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Control Strategies for V2X Integration in Buildings

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[1] https://ev4eu.eu/

Executive Summary

The Control Strategies for V2X Integration in Buildings deliverable presents decision-making models capable of integrating Vehicle-to-Everything (V2X) in the optimal energy management of buildings with local generation capabilities. The developed control methods will be considered in the Portuguese demonstrator of the EV4EU project, in São Miguel Island, Azores, and the Danish demonstrator, in the island of Bornholm, Denmark, to test the benefits of smart charging techniques.

Both developed control frameworks rely on collecting and utilizing historical data (on building load, photovoltaic (PV) production and Electric Vehicle (EV) data) for forecasting purposes. The Danish framework utilizes a forecasting-assisted rolling-horizon optimisation approach, while the Portuguese framework utilizes a daily planning stage (which determines a predefined goal), followed by the real-time operation stage.

The control objective in the Danish case is to optimally manage EV charging for minimizing energy costs while respecting a reduced line limit for the aggregated EV charging power, while for the Portuguese case various scenarios are considered, whose objective, apart from minimizing energy costs, is the activation of grid services, specifically targeting smaller islanded systems, such as the one in Azores.

The developed strategies were tested on a number of simulation scenarios which relied on historical data from the sites and a few available sources to replace the missing EV data because during the execution of the task the demonstration sites were not yet operational. Simulation results showed that the inclusion of forecasts and an optimisation-based control approach can bring substantial economic benefits and reduce peak power, thus reducing the required grid connection size for the chargers. Additionally, those preliminary results indicate that the added benefit of using sophisticated forecasting techniques is rather low, pointing at the use of simple and easy-to-implement methods which strike a better balance between simplicity and performance.

It should be noted that the economic benefit largely relies on the amount of installed chargers, the share of EV load compared to the building's consumption and the tariff/price structure. Longer plug-in durations and higher EV power capacity lead to higher potential cost savings by employing the developed control strategies, and a more realistic quantification will be carried out during the demonstration phase of the project.

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Keywords, Acronym

aSoC	Aggregated State of Charge
BEMS	Battery energy management system
CDF	Cumulative distribution function
CPO	Charge point operator
DER	Distributed energy resource
EMS	Energy management system
EV	Electric vehicle
LREC	Laboratório Regional de Engenharia Civil
LV	Low voltage
ML	Machine learning
OF	Objective function
PDF	Probability density function
PV	Photovoltaic
SoC	State of charge
SS	Secondary substation
ToU	Time of use
V2B	Vehicle to building
V2G	Vehicle to grid
V2X	Vehicle to everything
WP	Work package

Nomenclature

Danish demonstration

ΔT	Normalized control step duration
η	Overall efficiency of the EV and charger joint system
t	Time step index
k	Charging session index
p_t^{L}	Average consumption at step t
p_t^{PV}	Average PV generation at step t
$p_{t,j}^{\mathrm{EV}}$	Average consumption of EV j at step t
arr_{j,j_k}	Arrival timestamp of EV j and session k
dep_{j,j_k}	Departure timestamp of EV j and session k
e_{j,j_k}	Energy needs (in kWh) of EV j and session k
η	Charging efficiency
p_j^{Nom}	Charging power capacity of EV j
p^{conn}	Chargers grid connection limit in kW
N^{CH}	Number of charging points
p_t^{im}	Average importing power at step t
p_t^{ex}	Average exporting power at step t
j_k	EV j and session k-th session of EV j
λ_t^{im}	Electricity import price
λ_t^{ex}	Electricity export price
σ_j	Non-delivered energy (in kWh) for session j
μ	Penalty for each non-delivered kWh
T	Number of steps in the optimization horizon
g_t	Binary charging variable at step t
h_t	Price for self-consumed energy per kWh at step t
$\hat{p}_t^{\mathrm{PV}}$	Forecasted average PV generation at step t
$\hat{p}_t^{\mathrm{L}}$	Forecasted average consumption at step t

Portuguese demonstration

Δ_t	Time step duration
ev	EV index
t	Time step index
T	Simulation time duration
η	Overall efficiency of the EV and charger joint system
$P_{ev,t}^{genrelax}$	Relaxation variable for generation congestion management at time t and EV ev
$P_{ev,t}^{consrelax}$	Relaxation variable for consumption congestion management at time t and EV ev
$P_{ev,t}^{curtrelax}$	Relaxation variable for wind curtailment mitigation at time t and EV ev
α_t^{curt}	Activation of wind curtailment mitigation at time t
α_t^{gen}	Activation of generation congestion management at time t
α_t^{cons}	Activation of consumption congestion management at time t
$price_t^{sell}$	Electricity export (sell) price at time t
$price_t^{buy}$	Electricity import (buy) price at time t

P_t^{PVused}	Power produced by the PV and consumed by the EVs at time t
P_t^{import}	Total power imported at time t
P_t^{export}	Total power exported at time t
$P_{ev,t}^{gridfromEV}$	Power exported from EV ev to the grid at time t
P_t^{fromEV}	Power from the EV system at time t
P_t^{fromPV}	Power from the PV system at time t
$P_t^{fromgrid}$	Power from grid at time t
$penalty_t$	Economic penalty for the non-participation in a grid service, at time t
th_t^d and th_t^i	EV user's respective thresholds for the electricity price discount and incentive associated with grid service activation
$E_{ev,t}^{SOC}$	SOC at time t and EV ev
P_t^L	Household load at time t
$P_{ev,t}^{dch}$	Discharging power rate of the charging station of EV ev at time t
$P_{ev,t}^{ch}$	Charging power rate of the charging station EV ev at time t
$P_{ev,t}^{EVdch}$	Discharging power rate of EV ev at time t
$P_{ev,t}^{EVch}$	Charging power rate of EV ev at time t
P_t^{PV}	PV power output at time t

1 Introduction

Electric vehicle (EV) chargers are expected to be an integral part of many buildings in the near future, especially public ones such as educational facilities, public administration buildings, office buildings etc. Smart charging has shown to be beneficial, especially when local photovoltaic (PV) generation is also available. Therefore, exploring the benefits of employing Vehicle-to-Everything (V2X) strategies in the overall energy management of buildings with local generation capabilities and demonstrating them under real-life conditions is an important step towards optimally integrating EVs in the energy system.

1.1 Scope and objectives

This document presents decision-making models and control algorithms for the effective integration of V2X strategies in the optimal management of buildings. Focus is mainly given on larger administrative buildings equipped with PV units, though the proposed methods can be used for any type of building, with or without local generation.

The main objective is to design, develop, describe and preliminarily evaluate the performance of the proposed control strategies in two of the demonstration sites to be used in EV4EU: the Danish site (located in Campus Bornholm in Rønne, Bornholm) and LREC's (*Laboratório Regional de Engenharia Civil)* office building located in Ponta Delgada, in the island of São Miguel, Azores. The Danish demonstrator has a secondary demonstration site in Risø Campus of the Technical University of Denmark, located close to the city of Roskilde.

The control objective in the Danish demonstrator is to optimally manage EV charging for minimizing energy costs while respecting a reduced line limit for the aggregated EV charging power. In the Portuguese demonstrator various scenarios are considered whose objective, apart from minimizing energy costs, is the activation of grid services, specifically targeting smaller islanded systems, such as the one in Azores.

1.2 Structure

The present document is divided into 6 sections. After the introduction section, section 2 provides some insight on EV user behaviour and acceptance with regards to EV charging, presenting a user-centric view. Section 3 presents a technical description and the control objectives for each of the two sites (Denmark and Portugal). Section 4 details the developed control strategies and section 5 presents some preliminary results from some constructed case studies. Finally, section 6 concludes with some overall conclusions and recommendations for the real-life demonstrations.

1.3 Relationship with other deliverables

The work of this task and deliverable is closely linked to *D2.1 Control strategies for V2X integration in houses* [1]. This deliverable is an extension of D2.1 from a household to a building level. The considered scenarios for the simulations in PT site are based on the insights regarding the evolution of the Portuguese electromobility market – *D1.1 Electric Road Mobility Evolution Scenarios* [2]. The Portuguese regulatory framework for pricing and compensation can be found in *D1.3 Regulatory opportunities and barriers for V2X deployment in Europe* [3]. Further, the considered grid services are based on the business models and subsequent business use cases applicable to the Portuguese electromobility market – available in *D1.4 Business models centred in the V2X value chain* [4] and *D1.5 V2X Use-cases repository* [5], respectively.

The present deliverable will serve as the basis for a part of the demonstrations in the Portuguese site, detailed in deliverable *D6.1 Implementation plan for the Azores demo*, and the demonstrations in the Danish site, detailed in deliverable D9.1 *Use case specification, development, installation, commissioning, demonstration, and evaluation planning for the Danish demo.* The deliverable will also provide much of the theoretical backbone for the control methods to be used in the demonstrations of WP6 and WP9.

2 EV user considerations

In this section, two approaches are explored, regarding user acceptance related to Vehicle-to-Grid (V2G) and V2X technologies. In subsection 2.1, user perceptions and needs regarding these technologies are discussed. The importance of understanding user needs and how to communicate the benefits of V2G and V2X technologies in a clear and transparent way are also explored. In subsection 2.2, an examination of a successful program is made, which implemented V2G technology in the UK, highlighting the importance of understanding customer motivations and needs. The program's success is discussed, as well as the role of customer education and research in addressing concerns and misconceptions surrounding V2G and V2X technologies. Some relevant conclusions are drawn and presented in subsection 2.3.

2.1 EV4EU research findings

As seen in *Deliverable 3.1 - EV User's Needs and Concerns – Preliminary report (D3.1)* [6], a "clear majority [of survey participants] identified ecologic reasons as main drivers [for EV adoption], while during interviews economic factors were almost always identified as the most important motivators". It was also seen that "people seem to prefer having a way to charge at home, when that's possible to install, due to increased convenience and lower prices".

This leads to a belief that, when given the choice between saving money or adopting more ecological behaviours, the money aspect prevails, just as mentioned in D3.1: "It was noticed that, even though sustainability has a big role in this subject, population's main driver seems to be related with economic issues, both when considering initial investments for EV adoption, and economic gains perceived with using electricity instead of fuel to charge their cars" [6].

Nevertheless, this is seemingly most applicable to users that must support charging costs. When different acquiring models are in place (for example, if it is a company car), lowering charging costs is no longer a concern, and that leads to a perception that a "greener alternative" would be preferred in those cases. In D3.1 it was also discovered that people seem to accept V2G and V2X technologies: "V2X seems to be perceived as an interesting technology, but people need assurances regarding *impact on battery degradation, economic advantages, and ability to control the system, to assure personal mobility needs*" [6].

Assurances seem to be related to a lack of clarity regarding how V2G and V2X technologies work. "People are not aware of what this technology is, and what impacts it might have in their daily lives. In general, people assume there could be benefits for them, but some struggle to identify them, mainly because they feel it will benefit the energy companies more than themselves" [6]. Here, an important principle to keep in mind is that the more transparently, clearly, and simply the technology is communicated, the better people will understand it, and consequently adopt it. This is based on known principles of usability like [7] that even though they're mainly directed to interface design, they can be extrapolated to any service or experience.

This principle should also be applied when talking about the experience when using V2G, as users assume that their crucial concern is assuring "control over the system". Users stated that they "need to assure that they have enough battery for their daily needs, and expect to be able to set limits, such as only allowing the grid to take a certain percentage per day, or even asking to assure a specific range at a specific time." Additionally, "they also expect to be informed of how much energy was taken from their batteries, but they expect this to happen with a notification, or preferably included in their electricity monthly invoice" [6].

This demonstrates a need to keep the whole experience very transparent and straightforward, as well as communicate a clear status of the system at each moment, so that users easily understand what's happening, and adjust their actions and expectations accordingly. Assuming a V2G acceptance, "economic advantages are expected, and almost seen as mandatory" [6]. This expectation is apparently related to the concern of V2G increasing battery degradation, and therefore a financial incentive is expected to cover the extra cost it might represent in a battery exchange earlier than predicted.

Regarding this economic advantage, "people are divided between receiving direct adjustments for energy shared or having discounts on electricity prices, but both seem to work, as long as people feel they are getting this monetary compensation" [6]. Additionally, there was a perception that, in some cases, a sense of community and mutual support might prevail over the monetary concerns, with an expectation that, by giving away when others need, people would get it back if they needed it themselves.

There's also a possibility that, when a user provides energy to the grid, one of two scenarios happens: (1) they might have to unplug the car sooner than expected, and that might mean having less energy than what was initially expected; (2) the grid might not be able to assure enough energy, and so the user might have less battery than what they expected to have.

In scenario 1, where we assume an action by the user might affect the desirable outcome, a recommendation of assuring a transparency policy is here reinforced. Before agreeing to participate in V2G exchanges, it should be clear to the user what will happen and what are the consequences associated with the experience. If the user is asked to set a specific time when they'll unplug the car, then they must be made aware that they might have less energy than expected if they do it sooner. It's important to note here that some users interviewed mentioned they would like to set these types of timers (stating time of departure and range needed at that time), but it was also mentioned the possibility of stating a limit of battery percentage that could be used to V2G (user could define that only 5% of their battery was available to give to the grid), thus it's not clear what is the preferred method for the majority of users.

In scenario 2, where the failure to meet expectations lies with grid capacity, a clear statement of this "risk" should be communicated to users. Additionally, and based on what users mentioned in research done for D3.1, there's a perception they might expect compensation for this failure to meet expectations. As a recommendation, it might be interesting to explore the possibility of communicating an energy interval, instead of specific values, thus creating an adjustment in user expectations and consequently reducing frustration if only a lower limit is assured.

2.2 V2X technology acceptance example

OVO[2], one of the leading energy service providers in the UK, joined forces with major automaker Nissan[3] and software provider Kaluza[4] to launch the world's first and largest deployment of residential V2G technology. This groundbreaking project [8] marked a significant achievement in demonstrating the capabilities and benefits of V2G technology. It also highlighted the crucial obstacles that need to be overcome to fully utilize this technology on a larger scale within the electricity system.

Typically, an EV is usually connected to a V2G charger during the evening peak period in the UK (between 17:00 and 21:00). This charger promptly begins transferring excess energy from the EV back into the grid when there is high demand for electricity. This process aids in alleviating congestion within the power system. Following the evening peak period, the majority of EVs enter an idle state where they neither charge nor discharge. Instead, they maintain a state of charge at approximately 30%. This minimum threshold is predetermined by the customer to ensure that they have enough battery power for any unexpected trips that may arise. Starting from 03:00, when electricity prices were lower and CO_2 intensity was reduced, a gradual charging process began. The objective was to achieve a fully charged battery by 07:00, aligning with the customer's scheduled car readiness time. Often, the peak period for customers plugging in their vehicles was observed between 17:30 and 18:00. Conversely, the unplugging activity peaked between 07:30 and 08:00.

