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MASTER THESIS

From V1G to V2G: Optimization Strategies for Bidirectional EV Charging with Solar PV Integration

Da V1G a V2G: Strategie di Ottimizzazione per la Ricarica Bidirezionale dei Veicoli Elettrici con
Integrazione del Fotovoltaico

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ABSTRACT

The rapid growth of electric vehicles (EVs) worldwide has led to a significant increase in electricity consumption, placing new pressures on distribution networks and highlighting the need for intelligent and adaptive energy management strategies. As EV penetration continues to accelerate, smart control of charging behavior becomes essential to ensure grid reliability, minimize congestion, and optimize the use of renewable resources. Recent advancements introduced by the ISO 15118-20 standard, most notably the enablement of bidirectional charging, provide a foundation for vehicle-to-grid (V2G) applications, expanding the role of EVs from passive loads to active energy assets. This new capability is central to the objectives of SEED 2, a project developed at SeH, a Milan-based hardware and software company focused on innovative energy solutions. SEED 2 explores how standardized communication, smart scheduling, and bidirectional power flows can enhance EV integration and improve overall system efficiency. Despite the potential, networks must still contend with issues such as unpredictable load patterns, local congestion, and limitations in distribution infrastructure. This thesis investigates how EV chargers, equipped with smart optimization algorithms and ISO 15118-20 compliant features, can actively mitigate these challenges offering services such as load shifting, cost reduction, and peak shaving, ultimately demonstrating how advanced EV charging strategies can transform network problems into opportunities for greater flexibility and resilience.

Keywords: EV, grid reliability, congestion, renewable resources, V2G, efficiency, optimization, load shifting, cost reduction, peak shaving, grid support.

SUMMARY

This thesis investigates the techno-economic performance of three electric vehicle (EV) charging strategies within a residential photovoltaic (PV) self-consumption framework. The three models analyzed are:

1. **Uncontrolled Unidirectional Charging (V1G Uncontrolled)** – a baseline scenario in which EV charging occurs immediately upon connection without coordination.
2. **Controlled Unidirectional Charging (V1G Smart)** – a managed charging strategy that optimizes charging sessions based on PV generation and electricity pricing signals.
3. **Controlled Bidirectional Charging (V2G Smart)** – an advanced strategy enabling bidirectional power flow, allowing the EV battery to discharge energy back to the household or grid.

The comparative analysis demonstrates that Controlled Unidirectional Charging (V1G Smart) consistently outperforms Uncontrolled Unidirectional Charging (V1G Uncontrolled) across all evaluated metrics. V1G Smart delivers proportional improvements in energy efficiency, cost reduction, and PV investment optimization, with gains scaling directly with PV availability and charging flexibility.

Controlled Bidirectional Charging (V2G Smart) introduces additional capabilities that extend beyond V1G Smart. Beyond optimizing self-consumption, V2G Smart enables peak shaving by discharging during periods of high household demand, reducing peak load and associated demand charges. It also provides voltage fluctuation intervention, actively stabilizing grid voltage through by stabilizing power consumption. While V2G Smart yields only marginal gains over V1G Smart in certain scenarios it achieves substantially superior performance in contexts characterized by high electricity price volatility, unfavorable feed-in tariffs, or significant peak demand charges. These unique grid-supportive capabilities position V2G Smart as a strategically valuable solution that unlocks value streams unattainable through unidirectional control alone.

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LIST OF ABBREVIATIONS

V1G	Unidirectional Vehicle to Grid Energy Flow
V2G	Bidirectional Vehicle to Grid Energy Flow
PV	Photovoice
EV	Electric Vehicle
SoC	State of Charge
AC	Alternating Current
DC	Direct Current
CCS2	Combined Charging System Type 2
ISO	The International Organization for Standardization
IEC	The International Electrotechnical Commission
IGBT	Insulated-Gate Bipolar Transistor
SiC MOSFET	Silicon Carbon Metal-Oxide-Semiconductor Field-Effect Transistor
EVSE	Electric Vehicle Supply Equipment
EVCC	Electric Vehicle Communication Control
SECC	Supply Equipment Communication Control
CAN	Controller Area Network
OCPP	Open Charge Point Protocol
CMS	Central Management Systems
DERs	Distributed Energy Resources
DSOs	Distribute System Operators
TSOs	Transmission System Operators
ECUs	Energy Control Units
TLS	Transport Layer Security
ICT	Information and Communication Technology

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1 Introduction

1.1 Background and Motivation

The global transportation sector is undergoing a significant transformation, driven by the urgent need to decarbonize and lessen dependence on fossil fuels. A key component of this transition is the rapid adoption of electric vehicles (EVs), which is reshaping not only transportation but also the structure and operation of modern power systems. In 2024, global EV sales reached approximately 17 million units, accounting for about 25% of new car sales worldwide, with a remarkable year-on-year increase of 35% in early 2025 [1]. This upward trajectory suggests that by 2035, the global EV fleet could exceed 840 million vehicles, collectively imposing a substantial new load on electricity grids [2].

Focusing on the Milanese context, it is pertinent to evaluate the power capacity of the EV fleet in relation to the existing generation and distribution infrastructure. Milan and its surrounding province encompass about 1.3 million households, with peak electricity demand in the city center reaching approximately 1.2 GW during winter months [3]. The local distribution network, managed by Unareti, is designed to accommodate gradual load growth; however, it is increasingly strained by the concentration of EV adoption in urban and suburban areas [4].

Lombardy, the region surrounding Milan, leads Italy in EV adoption, representing over 20% of the national fleet. With Italy aiming for 6 million EVs on the road by 2030, Lombardy alone is expected to host around 1.2 million EVs [5]. Each vehicle, typically equipped with a 50–75 kWh battery, serves as both a significant load and a valuable storage asset. When charging concurrently at a standard rate of 7 kW per vehicle, one million EVs would impose a load of 7 GW, exceeding the peak demand of Milan by nearly six times and surpassing the combined output of all thermal and hydroelectric generation capacity in Lombardy [6].

This analysis underscores the potential impact of uncoordinated EV charging on the local grid infrastructure. In a densely populated urban setting like Milan, where distribution network constraints are already prevalent, simultaneous charging of thousands of EVs during peak hours poses risks of

overloading feeders, increasing voltage deviations, and necessitating costly infrastructure upgrades. These challenges highlight the urgent need for intelligent charging strategies tailored to the specific constraints and opportunities within the Milanese energy landscape.

1.2 Problem Statement

Energy exists in one of two states: it is either stored or consumed. Every moment that a storage unit remains idle represents a missed opportunity to extract value; whether through self-consumption of on-site generation, price arbitrage, or grid support. The accelerating adoption of EVs introduces a major increase in the demand profile, transforming millions of vehicles from passive assets into significant grid loads. When charging occurs without coordination, these loads aggregate into sharp peaks that strain distribution networks, increase operational costs, and risk exceeding infrastructure capacity. The central problem, therefore, is how to manage this growing fleet of mobile storage assets to mitigate grid stress while maximizing economic and operational value.

1.3 Bidirectional Charging as a Solution

Bidirectional charging, commonly referred to as vehicle-to-grid (V2G), offers a standard shift in how EVs interact with the power system. To appreciate its significance, it is useful to contrast the fundamental characteristics of conventional generation technologies with those of battery-based systems.

A combustion engine operates on a fundamentally different principle: fuel must be consumed to produce power, with response times constrained by mechanical inertia, ramp rates, and thermal dynamics. Once fuel is combusted, the energy is permanently lost. Nuclear power plants, while providing reliable baseload generation, require hours or even days to adjust output, making them inherently inflexible in responding to rapid demand fluctuations.

