maintaining the balance between supply and demand of energy within their portfolio. All connections have a corresponding BRP. Together all BRPs represent all connections within a scheduling area).

Beyond stakeholders getting value from smart charging (a given service), other actors are enabling smart charging (from the EV to the grid).

- **The EV driver** (charger owner or not) can provide information about the desired charge of the vehicle (eg departure time, required minimum state of charge). For example: employee charging their company car at the office
- **The Charge Point Operator (CPO)** operates and is responsible for the Operations & Maintenance of the charging infrastructure. It also manages the purchasing of electricity in accordance to energy demand at the charging stations.
- **An Energy Service Company ESCO** in buildings offers energy services which may include implementing energy-efficiency projects (along with renewable energy projects), in many cases on a turn-key basis.
- **The aggregator/flexibility operator** aggregates near real-time consumption data (shaving, injection, extraction modulation capacities, etc.), predicts the available capacity in future, schedules and activates prosumer consumption adjustment, connects available energy capacity with energy trading platforms or receives energy from DSO/TSO network management system.
- **The Energy Retailer** supplies at least one final consumer with electricity either from energy that it has produced or from energy that it has purchased.

Other Stakeholders are involved but of less direct impact:

- **Real-estate owner** (Building / Home / Multi-dwelling / Commercial Buildings)
- **EMSP:** mobility service provider for EV users including charging access services.
- **Car and charger manufacturers**
- **Charger installers**
- **Energy market players** like energy traders

Annex 2: Details on the modelling methodology for customer bill savings

As explained in the core of the paper, three blocks of parameters constitute a use case: basic environment parameters, configuration of the building energy system, and configuration of the charging system. These three building blocks are not independent from each other. For instance, given a country and a segment, only a limited number of retail tariff options are available, and optimization levers further depend on the retail tariff choice (Figure 3).

We provide here some detail on the range of parameters controlled for each use case identified.

Block 1: Context & general Assumptions

Analysis is focused on **3 building types** where EV users do most of their everyday charging:

- Individual **Households,** representing an important share of all housing in mature countries.
- **Multi-dwelling residential,** with underground or ground level private parking spaces.
- **Commercial Buildings,** with a specific focus on large office buildings. The case of retail buildings would be similar but offers less opportunities for charging optimization given that EVs do not stay parked as long as in office buildings.

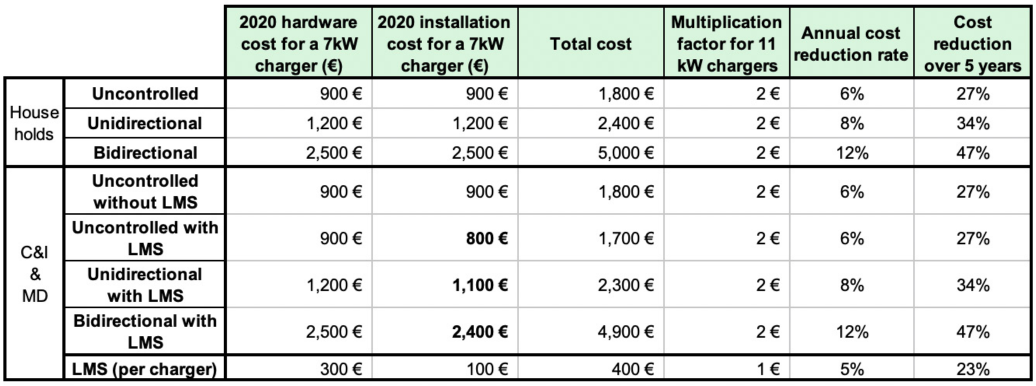
The four different geographies we selected enable us to clarify local rules and specificities and how they impact the value of smart charging:

- In France, EVs are rapidly gaining market shares but the electric system is robust and transforming slowly.
- Germany is currently more ambitious in the integration of distributed energy resources.
- In Spain, advanced electricity tariffs were recently implemented.
- In California state, both customer-sited PV and EVs are growing rapidly, creating new opportunities and challenges on the existing power system.