On an average day, ~61% of the V2G portfolio was accessible between the times of plugging in and plugging out. This statistic highlights the substantial potential for system flexibility that V2X technology offers when combined with an attractive customer proposition on a larger scale. On average, when vehicles were plugged in, their batteries had a state of charge of 43% and the majority of customers set their car's maximum state of charge at 90%.

Customer experience

Customer experience was a key focus for OVO. They captured the full value of load shifting and passed it on to their V2G customers through an innovative proposition. The drivers were credited with \$0.36/£0.30 per kWh exported to the grid, which was reflected in their monthly energy bills accessible via a mobile app[5]. To encourage desirable behaviours, the customer mobile app was designed with user-friendly features and adaptability in mind. The app allowed customers to easily schedule their charging, gain valuable insights into their vehicle's current behaviour and state of charge, as well as track the history of energy imports and exports.

Considering feedback from trial participants, a minimum state of charge feature was developed to ensure a baseline level of energy was always preserved in case of emergencies. This feature provided drivers with confidence that their vehicles would always be usable. Additionally, customers were educated about the benefits of maintaining a minimum state of charge to enhance battery health, addressing any initial concerns among the group.

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[2] https://www.ovoenergy.com/
[3] https://www.nissan.co.uk/
[4] https://www.kaluza.com/
[5] https://play.google.com/store/apps/details?id=com.kaluza.flex.anytime&pli=1

Customer benefits

The project proved highly advantageous for customers who actively participated. They enjoyed substantial benefits as a result. Many of them received payments that exceeded double the amount they initially spent on charging their vehicles. On average, customers received monthly rewards of approximately $41/£35 for exporting energy through V2X, resulting in an average reduction of 40% in their monthly energy bills. The most active and engaged participants went even further, earning up to $960/£800 per year through V2G, effectively eliminating their household energy costs entirely.

An overwhelming majority of participants, reaching 93%, expressed satisfaction or high satisfaction with their V2G experience. Notably, concerns about battery health decreased significantly from 61% at the start of the trial to 24% by the end. Similarly, worries regarding cost savings while using V2G declined from 43% to 28%.

EV Drivers

As part of the UK program [8], participants were surveyed to gain insight into their motivations for joining. The survey results revealed that the primary driver for participation was the financial incentive [8]. Following closely behind was the desire to be an early adopter of innovative technology, and in third place, the motivation to reduce their carbon footprint [8].

These valuable insights played a crucial role in shaping the customer proposition and guiding the development of the accompanying mobile app throughout the trial. By aligning with participant motivations, the program achieved a notably high satisfaction score among the participants.

The key to a successful program lies in helping customers achieve their desired goals or fulfil their needs, while also incentivizing the specific behaviours that generate the maximum value from the technology. A notable example of this was observed in the UK program through the development of the "charge path feature." This feature allowed participants to visualize how their vehicle would be charged in the upcoming minutes and hours, instilling trust in the software optimisation process. As a result, there was a remarkable 40% increase in the number of hours during which customers allowed the software to optimize their charging [8].

Furthermore, by educating customers about the software's functionality and the consequences of overriding it, there was a significant 141% rise in the number of flexible charging hours [8]. This increase in flexibility enabled customers to generate more value and cost savings. By incorporating these design elements and fostering customer understanding, the program was able to deliver enhanced benefits and foster greater trust in the technology.

The feedback received emphasized two significant areas of focus:

- Make rewards simple and engaging: Effectively communicating the rewards structure is crucial, especially when dealing with a relatively complex technology like V2X. It is essential to tailor the messaging to diverse customer segments and ensure clarity. Conducting customer research plays a vital role in understanding their needs and preferences. As V2X technology continues to scale, investing in customer research remains crucial for success.
- Invest in educating customers: Investing in customer education is key to addressing concerns and misconceptions surrounding the technology. By providing accurate and accessible information, trust can be built, enabling drivers to maximize the benefits of their EVs for an extended period. Empowering customers to easily configure their V2X charging settings for optimal battery performance is a vital component of ensuring the scalability of V2X adoption.

2.3 Conclusions

In subsection 2.1 focus was given on understanding user needs and perceptions of V2G and V2X technologies. It was discovered that people seem to prefer having a way to charge at home, which should be considered when implementing these technologies. Furthermore, it's important to communicate V2G and V2X technology in a clear and transparent way to ensure user understanding and adoption.

Subsection 2.2 discusses a successful program that implemented V2G technology in the UK, highlighting the importance of understanding customer motivations and needs. The program's success was attributed to effectively communicating the rewards structure and investing in customer education.

Based on these two studies, it's clear that understanding user needs and motivations is crucial for successful implementation of V2G and V2X technologies. It's important to communicate the benefits of these technologies in a way that is clear and understandable to users. Additionally, providing incentives and rewards that align with user motivations can encourage adoption and engagement.

The success of the program in the UK demonstrates that investing in customer education and research is important for addressing concerns and misconceptions surrounding V2G and V2X technologies. By providing accurate information and empowering users to optimize their charging settings, trust can be built, and benefits can be maximized. Overall, these approaches emphasize the need for a user-centric approach to implementing V2G and V2X technologies. By understanding user needs, motivations and concerns, and by effectively communicating the benefits of these technologies, adoption and engagement can be improved, leading to more sustainable and efficient energy systems.

3 Setup description

This section provides an overview of the two setups used as a basis for the developed control algorithms. One setup is based on the Danish site (subsection 3.1) and the other on the Portuguese site (subsection 3.2). These sites will be used later on during the project to demonstrate the described algorithms in real-life conditions. A high-level technical description is followed by the control objectives of the proposed algorithms.

3.1 Danish site

3.1.1 Technical description

Campus Bornholm (shown in Figure 1 and Figure 2) is an educational institution located in Rønne, the main city of the Danish island of Bornholm. It offers education and courses both for young people and adults through 25 vocational courses, 4 upper secondary education tracks, Danish courses, and adult and continuing education. The Campus will host the demonstration performed in EV4EU, where 6 smart EV chargers with 12 charging outlets will be installed in the parking lot of the campus. The chargers that will be deployed have been developed in cooperation with Circle Consult within the ACDC project[6] [9].

Figure 1 – Campus Bornholm, located in Rønne

(photo taken from: https://campusbornholm.dk/om-campus-bornholm/)

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[6] https://www.acdc-bornholm.eu/

Figure 2 – Top view of the campus

(photo taken from Google earth)

Figure 3 – The PV installation on Campus Bornholm

The PV system on the rooftop of the educational institution Campus Bornholm (shown in Figure 3) has a total power capacity of 176.76 kW, consisting of 667 monocrystalline Trina TSM 265 W PV modules. The PV plant is divided into three parts, and each part is connected to an SMA Sunny Tripower inverter rated at 60 kW. While two inverters connect 10 strings, one connects 9 strings with 23 modules, leading to a power rating of 60.95 kWp for the first two parts and 54.86 kWp for the last [10]. Figure 3 shows the almost southward-facing installation with an inclination of around 30% following the shape of the roof.

3.1.2 Control objectives

The building of the Campus is seen as a non-controllable load, which means that its consumption is assumed to be an input, and load cannot be shifted in time or curtailed. The same goes for the PV, which is assumed to be non-curtailable, to avoid renewable production spillage.

The EV charger output can be controlled to achieve various objectives. Two types of control strategies are investigated in this task:

- Uncontrolled charging, which can be considered as the business-as-usual control mode. With this strategy EVs are charged at full capacity until their charging needs are satisfied.
- Optimisation-based smart charging, which optimizes the charging power of the EVs based on formulating and solving an optimisation problem. This is done in a rolling-horizon fashion, as will be described in more detail in Section 4.

With uncontrolled charging the goal is to satisfy EV energy needs as fast as possible, which means that explicit control objectives cannot be set. On the other hand, this is possible by using an optimisation approach. The parking lot manager may optimize EV charging with the goal of:

- Minimizing energy costs
- Minimizing energy exchange with the grid, and thus maximizing self-consumption
- Minimizing CO_2 footprint
- Achieving a trade-off between non-served energy to the EVs and a lower connection utilization (i.e., temporarily further reduce the grid connection power limit)

3.2 Portuguese site

3.2.1 Technical description

The Regional Laboratory of Civil Engineering (LREC, according to the acronym in Portuguese *Laboratório Regional de Engenharia Civil)* is a public administration body of the Azorean Regional Government which aims to evaluate and control construction quality in the Azores. Apart from being responsible for the quality control of construction materials and the general technical support of any regionally undertaken civil engineering construction works, LREC conducts and disseminates applied research studies on the geotechnical, structural, material, seismic, road and geology specificities of the archipelago. On this subject, LREC's main activity is the execution of laboratory tests and studies.

Figure 4 – LREC's office building, located in Ponta Delgada: main entrance (left) and top view (right)

LREC's office building (shown in Figure 4) was constructed in 2000 and is located in Ponta Delgada, in the island of São Miguel. It will host one of the demonstration sites of building environment tests performed in EV4EU, where 1 smart charger with 2 charging points – 1 CHAdeMO and Combined Charging System (CCS) connections – will be installed in one of its parking lots. In 2021, the necessary connecting infrastructure was installed between the foreseen EV charging parking spaces and the building's Low Voltage (LV) electrical panel. The charger will be procured by Smart Energy Lab.

The building's two floors serve more than 40 users through different sections (e.g., laboratories, offices, training rooms, auditorium, meeting rooms, archive, interior circulation, storage, technical areas), encompassing a total useful surface area of 2,751 m^2 and a total deployment surface area of 1,825 m^2. Energy-wise, the building has a contracted power of 116.25 kVA and annually consumes 113,066 kWh (2022 – 2023 data), in accordance with Table 1. The building's consumption needs are fully met electrically.

Table 1: LREC's office building monthly energy consumption

Month / Year	Jun/22	Jul/22	Aug/22	Sep/22	Oct/22	Nov/22
Energy Consumption (kWh)	8,950	12,454	14,149	13,416	10,570	11,100
Month / Year	**Dec/22**	**Jan/23**	**Feb/23**	**Mar/23**	**Apr/23**	**May/23**
Energy Consumption (kWh)	9,447	8,345	6,851	6,853	5,551	5,380

In the interest of self-consumption, LREC's office building is equipped with a solar PV system with an installed power of 15 kWp, consisting of 32 Trina 500 W PV modules connected to an SMA inverter rated at 15 kW (shown in Figure 5).

Figure 5 – Solar PV system installed at LREC's office building: solar PV modules (left) and inverter (right)

Finally, it is worth mentioning that LREC's office building is equipped with an Energy Management System (EMS) allowing for the disaggregated reading of energy consumption and environmental parameters (shown in Figure 6).

Figure 6 – EMS installed at LREC's office building: physical module (left) and visualisation dashboard (right)

3.2.2 Control objectives

For simulation purposes, only the chargers are regarded as controllable loads.

The charger output may be controlled to achieve several objectives. Three types of control strategies are investigated in this task:

- Uncontrolled charging: no discharging and uncontrolled charging, following a business-as-usual paradigm. Adopting this control strategy implies EVs are charged at the charger's nominal power as soon as connected until a State-of-Charge (SoC) of 100%;
- Optimisation-based smart charging: no discharging and controlled charging, which aims to optimize charging power according to an Objective Function (OF) assuming Machine Learning (ML) based forecasts for future solar PV power production and building load demand, while regarding grid service participation as voluntary;
- Optimisation-based Vehicle-to-Building (V2B): controlled charging and discharging, which aims to optimize charging power according to an OF assuming ML based forecasts for future solar PV power production and building load demand, while regarding grid service participation as voluntary.

The optimisation algorithm uses the CPLEX solver from IBM to solve a mixed integer linear programming mathematical programme [11].

Naturally, following an uncontrolled charging strategy means explicit control objectives may not be set. Nevertheless, each one of the optimisation control strategies may envisage control goals such as:

- Energy cost minimisation;
- Self-consumption maximisation (i.e., grid energy exchange minimisation);
- Grid service participation maximisation (this may be done for an individual grid service or for all).

4 Control strategies

This section details the control strategies developed within Task 2.2. These will then be used to simulate several case studies and derive some preliminary results. The developed methods will be later tested in the two demonstration sites (Danish and Portuguese demos).

4.1 Danish site

4.1.1 Model overview and assumptions

A schematic overview of the main components of the Danish site is shown in Figure 7.

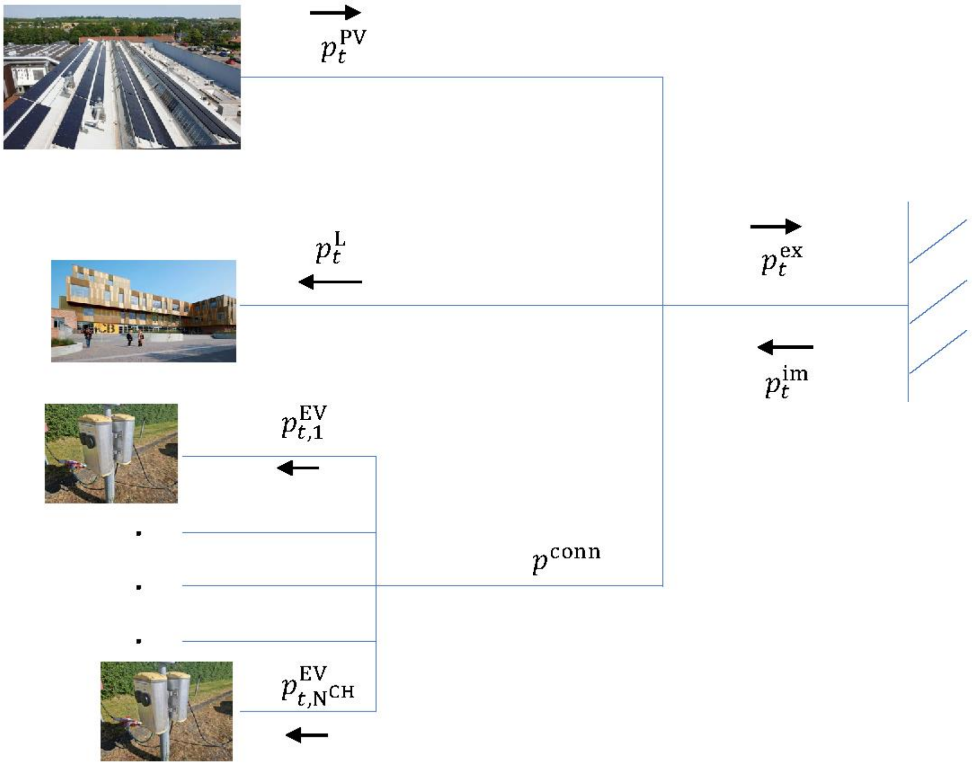

Figure 7 – Illustration of the Danish setup in the considered parking lot, including the building and PV.