Battery systems, in contrast, are inherently controllable and responsive. They can transition from charging to discharging in milliseconds, offering a dynamic range of operation that centralized generators cannot match. A lithium-ion battery is a dispatchable storage asset that can absorb energy when supply exceeds demand and release it when demand surpasses supply. This bidirectional capability transforms

the EV from a mere load into a distributed energy resource capable of providing grid services (peak shaving, voltage regulation, frequency response) while simultaneously delivering economic value to the vehicle owner.

The relevance of such capabilities is underscored by Italy's recent experience with grid instability. In August 2023, a storm caused transmission line failures in Sardinia, triggering the automatic disconnection of the SAPEI undersea interconnector linking Sardinia to central Italy. The sudden loss of approximately 1,000 MW of power flow caused a frequency drop on the mainland [7], forcing the transmission system operator to activate automatic load shedding that left thousands of households without electricity across central and southern Italy. This event illustrates how a localized disturbance can propagate through interconnected infrastructure, exposing the vulnerability of centralized grids.

Bidirectional charging offers a pathway to mitigate such phenomena. A distributed fleet of V2G-enabled EVs can function as decentralized frequency reserves, providing instantaneous power injection during underfrequency events. Aggregated EV batteries can respond within seconds, far faster than conventional generators, to arrest frequency decline before it triggers load shedding or cascading failures. Moreover, during grid disturbances, V2G-equipped vehicles can sustain critical household loads, transforming homes into resilient microgrids. By enabling bidirectional power flows, V2G technology empowers prosumers to become active participants in grid stability, reducing both the likelihood and the impact of future blackouts.

1.4 Objectives and Contributions

This research investigates the integration of a bidirectional electric vehicle (EV) charger with an existing photovoltaic (PV) system and an industrial load. The PV plant consists of 464 panels with a total installed capacity of 116kWp, Figure 1.1, while the load is represented by the historical energy consumption of an industrial facility over the past year. These real-world generation and consumption profiles are used to accurately evaluate the potential benefits enabled by the SEED 2 framework.



Figure 1.1: Google Maps Photo of the Industry

To conduct this assessment, three charger control models are implemented:

- **Traditional Charging**

The first model is a basic unidirectional charger whose sole objective is to charge the EV battery to its maximum state of charge as quickly as possible, with no regard for energy prices or grid conditions. This serves as a reference case.

- **Smart Unidirectional Charging (V1G)**

The second model introduces smart unidirectional charging. The charger monitors both PV production and the load profile, then executes an optimization that minimizes energy costs while ensuring user satisfaction by balancing economic savings with an acceptable final state of charge.

- **Bidirectional Charging (V2G)**

The third model implements a fully bidirectional charger, capable of both charging and discharging the EV battery. This model continuously evaluates grid conditions, PV availability, the load profile, and battery state of charge to determine the optimal energy flow. By leveraging

bidirectional flexibility, it maximizes system efficiency and provides the highest potential benefit to both the grid and the user.

The primary contribution of this work lies in the quantitative comparison of these three control strategies using real data. By evaluating their performance across key metrics such as energy cost, self-consumption rate, grid dependency, and user satisfaction, this research provides actionable insights into the value of bidirectional charging for industrial prosumers equipped with on-site PV generation.

2 Power Grid Behavior and Challenges

2.1 Traditional Power Grid Architecture

The traditional power grid operates on a fundamental principle: generation must always equal demand at all times. This balance is maintained by centralized power plants (coal, gas, nuclear, and hydroelectric facilities) that dispatch energy based on real-time consumption forecasts, Figure 2.1. The grid is designed as a unidirectional system: power flows from large-scale generators through transmission networks, then distribution networks, and finally to end-users. This top-down architecture assumes predictable load patterns and centralized control, with limited visibility into customer-side behavior. Any imbalance between generation and demand results in frequency deviations (e.g., $50 \text{ Hz} \pm \text{tolerance}$), which can trigger automatic load shedding or, in extreme cases, cascading blackouts.

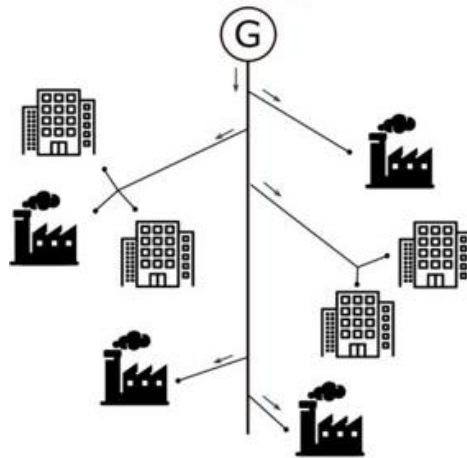


Figure 2.1: Traditional Power Grid Behavior

2.2 Load Characteristics and Demand Variability

Electricity demand is inherently variable, fluctuating on timescales ranging from seconds to seasons. Residential load profiles typically exhibit two daily peaks (morning (07:00–09:00) and evening (18:00–21:00)) driven by lighting, cooking, heating, and appliance usage. Industrial and commercial loads follow different patterns, often peaking during working hours.

The integration of photovoltaic (PV) generation worsens the mismatch between production and consumption. Solar generation peaks at midday, when residential demand is often at its lowest (occupants

are at work or school). Conversely, the evening peak in demand occurs after sunset, when PV output is zero. This temporal decoupling forces grid operators to rely on conventional generators to ramp up rapidly as the sun sets, creating the classic "duck curve" phenomenon, Figure 2.2. In regions with high PV penetration, excess solar energy during midday may be curtailed or exported at low prices, while evening imports occur at peak tariffs illustrating how renewable generation does not automatically align with consumption patterns.

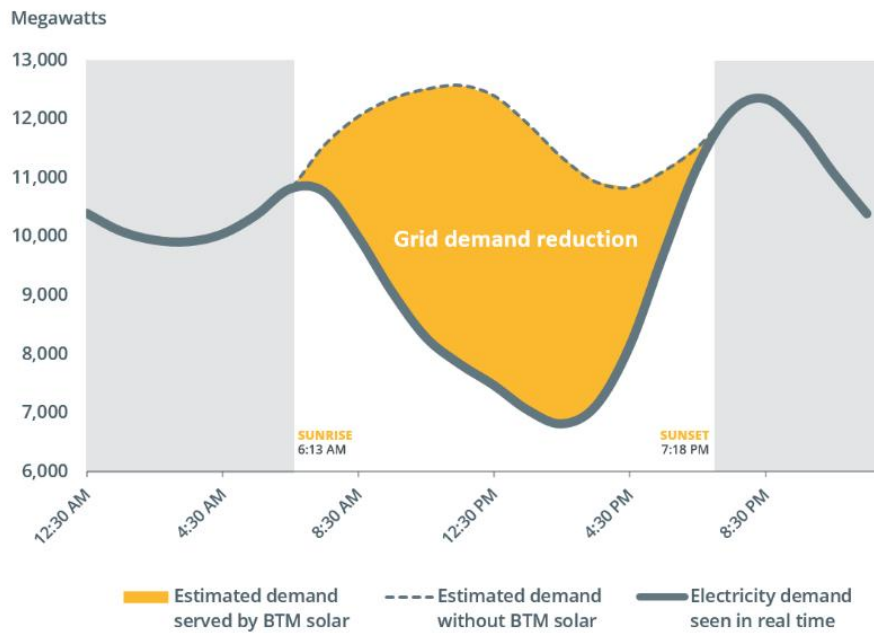


Figure 2.2: Duck Curve

2.3 Impact of Mass EV Integration on Distribution Networks

The mass adoption of EVs introduces a significant new load onto distribution networks that were not designed for such high, concentrated demand. A single EV charging at 7 kW to 22kW draws power equivalent to approximately three to nine households. When hundreds or thousands of EVs charge simultaneously during evening hours, coinciding with the existing residential peak; the cumulative effect can overwhelm local infrastructure.