EV Charger CAPEX

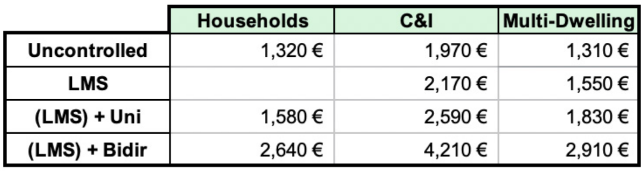
Setting upfront (Capex) costs of EV chargers is not trivial. If hardware costs are well referenced, installation costs vary significantly across building types and geographies. Moreover, smart chargers and especially bidirectional smart chargers are still at an early stage of roll-out, which makes their actual price irrelevant and their price evolution uncertain.

To determine prices, we conducted a benchmark of 2021 hardware and installation costs, then took some assumptions on cost reductions over the next 5 years (Figure 19 and Figure 20), and using this as our benchmark. This is because of rapid declines in costs of charging solutions which need to be factored in.



		2020 hardware cost for a 7kW charger (€)	2020 installation cost for a 7kW charger (€)	Total cost	Multiplication factor for 11 kW chargers	Annual cost reduction rate	Cost reduction over 5 years
House holds	**Uncontrolled**	900 €	900 €	1,800 €	2 €	6%	27%
	Unidirectional	1,200 €	1,200 €	2,400 €	2 €	8%	34%
	Bidirectional	2,500 €	2,500 €	5,000 €	2 €	12%	47%
C&I & MD	**Uncontrolled without LMS**	900 €	900 €	1,800 €	2 €	6%	27%
	Uncontrolled with LMS	900 €	**800 €**	1,700 €	2 €	6%	27%
	Unidirectional with LMS	1,200 €	**1,100 €**	2,300 €	2 €	8%	34%
	Bidirectional with LMS	2,500 €	**2,400 €**	4,900 €	2 €	12%	47%
	LMS (per charger)	300 €	100 €	400 €	1 €	5%	23%

Figure 19: Price hypothesis for EV chargers depending on the charging smartness level



	Households	C&I	Multi-Dwelling
Uncontrolled	1,320 €	1,970 €	1,310 €
LMS		2,170 €	1,550 €
(LMS) + Uni	1,580 €	2,590 €	1,830 €
(LMS) + Bidir	2,640 €	4,210 €	2,910 €

Figure 20: Final charging system cost (per charger) in 2025

For commercial buildings and multi-dwelling segments, an additional LMS (Load Management System) controller is purchased and installed in the 'LMS', 'Unidirectional', and 'Bidirectional' charger system configurations.

Public charging prices

Public charging prices are highly variable. Each Electromobility Service Provider has the right to set its own price depending on the service provided and these prices can have different structures (fixed initial cost + marginal cost depending on consumption and or time of charge, monthly or yearly fixed price subscription, etc.). This proliferation of actors and price schemes makes it very difficult to establish a mean charging cost country by country. To our knowledge, no publicly available study can provide such benchmark. We have used the following prices based on extensive literature review (Figure 21).

Country	Typical charging price	Data sources
France	27 €cts/kWh	Izivia, Automobile Propre, AUBE
Germany	40 €cts/kWh	Lichtblick (benchmark)
Spain	25 €cts/kWh	Motorpasion, Xataka, Movilidadelectrica, El Periodico de la Energia
USA	37 €cts/kWh	My EV, Green Car Journal, Drive Clean, Electrify America

Figure 21: Costs of charging at a public charging station in the four countries under study, based on various commercial information

This initial approach has been further confirmed by an economic analysis from BloombergNEF evaluating the cost surplus billed to end users for a public charging company to reach profitability. [14]

Block 2: Site/Energy configuration

From block 1 assumptions, key parameters of site configuration can then be retrieved:

- Retail electricity tariffs depend on the retailer offers in each geography and for each segment. For the commercial buildings segment, despite tariff schemes are often bespoke, we apply a similar scheme to every geography which is then adjusted to reflect local electricity tariffs.
- Building size and electric loads are defined as a standard for each use case across geographies.
- For multi-dwelling residential, the charging system is either separate or connected to the common area load.
- The number of chargers in each segment is derived from EV market share forecasts and behaviors. Their rated power is 7kW in households and multi-dwellings, 11kW in commercial buildings.
- When they exist, Distributed Energy Resources (PV, Battery Energy Storage System) are sized following optimization prior to any charger installation.
- EV presence patterns are designed to reflect driver's behaviors in each segment. Average mileage (and need for charging) are also input in the model.

Each of these parameters is chosen in coherence with the segment, the country and in some cases the year.

EV availability patterns

EV availability patterns can have a great influence on modelling results. These patterns are based on a multitude of assumptions on mileage, driver behavior, etc. However, scientific research on the subject exists. It is often based on localized data sets (Australia [25], Germany [26]) which makes them hard to use in a global study like this one. Nevertheless, they were a source of inspiration to create the patterns we use in this model. We have considered patterns to be identical across all countries and taken into account the variability of arrival and departure hours, as well as states of charge. More information can be found in Annex 3

Distributed Energy Resources (DER) CAPEX

In all of the use cases, PV and Battery Energy Storage Systems installations are considered existing prior to the installation of any EV charger, and thus do not impact on the economic results of the case. Some more extensive studies on DER sizing show that for new builds, smart charging strategy will have an influence on the optimal size of DERs to install. In general, the installations can be downsized compared to an uncontrolled charging case, leading to further cost reductions [27].

Building types detailed assumptions

Households:

In this segment, we study charging patterns in a 4 person, slightly above average size household.

Parameter	Dependance on location	Dependance on Electric system	Date Dependent	Remarks
House loads	Yes	No	No	Representative of a ‘typical house’ for each country (electrified heating in France, low electrification of heat in Germany, intensive use of AC in Spain and US Cal).
Retail tariffs	Yes	Yes (Prosumer specific tariffs possible in some countries)	No	Well-documented for individuals, with published and sometimes regulated tariffs. The bill structure varies widely between countries, a fact that has been considered. For instance, Germany is the only country where on-peak/off-peak rates are not available, and the Spanish tariff is more power-oriented (power subscription is dynamically priced and accounts for a large part of the bill).
Charging infrastructure	No	No	No	Remains consistent across countries and consists in an AC 7kW type 2 chargers.
Charging infrastructure	Yes (case study in Germany)	No	No	Also remains consistent across countries. It has been developed to mimic random behaviors respecting trends of departure and arrival times (work commuting during the week, etc.). For the EV pattern we made the strong assumption that the car is used intensively. This corresponds to the maximum of constraints on charging, so that the results obtained show the value of smart charging even in an unfavorable case. The car is set to travel between 1,800 and 2,000 kilometers per month - the average use of a car for heavy EV drivers in Europe according to Delta EE [28].
EV pattern	Yes	Yes	No	Defined by optimizing the financial return of the installation prior to the installation of the EV charger. This leads to similar capacities across France, Spain and Germany, even though the Capex and energy outputs are different.

Commercial Buildings:

The focus is on a large energy efficient office building where 30 chargers are needed.