The model characteristics and assumptions are listed below:

- We consider a normalized control step equal to ΔT, which is equal to 1 if resolution is hourly, 0.25 if resolution is equal to 15 min and so on. The simulation runs at a step equal to the said resolution. Any power variations within this period are neglected and average values are considered.
- Each EV charging session is characterized by three quantities: arrival time, departure time and energy needs (in kWh).
- We denote the building's average consumption over a time step t with p_t^{L}.
- We denote the average PV generation over a time step t with p_t^{PV}.
- We denote the j-th EV charger's average charging power over a time step t with $p_{t,j}^{\mathrm{EV}}$.

- We assume that the installation is subject to net metering, which is an energy billing method that incentivizes self-consumption [12]. Under instantaneous net metering, which is the practice in Denmark, the customer receives the hourly spot price for the total amount of energy injected to the grid during that hour and pays the buying price (which includes various fees/tariffs) for the energy imports during that hour. Note that instantaneous net metering may lead to concurrent energy imports and exports during an hour because those are not cancelled out.
- We assume that the controller has real-time access to building consumption and PV generation, but future values are unknown. For example, if the current simulation time is 2022-05-04 07:00:00, then consumption until 07:00 is known, but is unknown for the upcoming period 07:00-07:15 and beyond.
- We assume that data of EV charging sessions is unknown, and that the arrival time is known only when the user plugs in the EV at the current simulation time step t. Further, at t we assume that the departure time and energy need of the particular session become known (as EV user input).

An example of an EV charging dataset can be seen in Table 2. Each charger is associated with a "ChargerID". Each session belongs to a specific ChargerID and has its own identifier called "TransactionID". Each transaction is characterized by the arrival time, the departure time, and the energy need in kWh.

Table 2: Example of EV charging dataset

Index	Arrival Time	Departure Time	Energy Needs (kWh)	ChargerID	TransactionID
0	2022-05-04 07:00:00	2022-05-04 12:00:00	17	1515	125113
1	2022-05-04 07:15:00	2022-05-04 14:30:00	32	1588	125114
…	…	…	…	…	…

4.1.2 Methodology

Let p_t^{im} and p_t^{ex} denote the average imported and exported power during time interval t, respectively. The grid connection is denoted by p^{conn} and the number of stations N^{CH}. If j indicates the charger ID, then j_k indicates the k-th charging session ID of that charger. Charging efficiency is indicated by η.

Uncontrolled EV charging

Uncontrolled charging serves as the benchmark, and business as usual, control approach. Based on uncontrolled charging, all EVs start charging with their maximum power capacity until fully charged. An algorithmic description of dumb charging is depicted below:

- For each charger j, check if any charging session j_k is initiated, so that $t = arr_{j,j_k}$. Obtain the departure time dep_{j,j_k} and energy needs e_{j,j_k}. arr_{j,j_k} indicates the arrival time for the j_k-th station, and the same logic applies to departure and energy needs.
- Calculate the charging power of each station:

$$p_{t,j}^{\mathrm{EV}} = \begin{cases} p_j^{\mathrm{nom}}, & if\ t \geq arr_{j,j_k}, t < dep_{j,j_k}, \displaystyle\sum_{t=arr_{j,j_k}}^{dep_{j,j_k}} p_{t,j}^{\mathrm{EV}} \Delta T \eta < e_{j,j_k} \\ 0, & otherwise \end{cases} \quad (1)$$

  Note that the last non-zero value of $p_{t,j}^{\mathrm{EV}}$ is most often lower than p_j^{nom}, otherwise the EV would be charged with energy that exceeds e_{j,j_k}. For this reason, a check should be made to ensure that the total energy does not exceed e_{j,j_k}.
- If the grid connection is limited, then a load management controller is required to limit charging power to acceptable levels. If $\sum_{j=1}^{N^{\mathrm{CH}}} p_{t,j}^{\mathrm{EV}} > p^{\mathrm{conn}}$, then all $p_{t,j}^{\mathrm{EV}}$ values are multiplied by $p^{\mathrm{conn}} \,/\, \left(\sum_{j=1}^{N^{\mathrm{CH}}} p_{t,j}^{\mathrm{EV}} - p^{\mathrm{conn}}\right)$.

Optimisation-based EV charging

In this task a control approach based on rolling horizon optimisation that incorporates forecasts is employed. An example of applying rolling horizon optimisation is depicted in Figure 8. At the current step, say 16:30 at the first iteration (upper plot), the optimisation problem is formulated for the following 6 steps, until 18:00. Historical data until 16:30 is available, based on which forecasts can be cast.

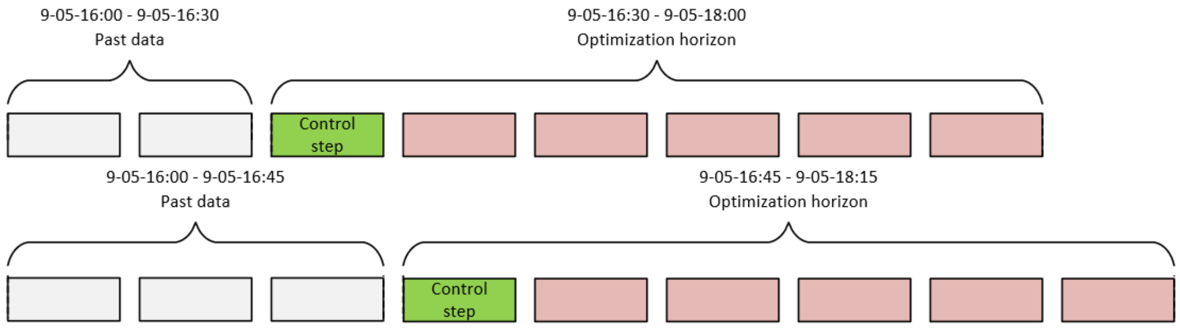

Figure 8 – Example of application of rolling horizon

The solution of the problem will produce optimal control actions for the following 6 timesteps. However, only the first action for the “control step” (16:30-16:45) will be implemented, and the procedure will be repeated after 15 minutes, which is the resolution of the example. As stated in the model assumptions of Subsection 4.1.1, at the time the optimisation problem is formulated and solved, PV and building consumption data until that point in time is available, i.e., until 16.30. Additionally, the latest EV-related data becomes available. In the above-mentioned example, EVs that arrived at 16:30 will be known to the controller, along with their departure time and energy needs.

At each new time interval, the controller runs, and based on the available EV data, a vector $\boldsymbol{d} = d_1, d_2, \ldots$ that contains the departure timesteps for each occupied charger is calculated. Set Ω contains the occupied chargers. The decision variables W contain all the EV charging setpoints, imported/exported power from/to the grid, and the slack variables of EV charging σ_j. These variables are used to penalize any non-served energy to the EVs. Further, a vector $\boldsymbol{e} = e_1, e_2, \ldots$ contains all the remaining energy needs of each occupied charger.

$$\begin{gathered}
\min_{W} c \\
0 \le p_{t,j}^{EV} \le p_j^{\mathrm{nom}}, \forall j \subseteq \Omega, 1 \le t \le d_j \\
\sum_{t=1}^{d_j} p_{t,j}^{EV} \, \Delta T \eta + \sigma_j = e_j, \forall j \\
\sum_{j \subseteq \Omega} p_{t,j}^{EV} \le p^{conn}, \forall t \\
\sum_{j \subseteq \Omega} p_{t,j}^{EV} + p_t^{ex} + p_t^{L} = p_t^{im} + p_t^{PV}, \forall t
\end{gathered} \tag{2}$$

Once a solution to the optimisation problem is obtained, the optimal charging schedules for all occupied EVs are calculated. However, only the first control action during the control step is implemented. At the next step, the remaining EV needs are recalculated, based on the energy provided to the EVs during the previous interval, and the controller checks if any EVs have departed or new ones have arrived.

The objective function can take different forms, depending on the objective. If EV users do not pay for the charged energy (e.g., given as benefit to employees), the following objective function can be used:

$$c_1 = \sum_{t=1}^{T} \left(p_t^{\mathrm{im}} \lambda_t^{\mathrm{im}} - p_t^{\mathrm{ex}} \lambda_t^{\mathrm{ex}}\right) \Delta T + \sum_{\forall j} \sigma_j \mu, \tag{3}$$

where λ_t^{im} is the energy import price at step t in €/kWh and λ_t^{ex} the energy export price in €/kWh. In the above objective function ΔT is used to account for the general case of any used time resolution, since p_t^{im} and p_t^{ex} are expressed in kW. A factor μ reflects the penalty for each non-delivered kWh. A very high value can be used to ensure that energy needs are always prioritized and satisfied unless this is technically not possible.

Often, Distribution System Operators apply a fee h_t in the self-consumed PV generation. In that case, the self-consumed part of production times the associated fee needs to be included in the objective function as

$$c_2 = \sum_{t=1}^{T} \left(p_t^{\mathrm{im}} \lambda_t^{\mathrm{im}} - p_t^{\mathrm{ex}} \lambda_t^{\mathrm{ex}}\right) \Delta T + \sum_{\forall j} \sigma_j \mu + \sum_{t=1}^{T} h_t \left(p_t^{\mathrm{L}} + \sum_{j \subseteq \Omega} p_{t,j}^{EV} - p_t^{\mathrm{ex}} \right) \Delta T \tag{4}$$

In this case a binary variable g_t is required to enforce that importing and exporting decision variables are mutually exclusive:

$$p_t^{\mathrm{im}} \leq \; g_t \, M, \forall \, t \tag{5}$$

$$p_t^{\mathrm{ex}} \leq \; (1 - g_t) \, M, \forall \, t \tag{6}$$

Where M is a sufficiently large positive number.

Note that in the previous formulation, perfect knowledge of the future building consumption and PV generation are assumed. In a real setup, those would be unknown. In that case, the respective power values are replaced with the forecasted ones, indicated by $\hat{p}$.

$$\sum_{j \subseteq \Omega} p_{t,j}^{EV} + p_t^{\mathrm{ex}} + \hat{p}_t^{\mathrm{L}} = p_t^{\mathrm{im}} + \hat{p}_t^{\mathrm{PV}}, \forall \, t \tag{7}$$

4.2 Portuguese site

4.2.1 Model overview and assumptions

The present work for the Portuguese site envisages the simulation of Vehicle-to-Everything (V2X) and Distributed Energy Resources (DER) control strategies, as well as grid service participation, within LREC's office building. For that effect, the decision-making model that has been conceived within *Deliverable 2.1 Control Strategies for V2X Integration in Houses (D2.1)* [1] was tailored to representative data regarding the building at issue.

In this manner, a comprehensive dataset has been postprocessed, either through direct data collection or assumption-based data generation:

- EV usage behavioural data;
- Load demand profile data:
    - Solar PV power output data[7];
    - Building load demand data.
- Network tariff data;
- Grid services data:
    - Wind curtailment data[7];
    - Consumption congestion data[7];
    - Generation congestion data[7].
- Weather data [13].

Network tariff data was collected via Electricidade dos Açores' (EDA) current electricity pricelist, as well as via the current electricity market daily and weekly cycling on the part of the Portuguese energy

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[7] Data retrieved from EDA's private database

regulating authority (Entidade Reguladora dos Serviços Energéticos) [14]. The remaining data were adapted to the building case or directly transcribed from D2.1 [1].

4.2.1.1 EV usage behaviour

Contrary to the typical households' case, multiple EV users will handle the chargers within LREC's office building. On that account, three distinct EV usage profiles were considered: (i) fleet worker (F); (ii) office worker (W); and (iii) visitor (V).

Fleet worker EV usage is relatively easy to predict, as mobility needs are consistent. On this subject, the fleet worker is assumed to use the fleet EV every weekday with an average yearly covered distance of around 20,000 km and departure and arrival times characterized by the Probability Density Functions (PDFs) in Figure 9, which were adapted from D2.1 [1].

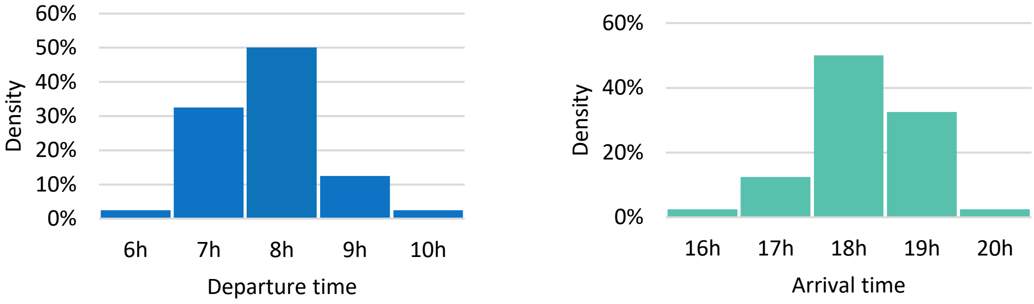

Figure 9 – PDFs of the departure (left) and arrival (right) times for a fleet worker

Additionally, the daily EV energy consumption of a fleet worker is represented in Figure 10, where the EV average daily covered distance and energy consumption / covered distance ratio were directly taken from D2.1. Note that LREC's office building is assumed as the sole place for a fleet worker to charge the fleet EV, meaning its energy requirements are directly linked to its mobility needs.

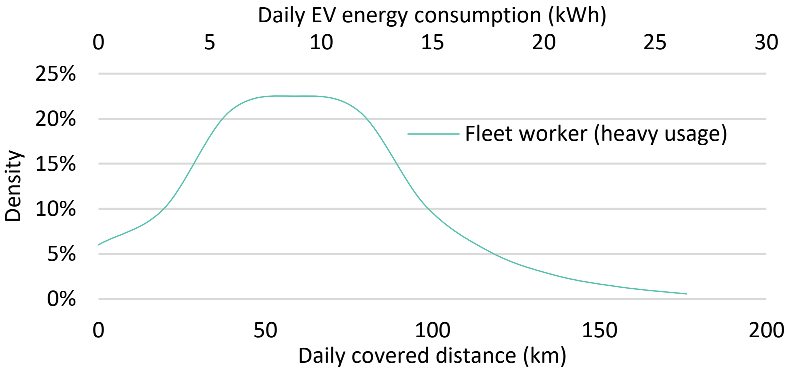

Figure 10 – PDFs of the daily covered distance and EV energy consumption for a fleet worker

On the other hand, the more erratic EV usage behaviour on the part of office workers and visitors makes these types of EV users more challenging to characterize. Based on extensive parking data available from Instituto Superior Técnico[8], ranging from October 2021 to November 2022, the office

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[8] Data retrieved from Instituto Superior Técnico's private database

worker and visitor EV usage profile were assumed to follow the EV usage behavioural patterns of people who parked for more and less than 2 hours, respectively. Moreover, it was assumed that no trips take place during weekend days.