2.3.1 Voltage Deviations

Distribution networks are designed to maintain voltage within specified limits. When high currents flow through line impedances, voltage drops occur along the feeder. Uncoordinated EV charging increases these currents, causing voltage at the end of long feeders to fall below acceptable levels. Under-voltage can cause equipment malfunction, increased losses, and irritation tripping of protective devices. Contrariwise, during periods of low demand and high PV generation, voltage may rise above limits, potentially damaging sensitive electronics.

2.3.2 Transformer Overloading

Distribution transformers are sized based on anticipated peak demand, with built-in thermal limits. A standard residential transformer serving 10–20 homes might be rated for 50–100 kVA. The addition of several EVs charging simultaneously at 7–22 kW can push the transformer beyond its rating. Sustained overloading accelerates insulation aging, reduces transformer lifespan, and can lead to thermal failure, particularly during summer months when ambient temperatures are high and cooling is least effective.

2.3.3 Network Congestion

Beyond individual transformers, network congestion refers to situations where the aggregate demand on a feeder or substation exceeds its rated capacity. This can occur even if no single component is overloaded. Congestion forces grid operators to limit demand or invest in infrastructure upgrades, adding new substations, or reinforcing transmission corridors. These upgrades require years of planning and significant capital expenditure, often passed to consumers through higher tariffs.

2.4 Limitations of Conventional Grid Operation

Conventional power grids were designed for a unidirectional power flow model: centralized generation (large power plants) transmits electricity to passive distribution networks, ending with consumption. While this model has served reliably for decades, it faces critical limitations when confronted with modern energy challenges.

2.4.1 Response Time

Conventional grids rely on slow, centralized control mechanisms. Generation adjustments at thermal or hydro plants take minutes to hours, and protection systems are designed for infrequent fault isolation, not real-time supply-demand balancing. This slow response makes the grid vulnerable to rapid fluctuations from variable renewable sources like solar and wind, forcing operators to maintain expensive spinning reserves to prevent instability.

2.4.2 Constant Increase in Load Demand

Global electricity demand continues to rise due to electrification of transport, heating, and industrial processes. In Italy, peak demand has exceeded 59 GW during heatwaves. Conventional grids, built with fixed capacity margins, require costly infrastructure upgrades, new transmission lines, substations, and transformers, to accommodate this growth. These upgrades face long permitting processes and public opposition, creating a bottleneck that delays electrification goals.

2.4.3 Lack of Visibility and Controllability at Distribution Level

Conventional distribution grids operate with limited real-time monitoring. Utilities often lack visibility into low-voltage networks where rooftop PV, EV chargers, and heat pumps are connected. This "blindness" prevents proactive management, forcing operators to apply conservative safety margins that underutilize existing capacity.

2.4.4 Unidirectional Power Flow Assumption

Traditional protection and control systems assume power flows only from higher to lower voltage levels. The proliferation of distributed generation (rooftop PV) creates reverse power flows, causing voltage rise, protection nuisance trips, and coordination challenges. This limitation directly impacts EV integration: a conventional grid cannot easily manage bidirectional charging without significant retrofitting.

3 Smart Grid Concept and Comparison

3.1 Definition and Key Features of the Smart Grid

A smart grid is an electricity network that uses digital communication, sensing, and control technologies to monitor and manage energy flows in real time, enabling bidirectional interaction between grid operators, consumers, and distributed energy resources, Figure 3.1.

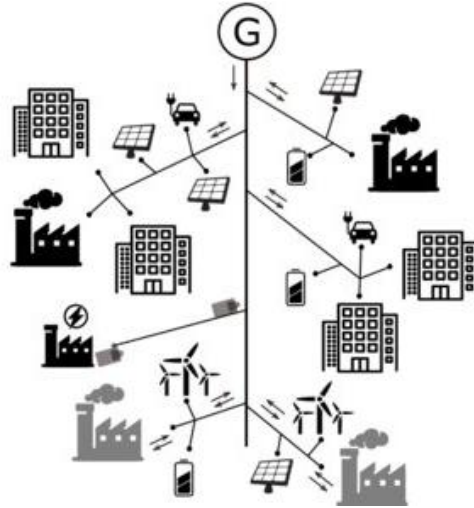


Figure 3.1: Smart Grid Behavior

Figure 3.2, highlights the real time grid demand prediction, against actual load measurement. Smart grid always attempts to match those two plots, to increase efficiency in production.

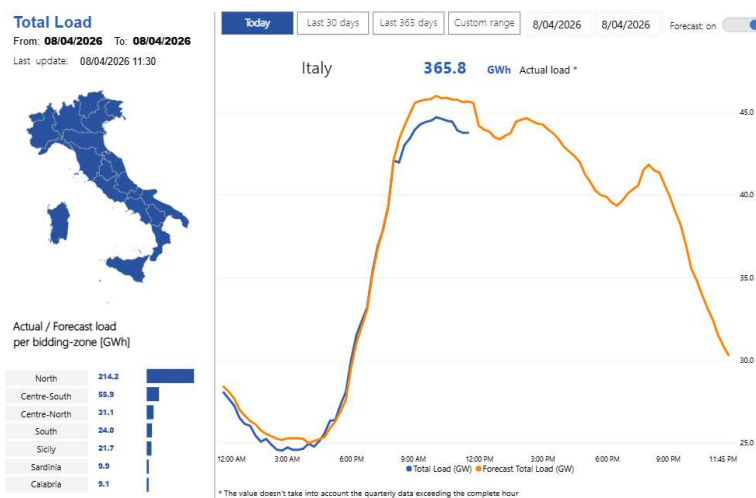


Figure 3.2: TERNA Real Time Energy Broadcast [12]

The European Commission defines the smart grid as "an electricity network that can intelligently integrate the actions of all users connected to it (generators, consumers, and those that do both) to efficiently deliver sustainable, economic, and secure electricity supplies.

Table 3.1: Conventional Grid vs. Smart Grid

Feature	Conventional Grid	Smart Grid
Power flow	Unidirectional (generation → consumer)	Bidirectional (prosumers, V2G)
Control	Centralized, slow response	Distributed, real-time
Monitoring	Limited (transmission only)	Widespread (including distribution)
Consumer role	Passive consumer	Active prosumer (produces, stores, sells)
Fault management	Manual restoration	Self-healing (automatic isolation and reconfiguration)
Integration of renewables	Limited by variability	Enhanced via forecasting and demand response
EV integration	Treated as additional load	Managed as flexible load and distributed storage

Table 3.1, summarizes the key features applications of smart grid against a conventional grid, and it's crucial to notice here that bidirectional technology is much more beneficial and active, in a smart grid power system or microgrid, to extract all the benefits in which it can deliver.

3.2 Role of ICT, Automation, and Distributed Energy Resources

3.2.1 Information and Communication Technology

ICT is the backbone of the smart grid, enabling real-time data exchange between grid operators, distributed energy resources, and end-users. Key components include:

- Advanced Metering Infrastructure
- Communication networks
- Data analytics platforms

ICT enables the ISO 15118 standard for EV charging, allowing secure communication between the EV and the charging station for Plug & Charge and V2G applications.

3.2.2 Automation

Automation transforms grid operation from reactive to proactive:

- Automatic fault detection, isolation, and restoration
- Voltage and reactive power control
- Demand response automation

3.2.3 Distributed Energy Resources

DERs are small-scale generation or storage units connected at distribution level:

Table 3.2: DERs Roles in a Smart Grid

DER Type	Examples	Smart Grid Role
Generation	Rooftop PV, small wind, micro-hydro	Reduce transmission losses; provide local voltage support
Storage	Behind-the-meter batteries, EV batteries	Absorb excess renewable generation; discharge during peaks
Flexible load	EV chargers, heat pumps, HVAC	Shift consumption to off-peak hours via demand response

The smart grid actively coordinates DERs through aggregators, which pool multiple small resources to participate in energy and ancillary service markets, Table 3.2.