Parameter	Dependance on location	Dependance on Electric system	Date Dependent	Remarks
Building loads	Yes	No	No	One building having both a low energy efficiency and a low EV penetration rate (15chargers) and one being energy efficient with a high EV penetration (30 chargers).
Retail tariffs	Not the structure, but the average price	Yes (Prosumer specific tariffs possible in some countries)	No	Retail tariffs are generally not well documented for important loads. However, they tend to look more similar between countries than they would in household cases. Almost all of them have a power component, a consumption component, and use time-varying prices. For this reason, a single tariff structure is applied to all countries, with prices then normalized to depict the average electricity price of a country.
Charging infrastructure	No	No	No	Remains consistent across countries and consists in an AC 7kW type 2 charger.
EV pattern	No	No	No	The EV presence pattern is also the same across countries. It has been developed to mimic random behaviors respecting trends of departure and arrival times (work commuting during the week for instance). Unlike in the household case, no assumption on EV use must be made. Chargers are simply used at a certain rate, with maximum use (all chargers have an EV plugged to them) during the week between 8 a.m. and 6 p.m. apart from Monday mornings and Friday afternoons.
PV and BESS sizing	No	Yes	No	PV sizing is not anymore constrained by optimizing financial returns. Rather, we estimate that for large surfaces, the Capex drops enough for the financial optimum to be reached with the maximum capacity possible. In that case, what limits PV power is the surface availability.

Multi-dwelling:

We focus here on a 5-storey residential building. In this segment, the electrical infrastructure behind the EV charger installation is of the utmost importance due to overall power capacity requirements and has a strong influence on smart charging strategies.

Parameter	Dependance on location	Dependance on Electric system	Date Dependent	Remarks
Building loads	No	Yes	No	We look at 3 options: • The building electrical system is too weak, the charging system is directly connected to the public grid. EV chargers do not have access to any information on the building energy needs. • The EV chargers power demand can be optimized alongside that of common areas in the building • A PV system is installed on the roof of the building. In that case, the only possibility for self-consumption is generally to connect the PV to the common areas[19] .
Retail tariffs	Yes	No	No	Retail Tariffs for the cars as well as for the common areas are the same as the ones used in the household case.
Charging infrastructure	No	No	No	The charging infrastructure is the same across locations and consists in AC 7kW chargers. The number of chargers is based on EV penetration and the equipment ratio assuming that each resident owns its charger.
EV pattern	No	No	No	The EV presence pattern is also the same across countries. It is like the one used in the household case, but this time with an average use of EVs, since assuming heavy driving patterns for all residents is unrealistic. EVs are set to travel about 1,500 or 1,600 km per month.
PV and BESS sizing	No	Yes	No	PV sizing is done using the same method as in the commercial buildings segment.

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[19] Connecting PV to each individual household is technically complex

Annex 3: EV use case modelling

This annex describes the different modelling tools and algorithms used as part of the study.

Method for cost quantification

The method for determining the cost of EV charging in each use case studied is the following:

1	Determine the energy balance at any time of the year of the building, depending on its configuration prior to any EV charger installation[20]. Calculate the total cost of electricity for this site.
2	From this preliminary energy balance time series, coupled with tariff information, EV presence patterns, and charging parameters, determine charging pattern of the installation.
3	Recalculate the energy balance of the site considering the EV charging load. Recalculate the updated electricity costs of the site.
4	The electricity cost difference between step 1 and step 3 corresponds to the electricity costs of charging for this use case. Add to this cost the annualized Capex of the charging system to compute the total annualized cost of charging (TCC).

EV presence pattern generation

Our model generates the time series defining the presence or absence of EV at a charger all year long, the initial state of charge (SOC) of the EV every time it connects to the charger point, and a final SOC setpoint depending on the charger and the user's choices. EV presence patterns will depend on the segment studied.

To account for the variability of behaviors within a use case, typical days are designed, depending on the day of the week and week of the year. Then, for each of these days, associated EV presence at site is created. EV presence is randomized using normal laws and varying standard deviations.

Design for Residential cases

In household and multi-dwelling segments, the charger and the EV are completely identified and are almost exclusively used together. A specific charger is only used to charge a single car, and this car will almost always get charged at this charger.

Two types of weeks exist, working week and holiday week. In the holiday week the car stays plugged in all day long. Randomness of day types within a working week is generated with a uniform law. For instance, each working day has a 1 in 5 chance to be a 'home' type and a 4 in 5 chance to be an 'office' type.

In the multi-dwellings segment, involving multiple chargers operating in parallel, the whole EV pattern is only a superposition of several single EV patterns.