Figure 11 displays the Cumulative Distribution Functions (CDFs) of the energy requirements per session for an office worker and a visitor.

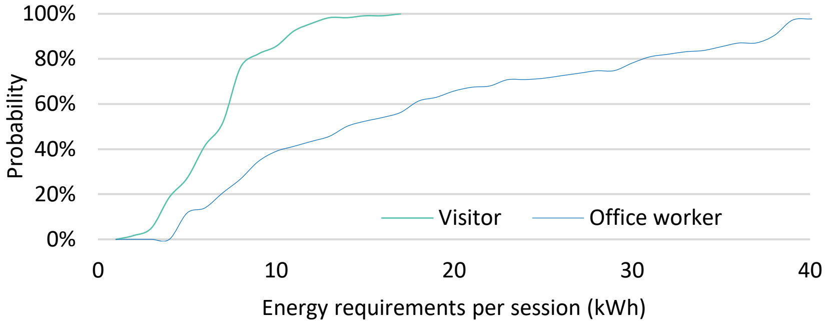


Figure 11 – CDFs of the energy requirements per session for an office worker and a visitor

Furthermore, the departure and arrival time of the office worker is assumed to be characterized by the PDFs in Figure 9, while a visitor's average trip duration is assumed to last between 1 and 2 hours, with arrival and departure times uniformly distributed from 09:00 to 18:00.

4.2.1.2 Load demand profile

Load demand profiling implies the collection of two additional datasets: (i) solar PV power output data; and (ii) building load demand data.

The power output of the PV system at LREC's office building is 15 kWp [15] However, since its installation was only concluded in 2023, there is not sufficient historical data to characterize its energy production. On that account, the solar PV energy production of LREC's office building was linearly extrapolated from that of the 2.22 kWp household PV system in D2.1 [1].

Figure 12 illustrates the building's average PV power output per time of day and season.

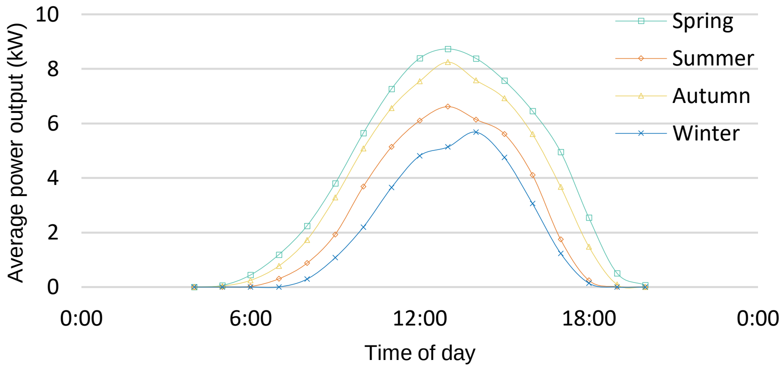


Figure 12 – Average PV power output per time of day and season for LREC's office building

In this manner, the yearly solar PV energy production of LREC's office building is estimated at around 18.5 MWh, which is in line with the prediction of about 20.8 MWh in [15].

Similar to solar PV power output data, there is no available timeseries data for the load demand within LREC's office building. For this reason, to acquire a representative dataset for the building's load demand, the household's load demand data in D2.1 was adapted to meet high load demand levels during working office hours (from around 09:00 to around 19:00) while being constrained to the monthly energy consumption of LREC's office building, as presented in Table 1.

Figure 13 illustrates the building's average load per time of day and season.

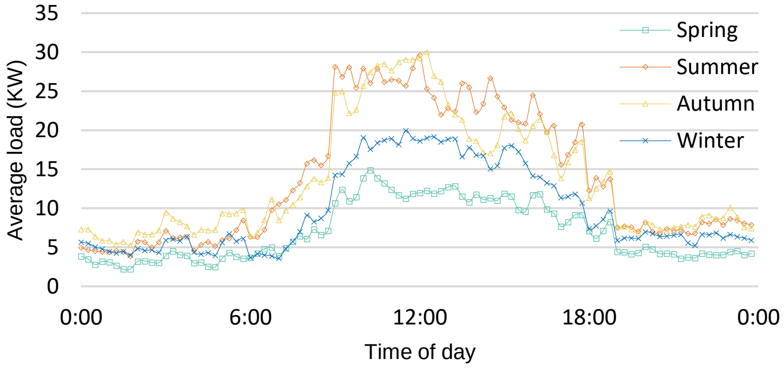


Figure 13 – Average load per time of day and season for LREC's office building

For spring, summer, autumn, and winter, a respective building average energy consumption of 5.9, 11.9, 11.7, and 8.2 MWh/month was calculated (113 MWh per year). Contrary to the household's case, summer is not the season when the least but the most energy is consumed. This is most likely due to increased air conditioning utilisation for room temperature control.

It is worth mentioning the proposed decision-making model is prepared to control dispatchable loads such as air conditioning and domestic hot water systems – which account for about 14% of the total energy consumption within LREC's office building –, according to measured room temperature [15]. Notwithstanding, for the purpose of this deliverable, it is considered that all the building's loads are uncontrolled, with the exception of the chargers.

4.2.1.3 Grid services

Unmanaged EVs may lead to the variability of load demand beyond what is deemed acceptable when considering local capacity constraints. V2B integration transforms an EV into a flexible load, unlocking the activation of grid services and hence various benefits for building owners and grid operator, with a strong emphasis on renewables integration.

The present subsection will focus on assessing the relevance of EV charging and discharging actions towards providing grid services, namely: (i) wind curtailment mitigation – the EV user is requested to increase consumption to avoid wind power curtailment; (ii) consumption congestion management – the EV user is requested to stop charging or discharge to decrease the local Secondary Substation's (SS) usage rate (ratio between load demand and total installed power), and (iii) generation congestion management – the EV user is requested to charge to increase the SS's usage rate.

Regarding wind curtailment, data was adapted from the Graminhais wind farm power output dataset in D2.1 [1] to account for curtailment technical limitations related to operation and maintenance actions and the grid's capacity to accommodate the curtailed power output.

In Figure 14, it is possible to observe the average power output at the Graminhais wind farm per time of day and divided by end use.

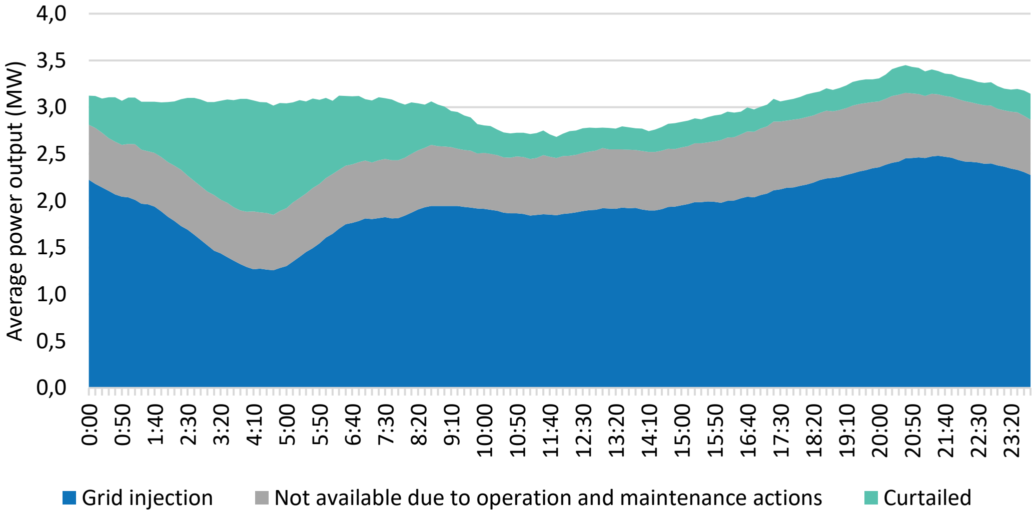


Figure 14 – Average power output at the Graminhais wind farm per time of day and end use

An average curtailed power peak is observable between around 03:20 and around 05:20, which corresponds to super off-peak time. Just as in D2.1, a pool size of 500 participating EVs is assumed.

Regarding congestion management, data was directly transcribed from the Arcanjo Lar's 630 kVA SS active power output dataset in D2.1 [1]. Figure 15 illustrates the average usage rate of the Arcanjo Lar's SS per type of day and time of day.

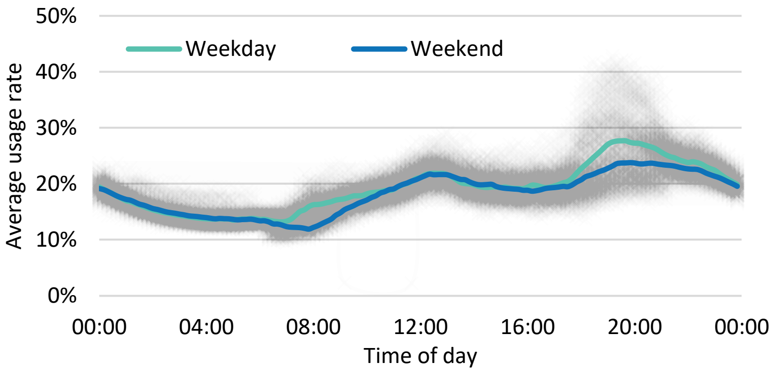


Figure 15 – Average usage rate of the Arcanjo Lar's SS per type of day and time of day

Note that São Miguel Island's power grid does not currently face any local congestion issues. However, to properly assess the congestion management performance of the decision-making model, congestion was intentionally assumed at the SS by employing a N-1 criterion.

For consumption congestion management grid services, participation was considered when the SS is above a congestion threshold of 30% (according to a N-1 criterion).

Additionally, a new generation congestion management grid service was created to replicate excessive local solar PV production fed to the SS. On that account, whenever, between 12:00 and 18:00, the SS is below a congestion threshold of 17.5% (according to a N-1 criterion), grid service participation was considered.

4.2.1.4 Network tariffs

The grid connection of LREC's office building is carried out using Medium Voltage (MV). Hence, the building's electricity prices are fixed according to seasonally dependent Time-of-Use (ToU) tariffs that vary in consonance with the tetra-hourly daily cycle represented in Figure 16.

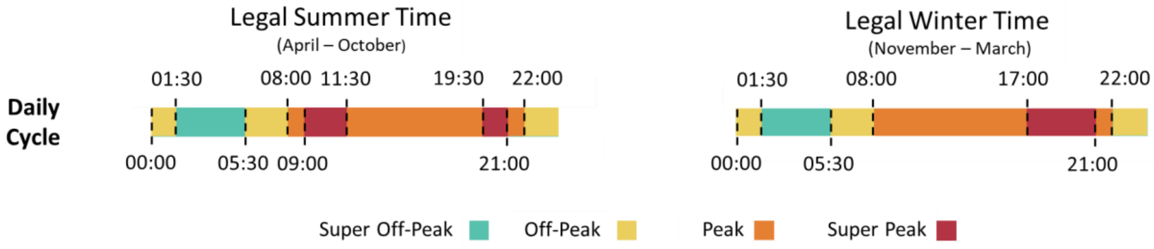


Figure 16 – Azorean electricity market daily cycle applicable to medium voltage clients

Electricity prices currently practiced for LREC's office building are summarized in Table 3 [14].

Table 3: LREC's office building electricity prices, by period

Price (€/kWh)	Period
0.1255	Super off-peak time
0.1363	Off-peak time
0.2315	Peak time
0.2922	Super peak time

It is worth stressing that, to incentivize grid service participation, the following electricity price variations were assumed:

- Wind curtailment mitigation – discount directly proportional to the otherwise curtailed wind power output, resulting in electricity prices ranging from 0.2 to 0.8 of the original electricity price;
- Consumption congestion management – compensation directly proportional to the SS usage rate, resulting in electricity prices ranging from 1 to 3 of the original electricity price when exporting energy back to the building or power grid;
- Generation congestion management – discount inversely proportional to the SS usage rate, resulting in electricity prices ranging from 0.2 to 0.8 of the original electricity price.

Figure 17 illustrates the assumed electricity price multiplier per time of day and grid service, based on SS usage rate and wind power output data for a whole year.

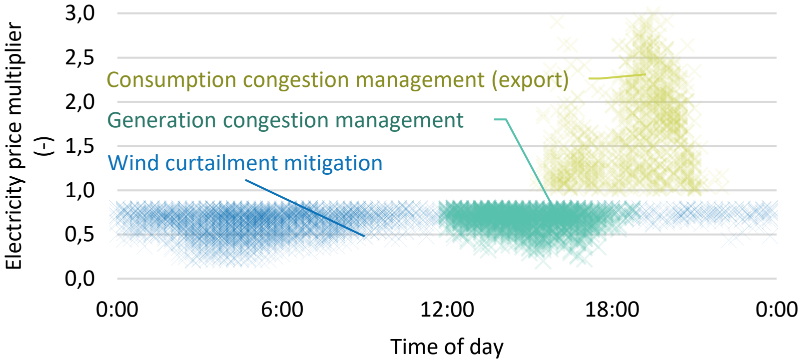


Figure 17 – Electricity price multiplier per time of day and grid service

4.2.1.5 Weather conditions

Concerning the weather conditions of Ponta Delgada, São Miguel Island, Azores, the dataset from D2.1 was directly transcribed.

In this regard, it is worth noting that LREC's office building encompasses a meteorological station, which may in the future prove useful to acquire more up-to-date and accurate weather conditions at the building's site.

4.2.2 Methodology

The decision-making model in Figure 18 will be implemented within LREC's office building. The model comprises three main modules, namely: (i) forecast; (ii) daily planning; (iii) and real time operation.