3.3 EVs as Flexible Loads and Distributed Storage

3.3.1 The Dual Role of EVs

An EV connected to a smart charging station is no longer just a load, instead a flexible grid resource. Depending on the control strategy, the same EV can:

- Act as a flexible load: shift charging to off-peak hours or moments of high renewable generation
- Act as distributed storage: discharge stored energy back to the grid during peak demand or grid emergencies

3.3.2 Flexibility Parameters

The flexibility of an EV is summarized in Table 3.3:

Table 3.3: EV Flexibility Parameters

Parameter	Typical Range	Description
Available energy	30–100 kWh	Total storage capacity
Power rating	3.7–22 kW (AC); 50–350 kW (DC)	Charge/discharge rate
Availability window	Parking duration (hours to days)	Time during which the EV is connected
User-defined constraints	Minimum departure SoC (e.g., 80%)	Ensures mobility needs are met
Battery degradation limits	0.2–0.5C discharge rate	Preserves battery lifetime

To achieve an insightful simulation, in Chapter 9, the flexibility parameters were modified for each scenario to examine the behavior of the model in different cases and validate its benefits.

4 Smart Charging and Bidirectional Operation

Smart charging represents an evolution from traditional uncontrolled EV charging to actively managed charging schedules that align with grid conditions, electricity prices, and user needs. This section distinguishes between V1G (unidirectional smart charging) and V2X (bidirectional vehicle-to-everything) operation, establishing the foundation for the optimization model presented in Chapter 8.

V1G refers to controlled charging where power flows only from the grid to the vehicle, but the timing and rate of charging are modulated based on external signals. V2X extends this capability by enabling power flow in both directions, allowing the EV battery to supply energy back to the grid (V2G), to a home (V2H), to a building (V2B), or to other loads (V2L). While V1G can shift load to off-peak hours and reduce peak demand, V2X unlocks additional value streams including grid frequency regulation, peak shaving, backup power during outages, and revenue generation for EV owners.

4.1 V1G Smart Charging Concepts

4.1.1 Traditional Charging vs Smart Charging

Traditional charging begins immediately when the vehicle is plugged in and continues at maximum power until the battery reaches its target state of charge. This behavior creates several grid challenges. When multiple EVs charge simultaneously upon evening arrival, they produce a new peak load that coincides with existing residential evening peaks, potentially overloading transformers and feeders. Traditional charging also misses opportunities to absorb excess renewable generation during midday hours when solar production is highest.

V1G smart charging optimizes the timing and intensity of unidirectional energy flow from the grid to the EV battery. The fundamental principle is to delay or reduce charging during periods of high grid stress or high electricity prices, and concentrate charging during periods of low demand or high renewable generation. This approach requires no hardware changes beyond a controllable charger and communication link, making it the most accessible smart charging strategy.

4.1.2 User Constraints and Charging Optimization

User constraints define the boundaries within which any smart charging algorithm must operate. These constraints ensure that the charging process does not interfere with the user's mobility needs. The three primary constraints are:

- **Departure time**

The user specifies when the vehicle will next be used, typically the following morning for commuting. The charging schedule must guarantee that the battery reaches the target state of charge by this departure time. Unlike traditional charging which finishes as early as possible, smart charging can delay charging to the cheapest or most grid-friendly hours as long as the deadline is met.

- **Target state of charge**

The user may request a specific final state of charge, ranging from a minimum needed for the next trip to a full battery. Higher targets require more energy and may force earlier charging start times.

- **Minimum state of charge**

Users may impose a lower bound on battery level during the charging session, reserving energy for unexpected trips. For example, a user might require that the battery never drop below 20 percent, even if smart charging has not yet started. This constraint is particularly relevant for bidirectional operation.

The optimization problem for V1G smart charging can be stated as follows: given a set of charging intervals between plug-in time and departure time, with known electricity prices or grid signals over that horizon, determine the charging power at each interval that minimizes total energy cost while satisfying battery dynamics, power limits, and user-specified departure time and target state of charge.

When multiple EVs are managed simultaneously, the optimization becomes a coordination problem. The aggregator must allocate available grid capacity among vehicles while respecting individual

user constraints. This coordination is typically formulated as a constrained optimization problem minimizing total cost or peak load, with each EV contributing its flexible charging demand as a decision variable.

4.2 Vehicle-to-Grid (V2G) Operation

Vehicle-to-Grid (V2G) enables bidirectional energy flow where the EV battery can discharge stored energy back into the electricity grid. This transforms the EV from a flexible load into a distributed energy resource capable of providing grid services. V2G operation is built upon the same power electronics and communication infrastructure as smart charging, with the addition of bidirectional converter capability and extended communication protocols.

The value proposition of V2G rests on several grid services. Peak shaving uses EV batteries to supply power during periods of highest demand, reducing the load on transformers and feeders and potentially deferring infrastructure upgrades. Frequency regulation leverages the fast response time of battery inverters to correct grid frequency deviations, a service for which grid operators pay premiums. Spinning reserves keep EV capacity available to respond within minutes to unexpected generation or demand events. Renewable integration stores excess solar or wind generation during periods of overproduction and discharges during periods of low production.

From the EV owner's perspective, V2G generates revenue or reduces net energy costs. When electricity prices are high, discharging to the grid yields income at the selling price. When prices are low, charging replenishes the battery. The net effect is arbitrage: buy low, sell high. However, V2G introduces additional constraints beyond those in V1G.

Round-trip efficiency losses. Energy discharged to the grid must first be purchased and stored. With charging efficiency of 95 percent and discharging efficiency of 95 percent, the round-trip efficiency is approximately 90 percent. This means 10 percent of the energy is lost as heat, reducing the arbitrage profit margin.

Minimum state of charge for mobility. Unlike V1G which only adds energy, V2G removes energy from the battery. The control algorithm must guarantee that sufficient charge remains for the user's next trip. This is typically enforced through a minimum state of charge constraint, often set to 20 percent depending on user preferences.

The optimization for V2G follows the same structure as V1G but with bidirectional power variables. The objective remains cost minimization, but negative power (discharging) now contributes revenue. The power balance constraint includes both positive and negative grid power, with binary variables preventing simultaneous buying and selling as presented in Section 8.4.

4.3 Vehicle-to-Everything (V2X)

Vehicle-to-Everything (V2X) is an umbrella term encompassing all bidirectional applications where the EV supplies energy to external systems. While V2G focuses specifically on grid interaction, V2X includes V2H, V2B, and V2L. Each application has distinct technical requirements, economic drivers, and regulatory contexts.

4.3.1 Vehicle-to-Home (V2H)

Vehicle-to-Home (V2H) uses the EV battery to power a residential home, typically during periods of grid outage, high electricity prices, or peak demand. The EV connects to a bidirectional charger installed at the home, which includes an automatic transfer switch to isolate the home from the grid during islanded operation.

V2H offers several benefits. During power outages, the EV serves as a backup generator, providing power for lights, refrigeration, communication devices, medical equipment, and many other. A 59kWh battery can power a typical home for one to three days, depending on consumption. During peak tariff periods, V2H can supply the home's load, avoiding expensive grid electricity. For homes with rooftop solar, the EV can store excess daytime generation for evening use, increasing self-consumption and reducing grid dependence.

The primary limitation of V2H is that the vehicle must be present and connected when needed. If the EV is away during an outage, the backup function is unavailable. Additionally, most V2H systems require hardware upgrades including the bidirectional charger, transfer switch, and home energy management system.

4.3.2 Vehicle-to-Building (V2B)

Vehicle-to-Building (V2B) extends the V2H concept to commercial and industrial buildings. Multiple EVs connected to bidirectional chargers can collectively reduce a building's peak demand, lowering demand charges which often constitute a substantial portion of commercial electricity bills.