Design for the commercial buildings segment

The design of EV patterns for the commercial building segment is slightly different, as several different EVs can be plugged to a charger across time. States of charge (SOC) at plug-in are thus completely independent one from the other and chosen depending on the time of plug-in.

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[20] The year is divided into units of time equal to 15min

EV charging pattern resolution

Two main steps are followed to build charging load time series associated to a use case:

- Time series segmentation: the model defines all the time frames inside which the charging will occur.
- Load calculation of the chargers: the algorithm implements the charging strategy and determines the power required within every time-series segment. If the charging system is composed of several chargers, the model also computes the optimal distribution of the power previously calculated amongst all the chargers.

Annex 4: Grid services

Potential services EV-to-Building-to-Grid schemes can provide

Grid services potentially available to EVs are no different from the ones stationary batteries can provide. The following list was designed by aggregating several sources [29], [30], [31]. The terminology used can vary across countries, but the principles are the same. 4 global types of services can be provided:

1. Grid Balancing

- Frequency support mechanisms (FCR aFFR/mFRR, RR) : The primary, secondary and tertiary reserves are activated automatically or manually for the tertiary one to contain the frequency deviation, restore the frequency to 50/60Hz and bring the energy exchanges back to their planned value. EVs could be particularly interesting for the primary reserve, which is built through a weekly bid. Indeed, EVs have rapid response time.
- DR/DSF (demand response/demand-side flexibility) mechanisms for wholesale: enabling players to value their curtailment directly on the daily and intraday energy markets by notifying the TSO of the load shedding they will activate the following day. This value stream could be used in situations where it is known that the EV will stay plugged for a long time.
- Balancing (EU) or real-time (US) market: last stage for trading electricity, this market is used to correct for differences between the projected supply and demand (which is subject to the day ahead market) and the actual supply and demand.

2. Adequacy services with capacity markets

Capacity mechanisms help ensure the security of supply during peak periods. It is based on the obligation of players to hold capacity guaranteed to cover their electricity consumption- or that of their customers- during periods of high consumption. A variety of capacity remuneration schemes exists across countries.

3. Wholesale market trading, BRP portfolio optimization (EU only)

Purchase and resale of energy blocks on short-term markets (extraction and injection networks).

4. Transmission & Distribution Network Operator constraint management

- Backup power supply for islanding & off-grid modes: in locations where the distribution grid is weak and risks of black out are high, EVs can play the role of backup power supply. For the EV to deliver power to a home in islanding mode, specific power electronics must be added to the charger.[22]
- Reactive power adaptation [32]: EV chargers can be equipped to compensate reactive power[23], thus avoiding losses and extra cable capacity. It could theoretically avoid costs, although the quantification of this value is difficult. In addition to reactive power adaptation, EVs could help solve other power quality issues. [33]
- Other quality related services: TSO/DSO services for congestion, overvoltage relief, etc.
- Avoided CAPEX related to grid reinforcement: smart charging can avoid building infrastructure costs by lowering the maximum demand charge.

Enabling EV-to-Buildings for Grid services

For all these potential services to be leveraged by smart charging, some key technological features are necessary. First, grid services often rely on **bi-directional charging**[24]. Without such capacity, some services are not available (market trading, backup supply for DSO, frequency regulation), while others may be partially available (load shedding mainly). The market is still in infancy with significant product development and standardization effort required across the industry. One of the key challenges to address is the need for seamless integration into the local infrastructure. Another one has to do with the diffuse nature of EVs which cannot single-handedly be integrated into energy markets. It is thus the combined contribution of a significant number of EV chargers which can provide valuable services, leading way to aggregator services and virtual power plants. The regulatory and technical environments are still at an early stage of development.

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[22] In this case the charger is said to be ‘grid forming’. It sets the voltage and frequency of the power system

[23] In this case the charger is said to be ‘grid supporting’. It influences voltage and frequency of an existing power system. A more classical charger will only be ‘grid following’, meaning it has no way to optimize voltage nor frequency.

[24] Even if V1G and V1B1G already has value for certain products

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