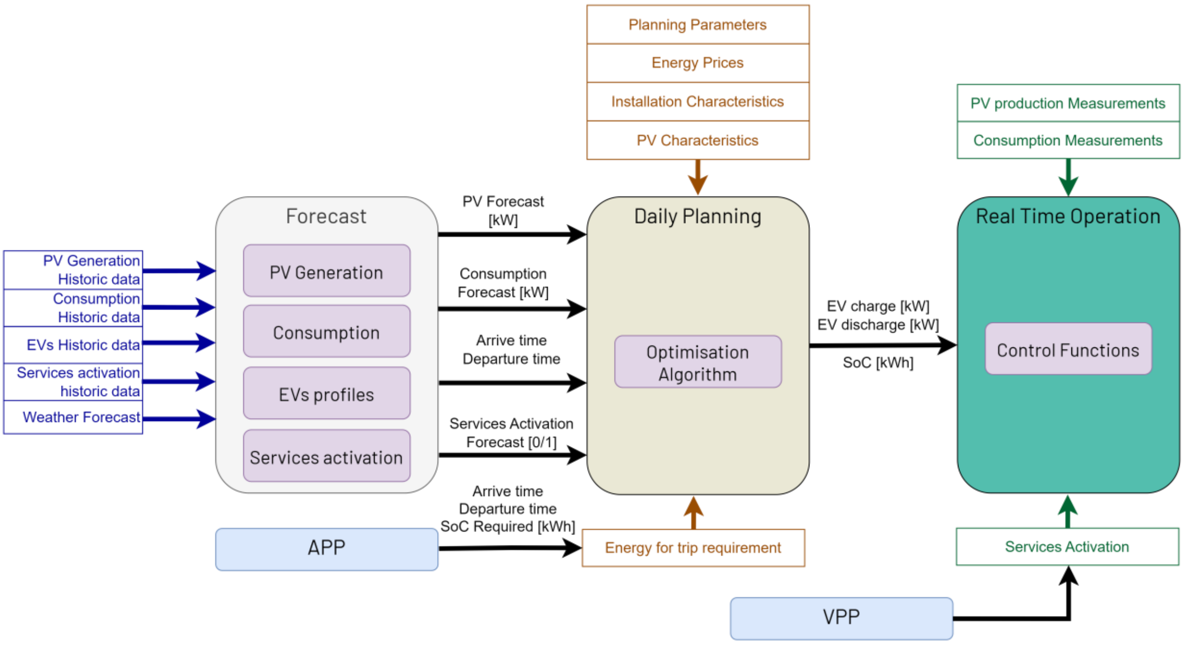


Figure 18 – Architecture of the decision-making model to be implemented within LREC's office building

The forecast module uses historical data related to solar PV power output, energy consumption, EV usage behaviour, grid service activation, electricity market pricing, and weather conditions. Resorting to this information, the forecast module can generate day-ahead data that will feed the optimisation algorithm in the daily planning module. The daily planning module, based on an optimisation algorithm, is responsible for conceiving a strategy which coordinates the charging and discharging actions within two charging points of the same charging station to fulfil one of three control objectives, namely: (i) minimizing the overall cost of operation of LREC's office building; (ii) maximizing self-consumption; or (iii) maximizing grid service participation. The real time operation module is fed by the daily planning module's resulting strategy and resorts to real-time data to control the EV charging and discharging cycle according to previously made decisions, to either satisfy the load of LREC's office building or export surplus energy to the power grid.

The creation of the proposed decision-making model encompassed the development of three distinct EV control methods, namely: (i) charge; (ii) discharge; and (iii) export (Figure 19). These methods stipulate instructions meant to define the optimal period to respectively charge or discharge the EVs, considering each EV's SoC ($E_{ev,t}^{SOC}$), LREC's office building load (P_t^L) and solar PV power output (P_t^{PV}), as well as each EV user's interest in exporting energy to the power grid, at time t. The charge method defines how much of each EVs' charging power ($P_{ev,t}^{EVch}$) originates from the power grid ($P_t^{fromgrid}$) and solar PV system (P_t^{fromPV}), at time t. The discharge method defines how much of LREC's office building load is fed with power from the power grid, solar PV system and the EVs (P_t^{fromEV}), at time t. The export method verifies if each EV user is interested in exporting energy to the power grid and defines how much power each EV exports to the power grid ($P_{ev,t}^{gridfromEV}$), according to the total power exported by the EVs (P_t^{export}), solar PV power output and solar PV power injection to both LREC and the EVs (P_t^{PVused}), at time t.

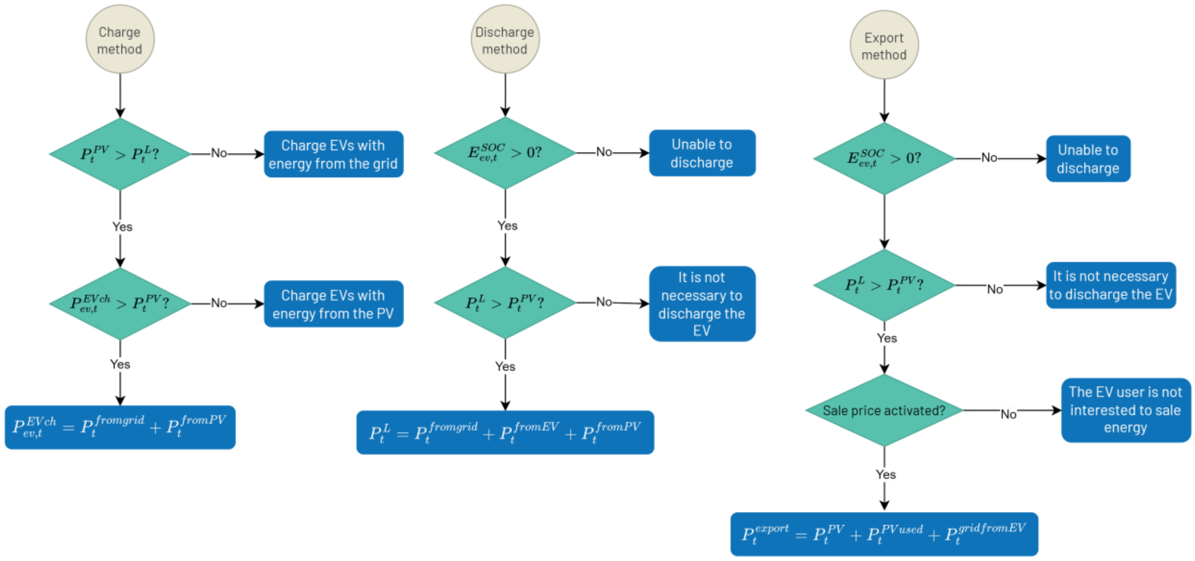


Figure 19 – Charge (left), discharge (centre) and export (right) methods

4.2.2.1 Forecast Module

The forecast module comprises 5 stages, namely: (i) inputs; (ii) pre-processing; (iii) feature engineering; (iv) model implementation; and (v) validation (Figure 20). In the context of the simulation of the proposed decision-making model, the forecast period corresponds to one month per season (21-05-

2019 to 21-06-2019 for spring, 23-08-2019 to 23-09-2019 for summer, 21-11-2019 to 21-12-2019 for autumn, and 20-02-2019 to 20-03-2019 for winter).

In the pre-processing stage, weather data was integrated, while missing values and data outliers were handled. In the feature engineering stage, lag and date/time features were created. In the model implementation stage, a Random Forest algorithm was developed to acquire accurate day-ahead predictions. In the validation stage, the module's performance was assessed using normalized root mean square error and R^2, while outputs were saved as csv files.

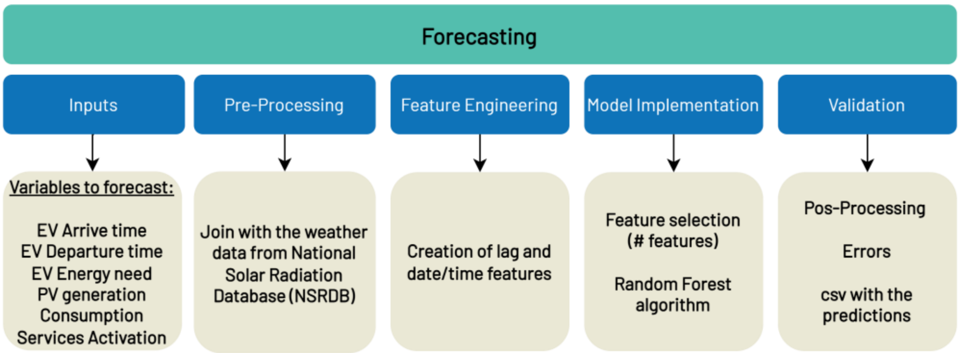


Figure 20 – Forecast module diagram

4.2.2.2 Daily Planning Module

The daily planning module, based on an optimisation algorithm, is an implementation of a mixed integer linear programming framework, using the CPLEX solver from IBM. The proposed model is highly configurable, making it possible to indicate whether to use V2B, or if dynamic pricing tariffs should be considered. At the core of the optimisation algorithm is the OF.

$$OF = \min(cost\ system + relax) \tag{8}$$

$$cost\ system = \sum_{t=1}^{T} (P_t^{import} . \Delta_t . price_t^{buy} . ps_t^{buy} - P_t^{export} . \Delta_t . price_t^{sell} . ps_t^{sell}) \tag{9}$$

$$relax = \sum_{ev=1}^{EV} \sum_{t=1}^{T} (P_{ev,t}^{curtrelax} . \Delta_t . penalty_t + P_{ev,t}^{genrelax} . \Delta_t . penalty_t + P_{ev,t}^{consrelax} . \Delta_t . penalty_t) \tag{10}$$

P_t^{import} and P_t^{export} indicate, respectively, the power imported/exported from/to the power grid, while $price_t^{buy}$ and $price_t^{sell}$ represent, respectively, the energy import/export price from/to the power grid, at time t. $P_{ev,t}^{curtrelax}$, $P_{ev,t}^{genrelax}$, and $P_{ev,t}^{consrelax}$ respectively indicate the relaxation variables associated with wind curtailment mitigation, generation congestion management, and consumption congestion management services, for a particular EV, at time t. $penalty_t$ indicates an economic penalty for the non-participation in a grid service, at time t. Δ_t indicates the simulation's time step, while T indicates the simulation's total duration and EV indicates the amount of considered EVs (in this case, two EVs were considered, since there are two charging points at LREC's office building).

Within the OF, grid service participation is deemed to be voluntary, and grid services are activated via a price signal sent by the electrical system operator, where ps_t^{buy} is a price signal related to the purchase of electricity and ps_t^{sell} is a price signal related to the sale of electricity. These price signals impact the OF once grid services are activated, as indicated below:

$$ps_t^{buy} = \begin{cases} 1, & if\ no\ grid\ services\ are\ activated \\ \leq 1, & if\ wind\ curtailment\ mitigation\ or\ generation \\ & congestion\ management\ is\ activated \end{cases}$$

$$ps_t^{sell} = \begin{cases} 1, if\ consumption\ \ congestion\ management\ is\ not\ activated \\ \geq 1, \quad if\ consumption\ congestion\ management\ is\ activated \end{cases}$$

Hence, in the case of excessive energy consumption within the electrical system, the sale price of energy exported to the power grid will increase, whereas, in the case of excessive energy production within the electrical system, the purchase price of energy exported to the power grid or the building will decrease. Therefore, EV users may or may not be interested in participating in grid services based on the discount and incentive.

Note the optimisation problem is subject to constraints related to EV operation, EV and system energy balance, grid service participation, and grid operation. The constraints related to grid service participation are shown below:

$$P_{ev,t}^{EVch} = P_{ev,t}^{ch} - P_{ev,t}^{curtrelax}, \ \forall ev, t\colon \alpha_t^{curt} = 1\ \&\ ps_t^{buy} \leq th_t^{d} \tag{11}$$

$$P_{ev,t}^{EVch} = P_{ev,t}^{ch} - P_{ev,t}^{genrelax}, \ \forall ev, t\colon \alpha_t^{gen} = 1\ \&\ ps_t^{buy} \leq th_t^{d} \tag{12}$$

$$P_{ev,t}^{EVdch} = P_{ev,t}^{dch} - P_{ev,t}^{consrelax}, \ \forall ev, t\colon \alpha_t^{cons} = 1\ \&\ ps_t^{sell} \geq th_t^{i} \tag{13}$$

$$P_{ev,t}^{EVdch} = 0, \ \forall ev, t\colon \alpha_t^{curt} = 1\ \&\ ps_t^{buy} \leq th_t^{d} \tag{14}$$

$$P_{ev,t}^{EVdch} = 0, \ \forall ev, t\colon \alpha_t^{gen} = 1\ \&\ ps_t^{buy} \leq th_t^{d} \tag{15}$$

$$P_{ev,t}^{EVch} - P_{ev,t}^{congrelax} = 0, \ \forall ev, t\colon \alpha_t^{cong} = 1\ \&\ ps_t^{sell} \geq th_t^{i} \tag{16}$$

In which, $P_{ev,t}^{ch}$ and $P_{ev,t}^{dch}$ are the charge and discharge power rate of the charging station, respectively. $P_{ev,t}^{EVdch}$ is the EV discharging power rate. th_t^{d} and th_t^{i} are the EV user's respective thresholds for the electricity price discount and incentive associated with grid service activation. When equal to 1, α_t^{curt}, α_t^{gen} and α_t^{cons} indicate the activation of wind curtailment mitigation, generation congestion management, and consumption congestion management services, respectively.

4.2.2.3 Real Time Operation Module

To ensure all plausible real time operation instructions are contemplated, forecast results were worsened by 10%: the solar PV power output was considered to be 90% of the forecasted, energy consumption was considered to be 110% of the forecasted, trips were considered to start one hour earlier than what was forecasted.

The real time operation module can yield four distinct instructions: to initiate any one of the three previously mentioned methods (illustrated in Figure 19), or to remain idle. Note that, while the daily planning module resorts to a digital twin of a charging station, the real time operation module calls upon a real charging station for that effect. In this sense, the simulation of the decision-making model carried out uses pre-defined real time operation data. Also, note that the real time operation module (Figure 21) verifies whether or not the EV is connected, given the possibility of error in this regard at the hand of the forecast module.