In a typical V2B installation, the building's energy management system coordinates EV charging and discharging to minimize the net load seen at the utility meter. During periods when building load approaches the demand charge threshold, EVs discharge to offset the excess. During low-demand periods, EVs recharge at lower energy rates. V2B does not require islanding capability, as the building remains grid-connected and the EVs simply reduce net import.

V2B is economically attractive for buildings with high demand charges, such as offices, retail centers, and industrial facilities. The value scales with fleet size.

4.3.3 Vehicle-to-Grid (V2G)

While V2G was introduced in Section 5.2, it is important to distinguish V2G from V2H and V2B. V2G refers to discharging to the grid, and local consumers depending on benefits. This distinction matters for regulation and metering. V2G exports energy past the utility meter, requiring bidirectional metering, export tariffs, and grid interconnection agreements. V2H and V2B operate behind the meter, avoiding these regulatory requirements but also missing the higher-value grid service markets, and operating only locally, without any intention to sell energy back to the grid.

Table 5.1: All Bidirectional Charging Technologies Summary

Application	Energy flow	Metering	Primary value	Hardware required
V2H	Home loads	Behind the meter	Backup power, tariff arbitrage	Bidirectional charger, transfer switch
V2B	Building loads	Behind the meter	Demand charge reduction	Bidirectional charger, BEMS integration
V2G	External grid	Past the meter	Grid service revenue (frequency regulation, peak shaving)	Bidirectional charger, bidirectional meter, grid agreement

This study adopted V2G technology, but it is important to note that the grid-level benefits of V2G implementation, such as frequency regulation, voltage fluctuation management, and power factor correction, were not fully addressed; since the model objective is to specifically reduce the monthly energy cost, without addressing unrewarding grid service. Instead, the focus was specifically on the user and the charging unit provider, advantages highlighted in Table 5.1.

4.4 Control Strategies for Bidirectional Charging

Bidirectional charging requires control strategies that manage the timing, direction, and magnitude of power flow while respecting both grid conditions and user constraints. Three primary control architectures exist: centralized, decentralized, and hierarchical.

4.4.1 Centralized Control

A single aggregator or grid operator computes optimal schedules for all connected EVs. This approach yields globally optimal solutions but requires complete information about all vehicles (state of charge, departure times, energy requirements) and reliable communication. The MILP model in Section 8.4 represents a centralized approach for a single EV, extensible to fleets. Centralized control is well-suited for V2G frequency regulation and peak shaving where coordination is essential.

4.4.2 Decentralized Control

Each EV makes local decisions based on price signals or grid conditions, without direct coordination with other vehicles. This approach scales to large numbers of EVs and is robust to

communication failures. However, decentralized control may produce suboptimal outcomes, such as simultaneous charging of all EVs at the start of a low-price period, creating a new peak. Decentralized control is commonly implemented using price-based mechanisms where EVs respond to real-time tariffs or grid frequency.

4.4.3 Hierarchical Control

This hybrid approach combines a central coordinator that issues aggregate targets or price signals, with local controllers that execute within their constraints. For example, a grid operator broadcasts a target load reduction for a feeder, and each EV decides locally how much to reduce charging or increase discharging. Hierarchical control balances optimality and scalability, making it suitable for most practical V2G deployments.

5 Network Services Enabled by Bidirectional EVs

Bidirectional EVs are not merely flexible loads but distributed energy resources capable of providing valuable services to the electricity grid. When aggregated in sufficient numbers, V2G-capable vehicles can support grid stability, reduce infrastructure costs, and enable higher penetration of renewable energy. This chapter examines the key network services that bidirectional EVs can deliver, from fast frequency response to long-term load leveling.

5.1 Peak Shaving and Load Leveling

Peak shaving refers to reducing electricity demand during periods of highest grid stress. Load leveling refers to flattening the overall demand profile by shifting consumption from peak to off-peak periods, Figure 5.1. Both services reduce the need for peaker plants, defer transmission and distribution upgrades, and lower wholesale electricity prices.

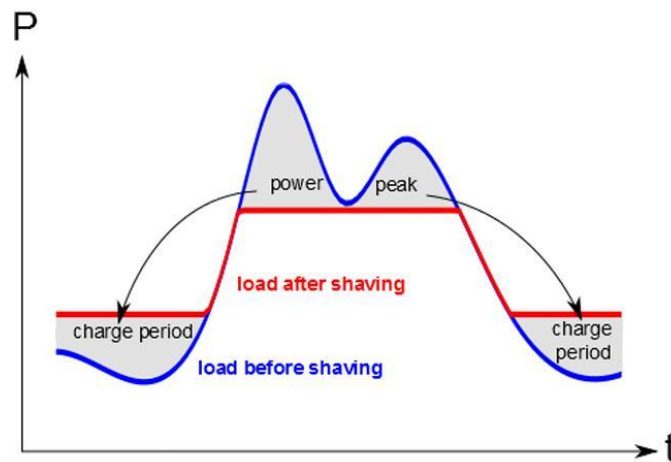


Figure 5.1: Load Before and After Shaving

Bidirectional EVs are uniquely suited for peak shaving because they can both shift charging to off-peak hours and discharge stored energy during peak hours. The combined effect is a reduction in net peak demand without compromising the mobility needs of EV owners.

5.2 Network Congestion Mitigation

Network congestion occurs when electricity demand exceeds the capacity of transmission or distribution lines, transformers, or substations. Congestion leads to voltage drops, thermal overloads, and, in extreme cases, equipment failure. Figure 5.2, highlights the large unpredictable rise in PV production mid-day, traditional solutions involve reinforcing the network (replacing cables, upgrading transformers), which requires significant cost and disruption.

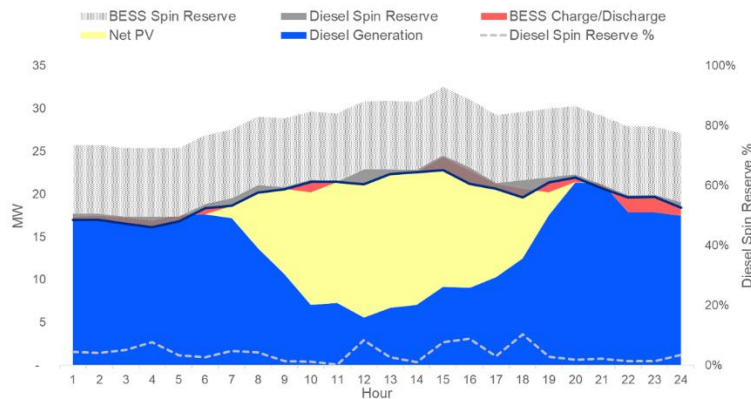


Figure 5.2: Power Generation by resource

Bidirectional EVs offer an alternative: localized congestion relief. When a specific feeder or transformer approaches its thermal limit, EVs connected downstream can reduce charging or begin discharging, effectively reducing the load seen by the congested asset. This response can be triggered automatically based on local voltage or current measurements, without requiring real-time communication with a central operator.

5.3 Voltage and Frequency Support

Voltage and frequency are the two fundamental measures of grid health. Bidirectional EVs can support both, though the mechanisms differ.

- **Voltage support**

Distribution networks experience voltage drops along feeders, particularly at peak demand. Low voltage can cause equipment malfunction, while high voltage can damage appliances. EVs can

support voltage through reactive power control (while charging) or active power injection (with discharging).

- **Frequency support**

Grid frequency is a system-wide variable; deviations indicate imbalance between total generation and total demand. EVs can provide frequency response by modulating charge/discharge power based on measured frequency.

5.4 Benefits for Grid Operators and Aggregators

The network services described above create distinct value streams for different market participants. Understanding these benefits clarifies the business case for bidirectional charging infrastructure.