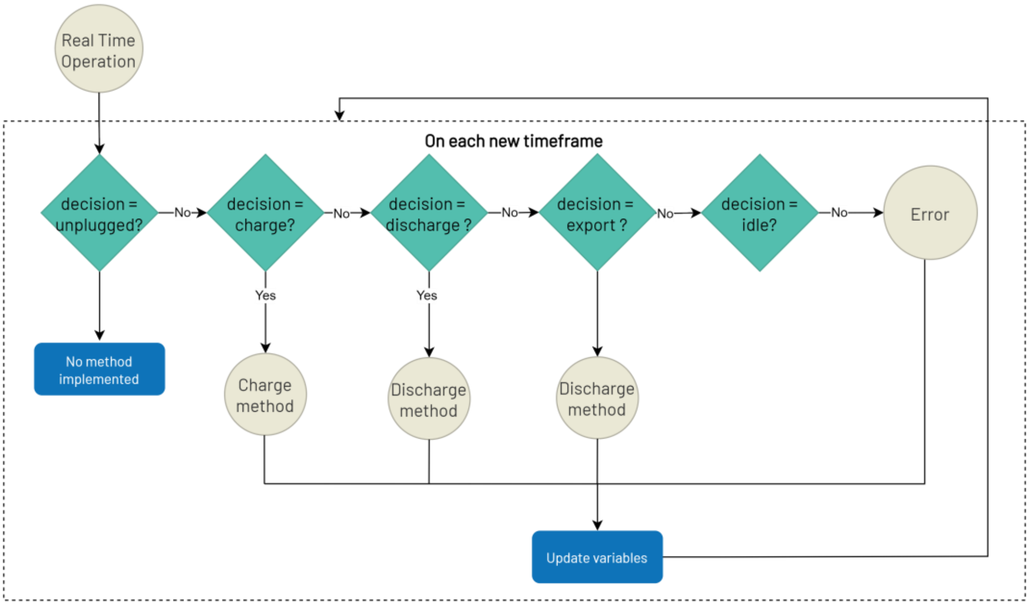


Figure 21 – Real time operation module diagram

5 Simulation results

This section presents some preliminary simulation results to illustrate some key features of the proposed V2X control strategies for integrating EV charging in buildings. Subsection 5.1 presents results for the Danish site and subsection 5.2 for the Portuguese site. Both subsections are structured such that first a description of the test scenarios is presented, followed by the presentation of the test results and a discussion of the main findings.

5.1 Danish site

5.1.1 Test scenarios description

A set of test scenarios are simulated for the DK site, and a summary is presented in Table 4. The scenarios are split between limited and unlimited connection. The purpose behind this distinction is to evaluate the impact of a limited grid connection of the EV chargers. By assigning a very large grid connection value (equal to the total installed capacity of all chargers), it is possible for all chargers to be used at the same time at full capacity.

Next, a distinction is made for the used control strategy when charging the EVs.

- Uncontrolled charging refers to the case where EVs charge at full capacity until their charging needs are satisfied. If the total charging power exceeds the grid connection, then power is reduced proportionally to alleviate congestion. This control strategy serves as a lower-bound benchmark, as a simple and easy to implement strategy.
- Smart charging (oracle) refers to the case where EV charging is done by minimizing energy costs via rolling-horizon optimisation, but assuming that the future PV and building load demand are perfectly known. This allows for taking the optimal control actions and optimally utilizing the flexibility of EV charging. This strategy serves as an upper-bound benchmark, as it will provide the best key performance indicator (KPIs), however, it is an unrealistic case.
- Smart charging (forecasts) refers to the case where the future PV and building load demand are unknown and forecasts are used. This is a realistic case and better represents how EV charging would be handled in a real setup. For these case studies a simple persistence forecast is considered (weekly for the building load and daily for the PV generation). More advanced methods will be tested during the demonstrations.

Table 4: Overview and naming of test scenarios for DK site

	Uncontrolled charging	Smart charging (oracle)	Smart charging (forecasts)
Unlimited connection	DC – UL	SCO – UL	SCF – UL
Limited connection (43 kW)	DC – L	SCO – L	SCF – L

The parameters used in the simulation are listed in Table 5.

Table 5: Summary of simulation parameters

Parameter	Value
Resolution [min]	15
Look-ahead optimisation horizon [hours]	24
Simulation period	May 1st 2022 – July 31st 2022
Value of non-served kWh in charging session [€ /kWh]	10

At the time of writing the deliverable the EV chargers at Campus Bornholm were not yet installed; therefore, relevant data was not available. As a temporary solution, EV data from a workplace parking lot provided by the Danish CPO Spirii was used [16]. The parking lot is located in Copenhagen, Denmark, and consists of 10 charging outlets. The simulation period covers May, June and July of the year 2022. PV and building consumption data from Campus Bornholm was used.

Denmark is split into two price zones: DK1 (Western Denmark) and DK2 (Eastern Denmark). Hourly spot prices from the Danish price zone DK2 (where Bornholm is located) are used. Customers receive the spot price when exporting energy to the grid, but pay various taxes and fees when importing energy. *Note that commercial customers are not subjected to taxes or VAT, in contrast to residential customers.* This makes the ratio of importing/exporting prices considerably lower. Below in Figure 22 the spot prices and fees imposed on imports are shown for the simulation period.

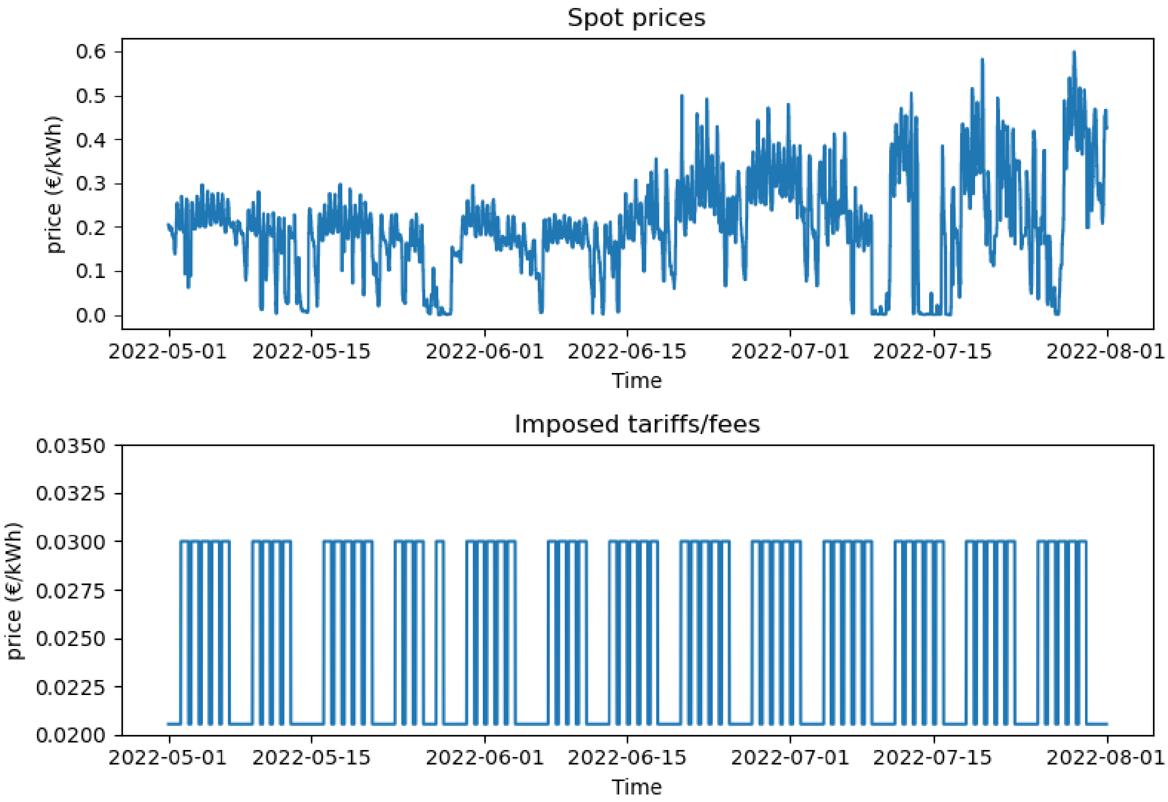


Figure 22 – Spot prices and imposed fees during the simulation period.

A small fee of 0.00358 €/kWh (0.358 cents/kWh) is imposed on self-consumed PV production. In Figure 23 the building's consumption and PV generation are shown.

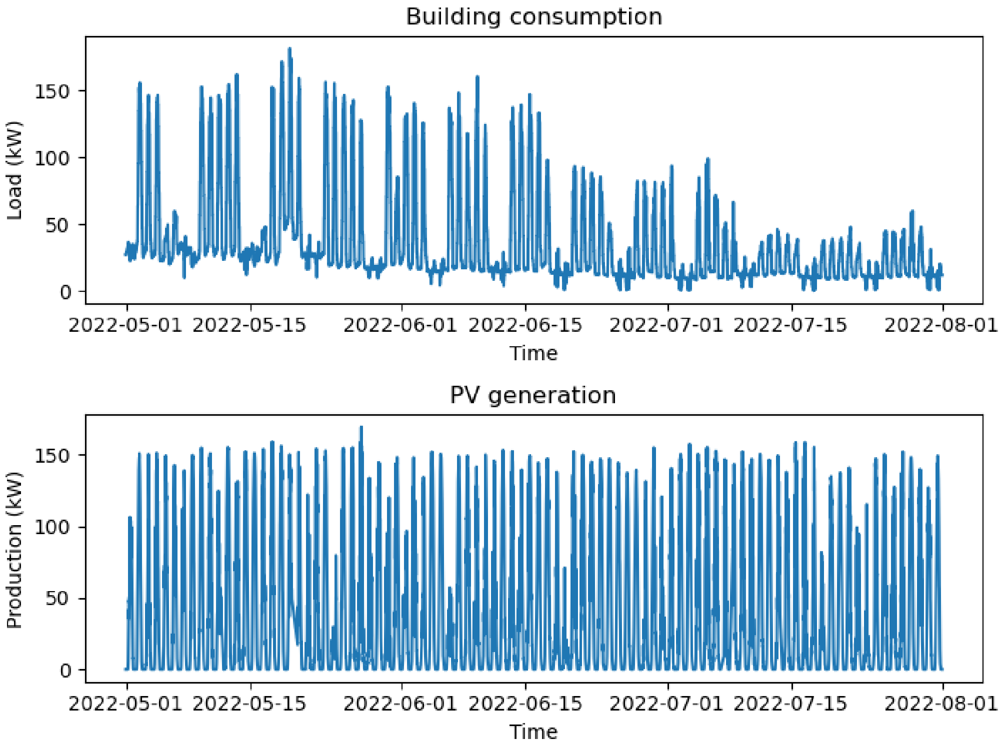


Figure 23 – Building consumption and PV generation during the simulation period.

5.1.2 Test results

The 6 different scenarios described in subsection 5.1.1 were simulated and key performance metrics are presented in Table 6. Additionally, the baseline scenario was simulated, in which EV charging is neglected. The following metrics are presented to evaluate the different scenarios:

- Energy imports over the period in MWh
- Energy exports over the period in MWh
- Charged EV energy over the period in MWh
- Self-consumed energy over the period in as %. This refers to the energy produced by the PV system and directly consumed by the building or the EVs, divided by the total PV production
- Self sufficiency over the period as a percentage. This metric reflects the share of the load (both building and EV load) supplied by local production. 0% means that all load was served through imports, and 100% means that all load was served by local production and none from imports
- Cost in euros over the simulated period
- Max EV load in kW

Table 6: Summary of key metrics for the considered scenarios

Scenario	Import (MWh)	Export (MWh)	Charged energy to EVs (MWh)	Self-consumption (%)	Self-sufficiency (%)	Cost (€)	Max EV load (kW)
DC – UL	34.2	36.2	6.2	51.7	53.4	2070	91.2
DC – L	34	36	6.2	51.9	53.6	2060	43
SCO – UL	33.6	35.5	6.2	52.5	54.2	1562	99
SCO – L	33.5	35.5	6.2	52.5	54.2	1566	43
SCF – UL	34	36	6.2	51.9	53.6	1573	99
SCF – L	34	35.9	6.2	52	53.7	1575	43
Baseline	30.8	39.8	-	55.5	61.8	827	-

The first thing to note is that the total EV demand (6.2 MWh) is rather low compared to the building load, which is equal to 80 MWh. Adding uncontrolled charging (DC – UL scenario) increases energy imports by 3.4 MWh and decreases exports by an almost equal amount, compared to the Baseline scenario. The effect on self-consumption is rather small, decreasing it by 3.8 percentage points, while the effect on self-sufficiency is greater, leading to a reduction of 8.4 points. However, there is a notable increase change in cost from 827 in the baseline scenario to 2070 euros for uncontrolled charging. Imposing a line capacity limit of 43 kW has a negligible effect on all metrics, with the notable exception of lowering the EV charging peak from 91 kW to 43 kW.

Results do not vary considerably in the other 4 scenarios, which are all based on optimisation. The impact may seem marginal for most metrics, compared to uncontrolled charging. Indeed, max loading is equal to 99 kW without a line limit, while it is kept at 43 kW when the line limit is imposed. As expected, the oracle case produces slightly better results than the case where actual forecasts are used. However, this difference is rather small on all 4 metrics.

Nevertheless, introducing a more advanced control approach based on optimisation leads to a significant reduction in cost, of approximately 500 euros across all 4 scenarios, compared to uncontrolled charging. This is a rather large improvement, as the additional cost of 1240 euros is reduced to 730 euros, leading to a cost reduction of 500 euros. What is interesting to note is that using simple persistence forecasts has practically no impact on performance, and a near-optimal cost in the considered case study can be achieved using persistence. This means that load/PV uncertainty has no noticeable effect and leads to no deterioration of control performance. This finding will be further tested during the demonstrations.

5.2 Portuguese site

5.2.1 Test scenarios description

In the Portuguese site's case, the scenarios for the simulation of the forecast and daily planning modules of the decision-making model are split according to a wide array of parameters, namely:

- Control strategy:
    - Uncontrolled charging refers to the case where EVs charge at the charger's nominal power until a SoC of 100%, while not discharging. This control strategy serves as a lower-bound benchmark, due to its implementation simplicity;
    - Optimisation-based smart charging refers to the case where EVs charge at a rate in accordance with the OF in (1), while not discharging. This is a realistic case representing how EV unidirectional charging would be handled in a real setup;
    - Optimisation-based V2B refers to the case where EVs charge and discharge at rates in accordance with the OF in (1). This is a realistic case representing how EV bidirectional charging would be handled in a real setup.
- PV power output – 0 (i.e., no solar PV production), 10, 15 or 20 kWp;
- Grid service participation –active (EV users accept grid service participation requests when a certain electricity price threshold is overcome) or inactive (EV users never accept grid service participation requests). In the case of active grid service participation, the electricity price threshold defining EV user grid service participation may be: (i) low – EV users accept grid service participation requests if the electricity price multiplier is lower than 1 for energy consumption and higher than 1 for energy export; (ii) high – EV users accept grid service participation requests if the electricity price multiplier is lower than 0.6 for energy consumption and higher than 1.5 for energy export.
- Energy export – active or inactive;

Table 7 displays the behavioural, technical, and economic parameters underpinning the reference case scenario for the simulation of the forecast and daily planning modules of the decision-making model.