1. **DSOs** are responsible for local network reliability. Their primary benefits from bidirectional EVs include:
 - Deferred or avoided infrastructure upgrades (transformers, cables, substations)
 - Reduced peak demand and congestion
 - Improved voltage profiles
 - Enhanced resilience during outages
 - Lower operating costs from reduced losses
2. **TSOs** manage the high-voltage grid and ancillary service markets. Their benefits include:
 - Access to fast, distributed frequency response
 - Reduced reliance on fossil-fuel peaker plants
 - Increased flexibility for renewable integration
 - Lower cost of procuring reserves
3. **Aggregators** act as intermediaries between EV owners and grid operators, pooling multiple EVs to meet minimum capacity requirements. Their benefits include:
 - Revenue from energy arbitrage (buy low, sell high)

- Payments for ancillary service provision
 - Fees from EV owners or grid operators
 - Data and software service revenue
4. **EV owners** receive payments or reduced charging costs in exchange for V2G participation.

Typical compensation models include:

- Fixed monthly payments for availability
- Per-kilowatt-hour payments for discharged energy
- Revenue sharing with aggregators
- Free or discounted charging

6 Implementation Challenges

6.1 Technical Challenges

Bidirectional chargers are more complex and expensive than unidirectional ones, additional power electronics and protection systems are required to safely manage energy flow in both directions. Communication standards between EVs, chargers, and grid operators are still developing, with diversity across different manufacturers [13]. Real-time coordination of thousands of distributed batteries demands low-latency, and cybersecurity-hardened networks.

6.2 Economic and Regulatory Challenges

Economically, the high upfront cost of bidirectional chargers and the need for upgraded grid connections deter widespread adoption without clear revenue models. Utilities and regulators must establish tariffs, metering, and compensation frameworks that fairly value V2G services, to both motivate manufacturers to invest developing bidirectional chargers, and ensure that EV users are the main beneficial. Liability and insurance questions remain unresolved, such as who bears responsibility if a V2G discharge causes grid damage or accelerates battery wear [14].

6.3 Battery Degradation and User Acceptance

A major concern for EV users is whether frequent V2G cycling accelerates battery capacity loss. While lithium-ion batteries degrade naturally with charge-discharge cycles, studies indicate that smart, shallow-depth cycling (e.g., maintaining state-of-charge between 30% and 80%) can limit additional degradation [15]. However, consumer perception often lags behind technical findings, and fear of reducing battery lifespan remains a significant barrier to V2G adoption. User acceptance also depends on giving drivers control over when their vehicle participates (e.g., setting minimum state-of-charge for departure times), transparent compensation, and warranties that cover V2G use. Without addressing these psychological and practical concerns, even technically feasible V2G systems may see low voluntary participation.

7 Electric Vehicle Charging Technologies

7.1 Overview of EV Powertrain and Battery Systems

Electric vehicle (EV) powertrains consist of three main components: the traction battery pack, the power electronics (inverter), and the electric traction motor. The battery stores energy, the inverter converts DC to AC for the motor, and the motor drives the wheels. For charging, the on-board charger (OBC) converts AC from the grid to DC for the battery. Figure 7.1 illustrates the typical architecture.

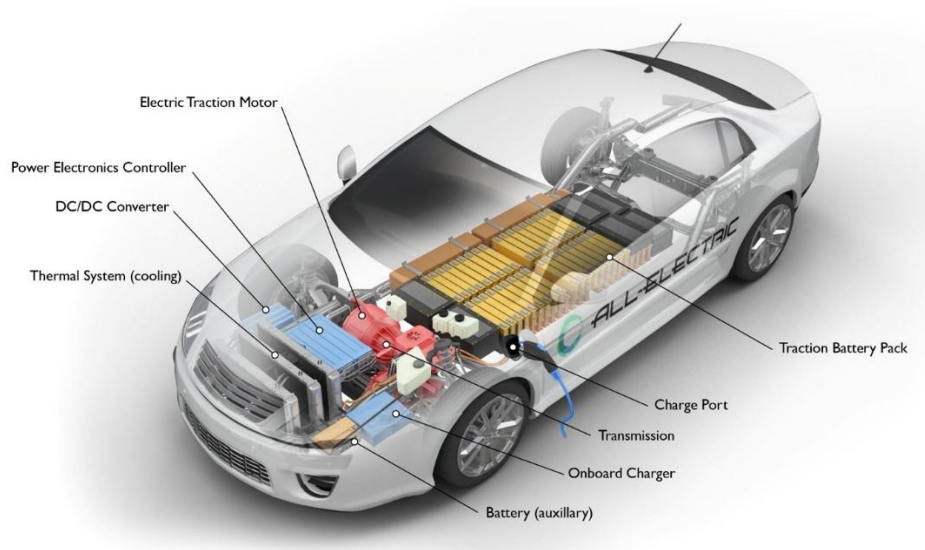


Figure 7.1: EV powertrain diagram [8]

7.1.1 Key Parameters for Charging

Several battery parameters directly influence charging behavior, Table 7.1:

Table 7.1: Battery parameters for EV charging

Parameters	Description	Range
SoC	Percentage of energy remaining	0 → 100%
Capacity	Amount of energy at full charge	30 → 100 kWh
Voltage	Charging voltage	350 → 1000V
C-Rate	Charge/discharge rate relative to capacity	0.2 → 0.5C for V2G; 1 → 3C for fast charging
Cycle Life	Number of full cycles before degradation	1000 – 4000 cycles

For bidirectional charging (V2G), degradation concerns are mitigated by limiting depth of discharge and operating within the 20–80% SoC range. Modern battery management systems actively manage these limits to preserve battery lifetime.

7.1.2 Electric Vehicle Charging Port

Electric vehicle charging connectors vary across global markets due to differences in grid infrastructure, voltage standards, and regional regulatory frameworks, Figure 7.2.

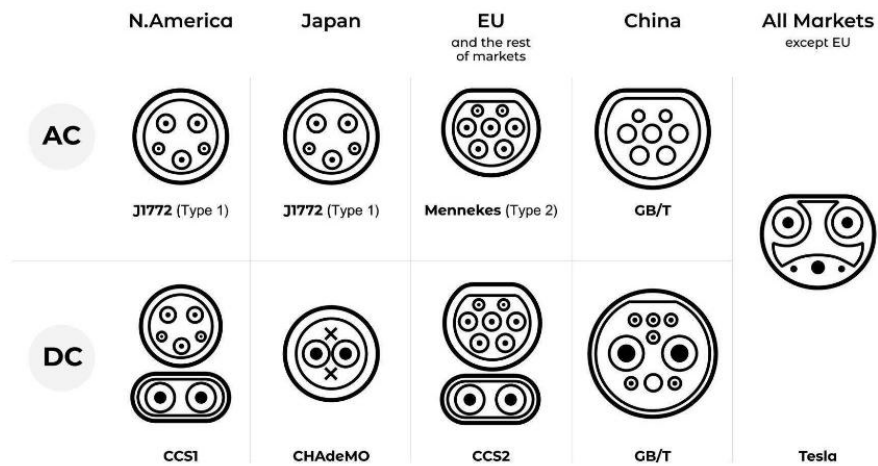


Figure 7.2: Global Distribution of EV Charging Connector Standards by Region

For this study, which investigates bidirectional charging strategies, a connector supporting DC power flow is required. Since this research is conducted in Europe, the CCS2 connector will be used. CCS2 integrates the Type 2 AC inlet with two additional DC pins and fully supports ISO 15118-20 [9] for bidirectional V2G operation.

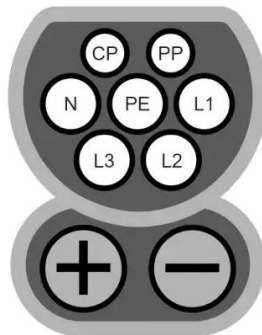


Figure 7.3: Pin configuration of CCS2 DC connector (Type 2 with DC pins)

The CCS2 connector, Figure 7.3, comprises nine main pins, summarized in Table 7.2.