Table 7: Parameterisation of the reference case (simulation scenario #1)

Control strategy	Fleet worker EV usage behavioural pattern	PV power output	Grid service participation	Energy export
V2B	Heavy usage	15 kWp	Inactive	Inactive

Table 8 displays the remaining scenarios for the simulation of the forecast and daily planning modules of the decision-making model, detailing, for each scenario, how parameterisation is altered compared to Table 7.

Table 8: Decision-making model's simulation scenarios

Cluster	#	Description
Reference case	1	See Table 7
Control strategy	2	Smart charging
	3	Uncontrolled charging
PV power output	4	0 kWp (no solar PV production)
	5	10 kWp
	6	20 kWp
Grid service participation and energy export	7	Active grid service participation with a low electricity price threshold
	8	Active grid service participation with a low electricity price threshold Active energy export
	9	Active grid service participation with a high electricity price threshold Active energy export

It is worth mentioning that, in the case of simulation scenario #8, participating in consumption congestion management grid services does not result in any energy export to the power grid, but solely in discharging actions from the EV to the building, to reduce the building's load demand and therefore mitigate congestion issues at the SS's level.

Important parameters are pre-defined and common to all simulation scenarios. These are listed below (Table 9).

Table 9: Summary of pre-defined parameters common to all simulation scenarios

Parameter	Value
Simulation's time step	15 min
Simulation's total duration	January 1st, 2019 – December 31st, 2019
PV power output and building load demand forecast horizon	24 h
Network tariff structure	Tetra-hourly (see Table 3)
Building contracted power ($\overline{\boldsymbol{P}}_{\boldsymbol{C}}$)	116,25 kVA
Building yearly energy consumption	113,066 kWh
Overall efficiency of the EV and charger system (η)	94.09 %
EV battery capacity ($\overline{\boldsymbol{E}}_{\boldsymbol{EV}}$)	40 kWh
Maximum charger charge power ($\overline{\boldsymbol{P}}_{\boldsymbol{CS}}^{\boldsymbol{CH}}$)	7.4 kW
Maximum charger discharge power ($\overline{\boldsymbol{P}}_{\boldsymbol{CS}}^{\boldsymbol{DCH}}$)	7.4 kW

Three main criteria were considered to evaluate the performance of the forecast and daily planning modules of the decision-making model, namely: (i) cost per unit of energy consumed; (ii) energy exchange between the PV system, building, EV, and power grid; and (iii) number of accepted grid service participation requests.

5.2.2 Test results

Figure 24 and Figure 25 illustrate the results for the simulation of the proposed decision-making model under scenario #1 for a few selected days during summer and autumn (autumn was selected instead of winter since it better portrays the model's V2B capabilities), respectively.

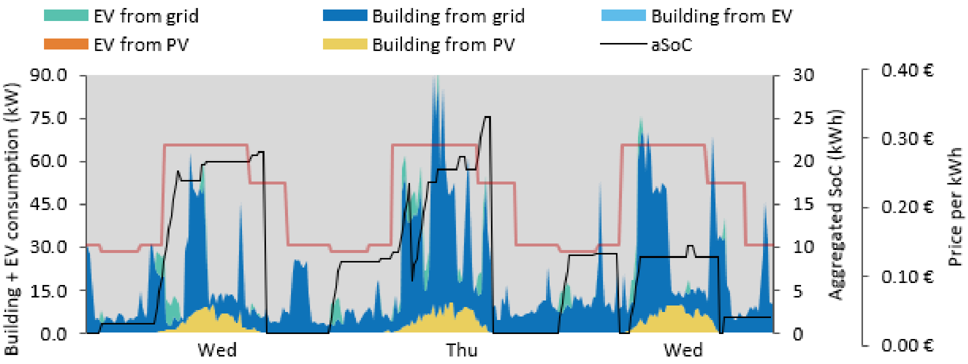


Figure 24 – Summer daily results for scenario #1

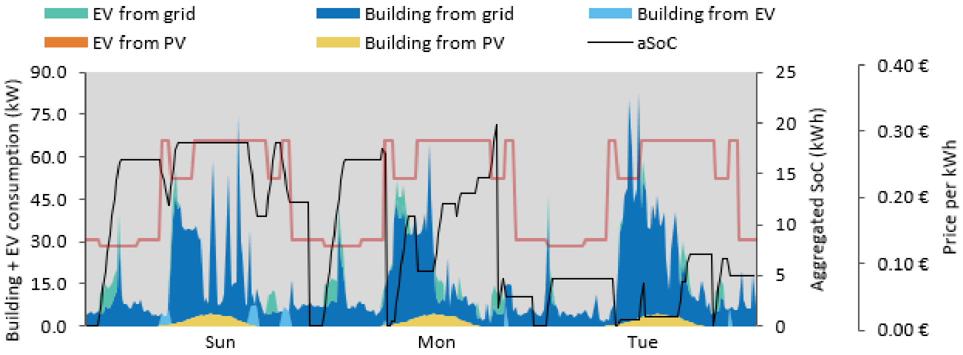


Figure 25 – Autumn daily results for scenario #1

Note that, contrary to the households' case study, the decision-making model does not frequently opt to perform V2X actions. In fact, the yearly total energy discharged from the EVs to LREC's office building was about 157 kWh, representing a contribution of around 0.15% to the building's energy consumption. This is so given the following factors:

- The proposed decision-making model was devised in a SoC agnostic manner with an aggregated SoC (aSoC) equal to the energy cumulatively charged within the charging station. In practical terms, this design alternative implies that an EV must always be charged at least as much as it is discharged, ultimately lowering the SoC boundaries within which V2B actions may be carried out;

- Both charging points exhibit a high utilisation churn rate. In this manner, charging sessions are frequently not long enough to allow for the execution of V2B actions;
- Since LREC’s office building solar PV power generation is typically below its energy consumption baseline, almost no solar PV excess energy can be leveraged to carry out V2B actions;

- The only EVs charging during the night period, when electricity prices are low, are those belonging to LREC’s fleet (commonly charging during super off-peak times to meet their energy requirements), which are typically disconnected during the day (this is observable via the average cost per kWh consumed by the EVs, which is around 0.28€ for visitors and office workers, and around 0.135€ for fleet workers). In this manner, electricity price differences are not frequently leveraged to carry out V2B actions.

Additionally, observing Figure 24 and Figure 25, it is possible to infer the decision-making model is severely restrained when optimizing the EV energy consumption cost, due to charging station utilisation occurring primarily during the day, when electricity prices are high. It is worth stressing that, during the early morning, the aSoC rises as EVs initiate their charging sessions, while a significant drop in the aSoC means an EV has finalized its charging session. Moreover, the charging profile of EVs belonging to office workers is performed in a manner that minimises imports from the power grid, via coordination with the building’s load (see Thursday during the day, within Figure 24).

Another takeaway from the analysis of Figure 24 and Figure 25 corresponds to the distinction between EV charging requirements according to different seasons. Overall, energy requirements are higher in summer than in autumn, mainly due to higher building energy consumption. However, during autumn, the building’s solar PV production to load demand ratio is higher than during summer, meaning the EVs are more prone to charge with solar PV energy and, thus, V2B actions are more frequent (note the decision-making model schedules the discharging of energy to the building during super peak times).

Figure 26 illustrates the cost relative to the V2B (#1), smart charging (#2), and uncontrolled charging (#3) control strategies.

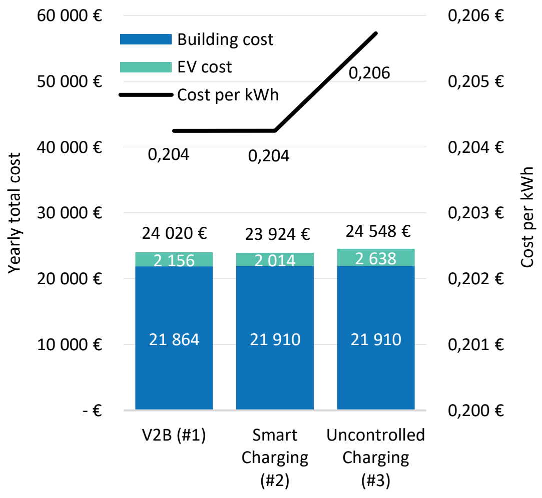


Figure 26 – Total annual energy cost for different control strategies - scenarios #1, #2 and #3

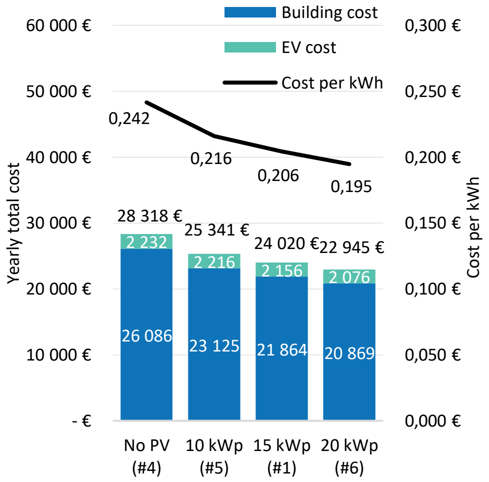


Figure 27 – Total annual energy cost for different solar PV installations - scenarios #1, #4, #5 and #6

Comparing the V2B (#1) and smart charging (#2) control strategies, note that, despite the latter resulting in an almost identical (slightly higher) cost per kWh consumed (the observed difference is extremely small since V2B actions rarely occur – a contribution of only 0,15% to the total building energy consumption), it exhibits a yearly total cost reduction of about 96€, that is, 0.40%, in comparison to the former. This discrepancy arises from the fact that scenario #2 depicts a lesser magnitude of energy exchange compared to scenario #1. This variation could be attributed to potential approximations and rounding applied to the calculated data, given that the estimated annual costs encompass diverse seasonal outcomes with short simulation periods (1 month per season).

In comparison to the uncontrolled charging control strategy (#3), the V2B control strategy (#1) exhibits a yearly total cost reduction of about 528€, that is, 2.15%.

Figure 27 illustrates the cost relative to the absence of a solar PV system (#4), as well as to the existence of a 10 kWp solar PV system (#5), a 15 kWp solar PV system (#1), and a 20 kWp solar PV system (#6).

In comparison to the absence of a solar PV system (#4), LREC's office building current 15 kWp solar PV system (#1) results in yearly total cost savings of around 4299€, in spite of EV charging accounting for only 606 kWh, which amounts to about 3.74% of the total solar PV energy generated. As expected, most of the solar PV production is absorbed by the building's self-consumption. On this subject, in the respective case of the 10 kWp (#5) and 20 kWp (#6) solar PV systems, around 1.82% and 5.49% of the total solar PV energy generated is employed to charge the EVs. As observable in Figure 27, the sizing of the solar PV installation can impact the cost per kWh consumed by the EVs, namely for visitors and workers. The yearly EV charging costs of visitors and office workers amounted to around 1630€ and 1560€ for scenarios #1 and #6, respectively. In the context of fleet charging costs, additional solar capacity exhibits negligible influence. This observation is consistent with the energy discharged into the building, where minimal to no impact is observable. This outcome stems from the unavailability of fleet vehicles to facilitate the load shift from inexpensive solar PV periods to high-cost ToU periods.

Regarding grid services, three distinct scenarios were examined based on service compensations and the user's price threshold. In the first scenario (#7), the user actively engages in requests with a low-price threshold (0% discount), and with no energy sale. The second scenario is very similar, but sales occur (with no extra incentive). Finally, the third scenario features both sales and the user setting a high price threshold for engagement in grid services (40% discount on energy consumption and a 50% increase in the energy sale price).

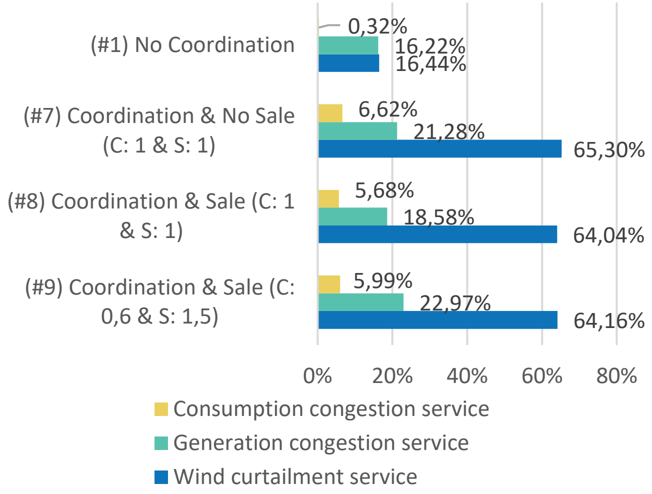


Figure 28 – Participation level in grid services

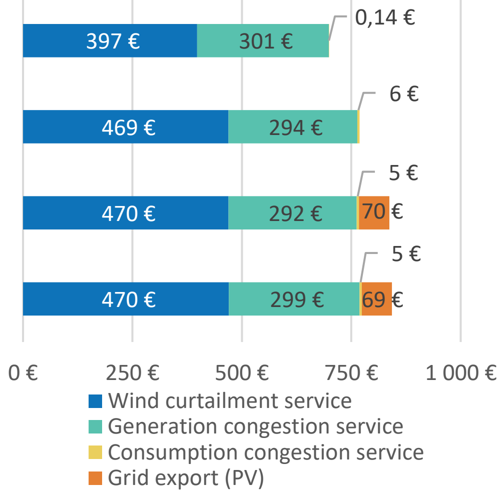


Figure 29 – Annual cost reductions by participating in grid services

Engagement in grid services offers the potential for additional revenue generation as presented in Figure 29. In the standard scenario without coordination, it becomes evident that participation rates are modest (Figure 29). Regarding the generation congestion management and wind curtailment mitigation services, the user participates in approximately 16% of the total requests. In contrast, non-coordinated participation in the consumption congestion service remains relatively minimal. This is largely attributed to the infrequent occurrence of V2B services by EVs during high demand peaks in the grid (7 to 9pm), compounded by limited EV availability and reduced building consumption as occupants are typically at home during this period.

Through effective coordination of EVs with grid requirements (scenario #7), these figures experience a significant increase, particularly in the context of wind curtailment mitigation and consumption congestion management services. Notably, the wind curtailment mitigation service emerges as that of most frequent participation, primarily attributed to the Fleet EV night downtime, which coincides with lower energy prices. Regarding the consumption congestion management service, a dual incentive structure is established. Firstly, it mitigates building consumption during high-priced electricity periods, and secondly, the additional energy discharged by the EV into the building secures further compensation. While the participation level remains moderate, given the aforementioned factors, the engagement rate surges from below 1% to over 6% participation.

Conversely, the change in the participation level between scenarios #1 and #7 within generation congestion management services remains modest. This outcome is largely attributed to the prevailing consumption patterns that predominantly occur during daylight hours, limiting the optimisation potential for vehicles. Furthermore, daytime periods often coincide with higher electricity rates, causing available compensations to be less economically attractive.

With the introduction of energy sale, a notable observation emerges in this case study: engagement in grid services yields a very slight reduction in the total savings, losing its appeal. The underlying rational behind this shift lies in the algorithm's objective to export PV energy as a strategy for minimizing the overall annual cost. By summing every compensation, in scenario #7 (no sale), the potential yearly cost reduction can reach 769€ (equivalent to 3.2% of the total annual cost), while in scenario #8 (with sale), the potential discount can escalate to 837€ (representing 3.5% of the total annual cost), due to the extra income by PV energy export to the grid.

An interesting phenomenon arises when users adopt a more selective approach when participating in grid services. The selectivity in participating in these services narrows down the available options, which seems to lead to a slightly higher cost reduction. This is particularly evident in generation congestion in which such discounts are more frequently and easily implemented in the load profile of the building. Nevertheless, this pattern is not observed in the other grid services, which can indicate that this result is specific to the present configuration of variables.

In conclusion, the findings presented in this study highlight the significant influence of the input variables on the observed outcomes. It is crucial to approach the conclusions with a certain level of caution, understanding that the results are intricately related with the specific parameters implemented. Despite these results, the most fruitful aspect of this work lies in the validation and calibration of the decision-making algorithm. The model's adaptability and modularity in simulating complex scenarios fitted for real-world application is particularly important for deployment in the Portuguese building demonstrator on São Miguel Island in the Azores. This validation and calibration process not only develops the understanding of the main control strategies and objective functions but also bridges the gap between the theoretical modelling and the demonstrator setup.

6 Conclusions and recommendations

This deliverable presented V2X control algorithms and concepts for integration in buildings with PV production. Only some preliminary conclusions can be drawn because the EV charging points were not installed during the execution of this task, and thus the relevant data was not available.

The Danish site comprises an educational institution, a large PV plant, and 12 charging points. The proposed control approach relies on a forecasting-assisted rolling-horizon optimisation method. The goal of the controller is to minimize energy costs while maintaining the total EV loading below a prescribed limit. The main objective of the simulations was to examine the better of smart charging and investigate the added benefit of more complicated forecasting methods.

While the total EV demand in the case study was low compared to the total building load (6.2 MWh vs 80 MWh), there was a notable increase in cost from 827 euros to 2070 euros when uncontrolled charging was assumed. Introducing an optimisation-based smart charging costs were reduced by approximately 500 euros, i.e., the additional cost due to EV charging fell from 1240 euros (uncontrolled case) to 730 euros (optimisation based). Imposing a line capacity limit of 43 kW has a negligible effect on costs, lowering the EV charging peak from 91 kW to 43 kW. Interestingly, using simple persistence forecasts has practically no impact on performance and a near-optimal cost in the considered case study can be achieved. This means that load/PV uncertainty has no noticeable effect and leads to no deterioration of control performance.

The preliminary results (i.e., the negligible impact of the line capacity limitation, the benefit of smart charging and the near-optimal performance when using persistence forecasting) need to be validated in the demonstrations under WP9. More specifically, recent consumption and PV data, together with actual EV data from Campus Bornholm, will be used. It will then be possible to examine whether the use of simple persistence forecasts leads to any noticeable performance deterioration. If that's the case, it will be a valuable learning that can lead to simpler deployment of V2X control strategies in buildings without any additional overhead. If a significant performance deterioration is observed, then simple to implement and with minimal requirements forecasting algorithms will be tested. It is important to stress though, that using real EV charging data from the demonstrator site will provide more realistic results and concrete conclusions. Finally, focus will be given on how the accuracy of user input with regards to energy needs affects the control objectives. As discussed in section 2, many users may be unfamiliar with the energy or SoC readings and may request an amount of energy that is higher than what the EV can charge with. It is interesting to examine how robust the control method is to such discrepancies.

Regarding the Portuguese site, the Regional Laboratory of Civil Engineering (LREC) serves as a proving ground for the exploration of charging control strategies: uncontrolled charging; optimisation-based smart charging; and optimisation-based V2B. The developed decision-making algorithm presents several modules, namely forecasting, daily planning optimisation, and real-time operation. The model coordinates the charging and discharging process by dynamically adjusting charging and discharging power based on forecasts of solar PV power production and building load demand while considering grid service participation as a voluntary contribution.

The main takeaway from the LREC building case study is that the effect on cost reduction is relatively limited when considering just one station with two charging points, whose charging sessions account for about 10% of the entire building's energy consumption.

Moreover, in the Portuguese case study, optimisation techniques have limited potential due to various constraints that restrict the algorithm's effectiveness. Most of the charging activity occurs during the daytime, which leaves less flexibility for visitors and workers with fixed timeframes during this higher energy cost periods. This situation is compounded by the fact that the solar PV system's impact on EV charging is minor since the system's installed power does not meet the building's energy consumption baseline for most periods. As a result, uncontrolled EV charging draws only 4% of its energy from PV generation, and even smart EV charging only slightly improves this figure, raising it to 6%. Overall, in the case of the LREC's building, a two-charging point station with uncoordinated charging control averages around 26 c€/kWh in cost, while the application of smart charging techniques can reduce this value to approximately 20 c€/kWh. This reduction is notably influenced by the tariff structure but serves as an illustrative example of the capabilities of the decision-making algorithm. On a practical level, the disparity between uncontrolled charging and smart charging techniques at LREC's building is reflected on potential savings of up to 600€ per year. As for V2B strategies, the unavailability of vehicles capable of balancing energy from low-cost to high-cost periods, combined with limited surplus energy from the solar PV installation, results in reduction of around 0.15% to the overall building energy consumption. However, with the introduction of multiple charging points, more building owned EVs, and expanded solar PV capacity, this figure could see a significant increase.

Regarding grid services, active participation holds additional revenue opportunities for users, alongside advantages for energy providers. While uncoordinated grid services present minimal benefits, coordination can leverage their potential, namely, when considering services aimed at mitigating wind curtailment. In the span of a year, the charging station at LREC's building could accommodate roughly 1MWh of otherwise wasted energy through such services.

In conclusion, these remarks serve as a catalyst for the development of a more detailed and tailored testing environment. These important insights gained from the development and validation of both algorithms underscore the critical importance of testing and refining these control strategies within real operational settings.

7 References

[1] J. Mateus *et al.*, “Deliverable D2.1, Control Strategies for V2X Integration in Houses." Ref. Ares(2023)4563356. Electric Vehicles Management for carbon neutrality in Europe (EV4EU) Horizon Europe funded project, grant agreement 101056765, submitted.

[2] H. Morais *et al.*, “Deliverable D1.1: Electric Road Mobility Evolution Scenarios,” Ref. Ares(2023)193473. Electric Vehicles Management for carbon neutrality in Europe (EV4EU) Horizon Europe funded project, grant agreement 101056765, 2023. Available online: https://ev4eu.eu/resources/, 2023.

[3] P. Pediaditis *et al.*, “Deliverable D1.3, Regulatory opportunities and barriers for V2X deployment in Europe,” Ref. Ares(2023)2413208. Electric Vehicles Management for carbon neutrality in Europe (EV4EU) Horizon Europe funded project, grant agreement 101056765. Available online: https://ev4eu.eu/resources/, 2023.

[4] M. Zajc *et al.*, “Deliverable D1.4: Business models centred in the V2X value chain,”. Ref. Ares(2023)2360646. Electric Vehicles Management for carbon neutrality in Europe (EV4EU) Horizon Europe funded project, grant agreement 101056765. Available online: https://ev4eu.eu/resources/, 2023.

[5] H. Morais *et al.*, “D1.5: V2X Use-Cases Repository." Ref. Ares(2023) 4414917. Electric Vehicles Management for carbon neutrality in Europe (EV4EU) Horizon Europe funded project, grant agreement 101056765, submitted.

[6] C. Rocha *et al.*, “EV Users’ Needs and Concerns - Preliminary Report.” Ref. Ares(2023)3047151. Electric Vehicles Management for carbon neutrality in Europe (EV4EU) Horizon Europe funded project, grant agreement 101056765, 2023.

[7] J. Nielsen, “https://www.nngroup.com/articles/ten-usability-heuristics/,” [Online].

[8] Kaluza, “What’s next for vehicle to everything? Learnings from the world’s leading program,” https://info.kaluza.com/whats-next-for-vehicle-to-everything, 2022.

[9] ACDC, “https://www.acdc-bornholm.eu/,” [Online].

[10] J. Engelhardt *et al.*, “Real-life demonstration of a hybrid EV fast charging station with reconfigurable battery technology enabling renewable-powered mobility,” in *18th Conference on Sustainable Development of Energy, Water and Environment Systems*, Dubrovnik, 2023.

[11] CPLEX, “‘IBM ILOG CPLEX Optimizer’. https://www.ibm.com/products/ilog-cplex-optimization-studio/cplex-optimizer (accessed May 17, 2023).,” [Online].

[12] C. Ziras *et al.*, “The effect of net metering methods on prosumer energy settlements,” *Sustainable Energy, Grids and Networks,* 100519, Volume 27, 2021.

[13] NREL, “https://nsrdb.nrel.gov/data-viewer,” [Online].

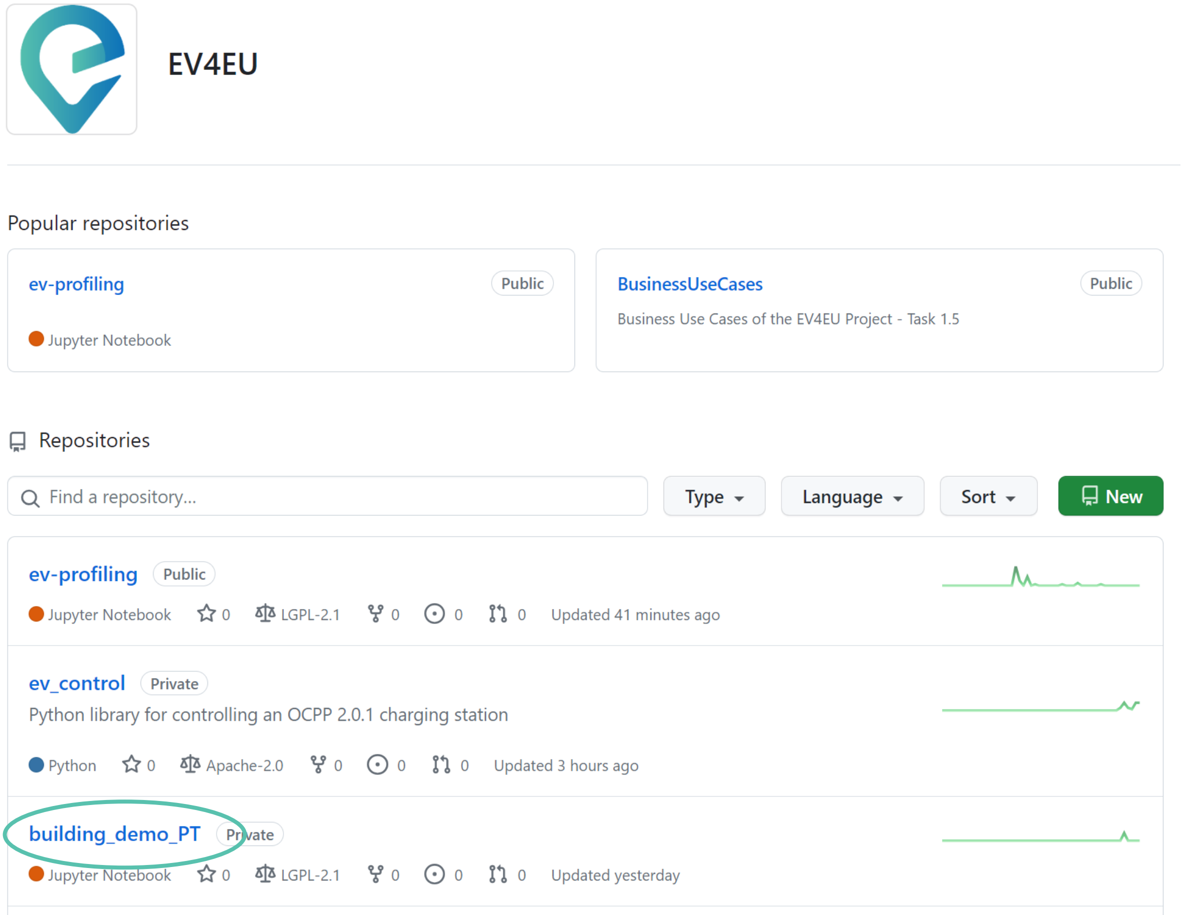
[14] ERSE - Entidade Reguladora dos Serviços Energéticos, “https://www.erse.pt/atividade/regulacao/tarifas-e-precos-eletricidade/#periodos-horarios,” [Online].

[15] P. D. A. SEGMA – Regional Civil Engineering Laboratory, “Energy certification report: Assessment of energy performance and identification of improvement measures in an existing service building (in portuguese),” 2023.

[16] Spirii, “https://spirii.com/en,” [Online].

Annex I – Decision-making model architecture for the Portuguese site

The source code of the decision-making model for the Portuguese site was developed and hosted on the GitHub tool. It is available in: EV4EU repository, as shown in Figure 30.



EV4EU

Popular repositories

ev-profiling Public
Jupyter Notebook

BusinessUseCases Public
Business Use Cases of the EV4EU Project - Task 1.5

Repositories

ev-profiling Public
Jupyter Notebook 0 LGPL-2.1 0 0 0 Updated 41 minutes ago

ev_control Private
Python library for controlling an OCPP 2.0.1 charging station
Python 0 Apache-2.0 0 0 0 Updated 3 hours ago

building_demo_PT Private
Jupyter Notebook 0 LGPL-2.1 0 0 0 Updated yesterday

Figure 30. Repository for the decision-making model's source code for the Portuguese site, in EV4EU´s GitHub

The repository includes the following folders and files:

- ".even.example" – template for how to create the paths necessary for the code
- ".gitignore" – indicates the file should not be sent to the repository;
- "README.md" – brief description of the simulators' functioning;
- "classes" – source code for the simulator's base implementation and specialisations, as well as other relevant files, such as the models for the functioning of the EVs and EV batteries;
- "_init_.py" – indicates the folder is a Python package;
- "ev_sim.ipynb" – carried out examples and test cases, as well as simple visualisations;
- "requirements.txt" – description of the libraries used;
- "scenarios2.2.json" – script with the characterisation of each scenario considered.
- "sim_testerD22.py" – script used for generating the simulation results.