Table 7.2: Pin Functions – CCS2 Connector

Pin	Name	Function
PE	Protective Earth	Safety grounding; connects the EV chassis to earth ground to prevent electric shock
CP	Control Pilot	Communication signal between EV and charging station; carries PWM duty cycle to indicate maximum allowable current, and enables state negotiation (e.g., charging start/stop, ventilation requirements)
PP	Proximity Pilot	Detects connector insertion and prevents vehicle movement during charging; includes a resistor that identifies the cable's current-handling capacity
N	Neutral	AC return path for single-phase or three-phase charging; carries return current under normal operation
L1	Line 1	First AC power line for single-phase (L1 + N) or three-phase (L1, L2, L3) charging
L2	Line 2	Second AC power line for three-phase charging
L3	Line 3	Third AC power line for three-phase charging
DC⁺	DC Positive	High-voltage DC positive conductor for fast charging (bypasses onboard charger)
DC⁻	DC Negative	High-voltage DC negative conductor for fast charging

Charging at high power is significantly simpler today using DC rather than AC due to the fundamental difference in where the power conversion takes place. With AC charging, the conversion from AC to DC must occur within the vehicle, requiring onboard power electronics that are limited by size, weight, and thermal constraints. Increasing AC charging power beyond 11–22 kW would demand substantially larger and heavier onboard components, which is impractical for passenger vehicles. In contrast, DC fast charging shifts the AC-to-DC conversion offboard to the charging station. The external

DC charger can be as large, heavy, and well-cooled as necessary, employing industrial-grade power electronics. The vehicle simply receives DC power directly to its battery via the CCS2 connector's DC^+ and DC^- pins, requiring no onboard conversion.

7.2 Unidirectional Charging (V1G – Conventional Charging)

Multiple charging technologies are available for recharging EVs, with the main differences between them lying in their cost, maximum power rating, and level of control sophistication. All electric vehicles are equipped with an OBC, Figure 7.4, a lightweight, relatively low-power AC/DC converter integrated into the vehicle. The primary purpose of this converter is to enable users to recharge their EV using standard, single or three phase, AC outlets when no dedicated external DC fast charger is available. For example, an EV owner can connect their vehicle to any NEMA 14-50 receptacle (common in residential garages and RV parks) or even a standard household NEMA 5-15 outlet, and the onboard charger will handle the AC-to-DC conversion necessary to charge the battery.

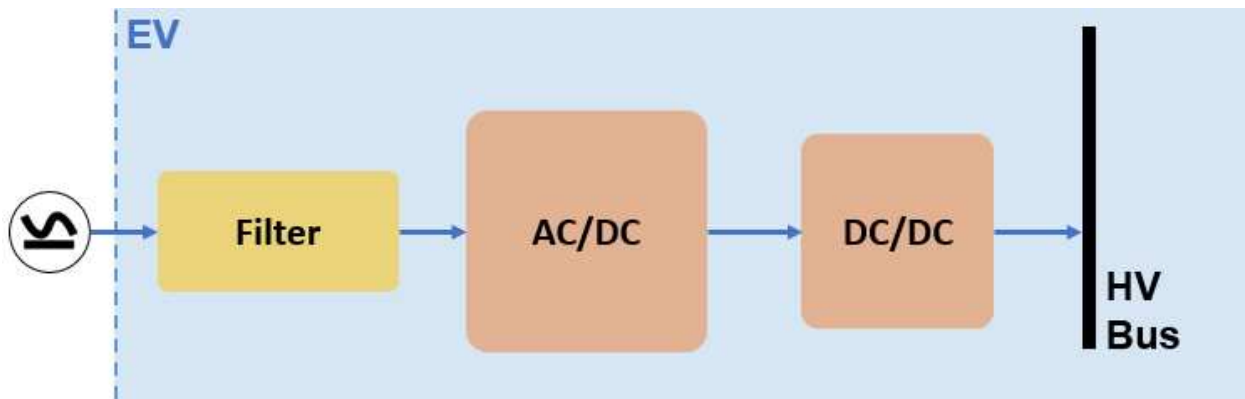


Figure 7.4: Onboard Charger (OBC)

Figure 2.4 presents a block diagram of a typical unidirectional onboard charger. The AC input from the grid first passes through an EMI filter to suppress electromagnetic interference, followed by an input rectifier (diode bridge) and a Power Factor Correction (PFC) stage (typically a boost converter or Vienna rectifier) that shapes the input current to achieve near-unity power factor. The PFC stage outputs a regulated DC bus voltage (typically 400 V or 800 V). This DC bus then feeds an isolated DC-DC converter, commonly a Phase-Shifted Full Bridge (PSFB) or LLC resonant converter, which provides

galvanic isolation via a high-frequency transformer and regulates the output voltage and current according to the battery's charging profile (constant current CC, then constant voltage CV). Finally, the output is delivered to the battery pack. A control unit (microcontroller) senses input voltage/current, DC bus voltage, and battery voltage/current, generating PWM signals to regulate both PFC and DC-DC stages.

While onboard chargers are suitable for overnight AC charging, they are limited by their power rating and thermal constraints. For rapid charging, offboard DC fast chargers are employed, which bypass the vehicle's onboard charger entirely. As shown in Figure 7.5, a DC fast charger consists of a three-phase AC input, a three-phase PFC, a DC-DC isolation stage, and a control system that communicates directly with the vehicle's battery management system via the CCS2 connector's CP pin and CAN bus. The charger supplies high-current DC directly to the battery through the DC+ and DC- pins of the CCS2 connector, bypassing the OBC entirely.

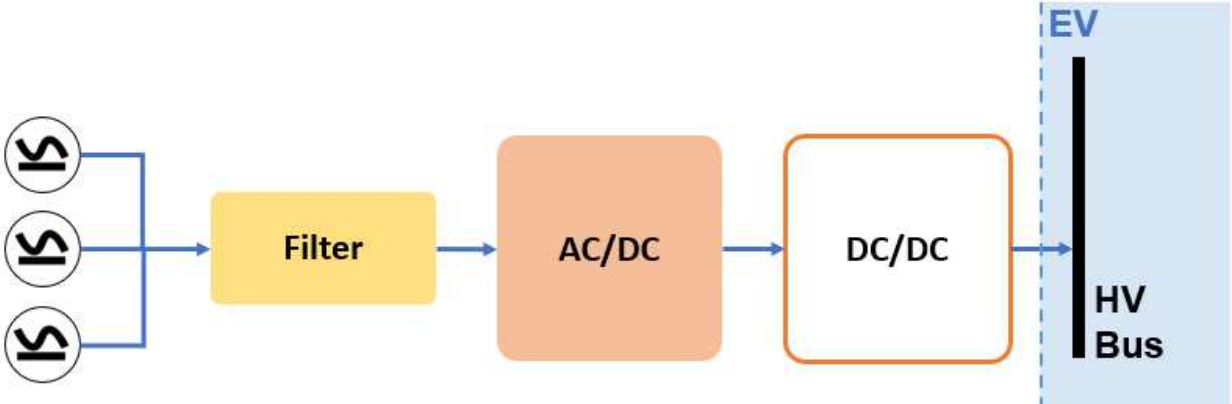


Figure 7.5: External Fast-Charger

It is worth noting that certain EV models, such as the Nissan Leaf, were equipped with onboard chargers that permitted bidirectional power flow, effectively enabling early vehicle-to-grid (V2G) and vehicle-to-home (V2H) functionality. However, because the Leaf's onboard converter was designed primarily as a low-cost, low-power unidirectional charger, its bidirectional capability was limited to small-scale, low-power applications. The converter's modest rating (typically 6.6 kW for AC charging and ~3 kW for V2H discharge) meant that while it could supply essential household loads during an

outage, it was insufficient for high-power grid services or full-home backup. This early implementation demonstrated the technical feasibility of bidirectional charging but also highlighted the need for purpose-designed bidirectional converters with higher power ratings, enhanced control algorithms, and robust thermal management to realize the full potential of V2G Smart strategies. Consequently, most modern bidirectional implementations now rely on dedicated bidirectional onboard chargers or external DC bidirectional converters rather than repurposed unidirectional hardware.

7.3 Bidirectional Charging Fundamentals

Bidirectional capability transforms the EV from a passive consumer into an active energy storage asset, complex technologies and standards need to be addressed to make this transformation safe and reliable.

7.3.1 Power Electronics and Converter Topologies

The bidirectional charging system is built around the Maxwell Bidirectional ACDC Power Module, a commercial off-the-shelf power electronics unit that forms the core of SEED 2 charger prototype, Figure 7.6 (a). This module handles the bidirectional conversion between AC grid power and DC battery power, enabling both charging and discharging operations without requiring external power electronics design or custom converter development.

The Maxwell module implements a bidirectional AC-DC converter topology, typically based on a voltage-source converter with active front-end rectification. On the AC side, the module connects directly to the single-phase or three-phase grid supply, while the DC side interfaces with the EV battery through the charging cable and connector. The bidirectional capability is achieved through fully controllable switching devices (IGBTs or SiC MOSFETs) arranged in an H-bridge or three-phase bridge configuration. By modulating the switching signals, the module can operate either as a rectifier (converting AC to DC for charging) or as an inverter (converting DC to AC for discharging back to the grid or home loads).

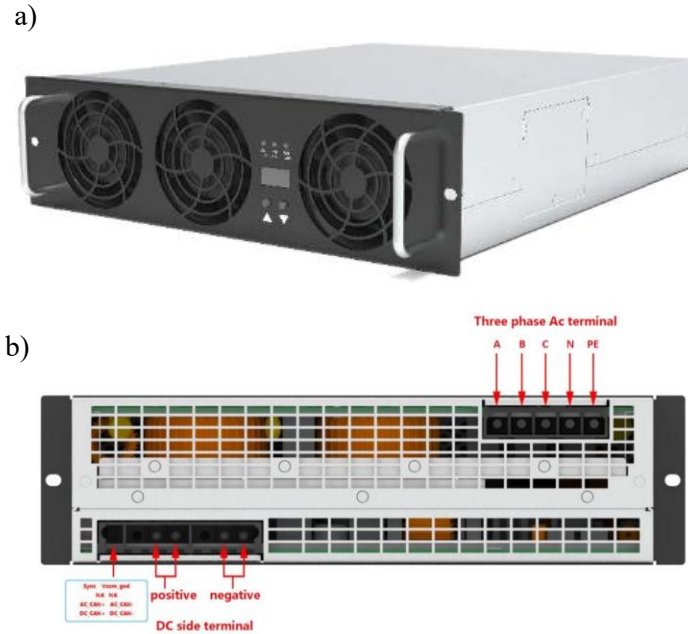


Figure 7.6: a) Bidirectional ACDC Power Module, b) Power Module Terminals

The Maxwell module integrates several key components (Figure 7.6 – b), within a single enclosure:

- AC input filter for electromagnetic interference suppression and grid compliance
- Bidirectional AC-DC converter stage with active switching devices
- DC-link capacitor bank for voltage smoothing and energy buffering
- DC output filter for clean battery charging current
- Built-in control interface accepting external commands for power flow direction and magnitude
- Protection circuits including overcurrent, overvoltage, and overtemperature shutdown

By selecting the Maxwell module, SEED 2 design effort focused on integration, communication, and control rather than power electronics development. The module accepts control signals via CAN bus or analog inputs that determine whether the system operates in charging mode (grid-to-vehicle) or discharging mode (vehicle-to-grid), as well as the instantaneous power level. This approach significantly reduced development time and ensured reliable, tested power stage performance.

The module's specifications are well-suited to bidirectional EV charging applications. While exact ratings depend on the specific variant, the Maxwell series typically supports power levels up to 22 kW, sufficient for home and light commercial V2G installations. The high efficiency (typically >95% in both directions) minimizes energy losses during bidirectional operation, which is critical for economic viability of V2G services.

For system-level validation, the Maxwell module was integrated with the Vector vSECC single communication controller (Figure 7.7), and a Golf Volkswagen EV.



Figure 7.7: vSECC – EVSE Control Unit

The control algorithm was implemented on a MYIR Linux board (Figure 7.8), which serves as the embedded controller managing the bidirectional power module. The MYIR board runs a Linux-based operating system and executes the charging/discharging logic, issuing real-time power commands to the Maxwell based on grid conditions, battery state of charge, and user preferences, completing the bidirectional charging system architecture.

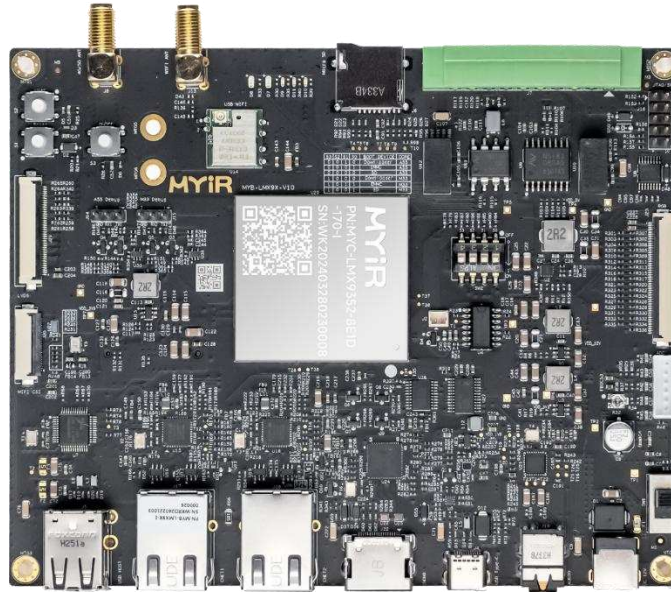


Figure 7.8: MYIR Development Board

7.3.2 Communication and Control Requirements

Bidirectional charging introduces significant communication complexity compared to unidirectional charging. The charging station must coordinate with the vehicle, the grid, the energy management system, and the user to ensure safe and efficient power flow in both directions.

EVCC resides inside the vehicle and manages communication with the charging station. The SECC is located in the charging station and handles the station-side communication. Together, these controllers exchange critical information including target state of charge, battery voltage and current limits, thermal status, grid connection parameters, and authorization data.

CAN bus is the primary communication protocol within the vehicle, connecting the battery management system, power electronics, and other ECUs. For bidirectional charging, CAN carries real-time data on battery voltage, current, temperature, and state of charge, which are essential for safe power delivery. In SEED 2 prototype, the MYIR Linux board communicates directly with the Maxwell bidirectional power module via CAN bus, issuing power commands and receiving operational status. The Vector vSECC single also uses CAN to control the power electronics, demonstrating the protocol's central role in bidirectional charging systems.

OCPP is the standard for communication between charging stations and CSMS. OCPP 2.1 includes extensive support for bidirectional charging, treating EVs as Distributed Energy Resources and enabling Vehicle-to-Everything applications [10].

To enable charging functionality without relying on an external cloud-based central system, a micro OCPP server that runs locally. This lightweight server handles OCPP communication internally, allowing the charging station to operate autonomously while maintaining full compatibility with OCPP-based messaging. The micro server processes charging requests, manages authorization, and relays power control commands between the energy management algorithm and the charging hardware. By merging the OCPP server with the control algorithm on the same MYIR board, external dependencies were eliminated allowing testing even without internet connectivity.

ISO 15118 defines the application layer protocol for secure communication between EVCC and SECC, supporting automatic authentication (Plug & Charge), TLS encryption, bidirectional power transfer for AC and DC charging, and dynamic charging schedules. ISO 15118-20 specifically addresses bidirectional power transfer requirements.

Figure 7.9 summarize the prototype architecture.

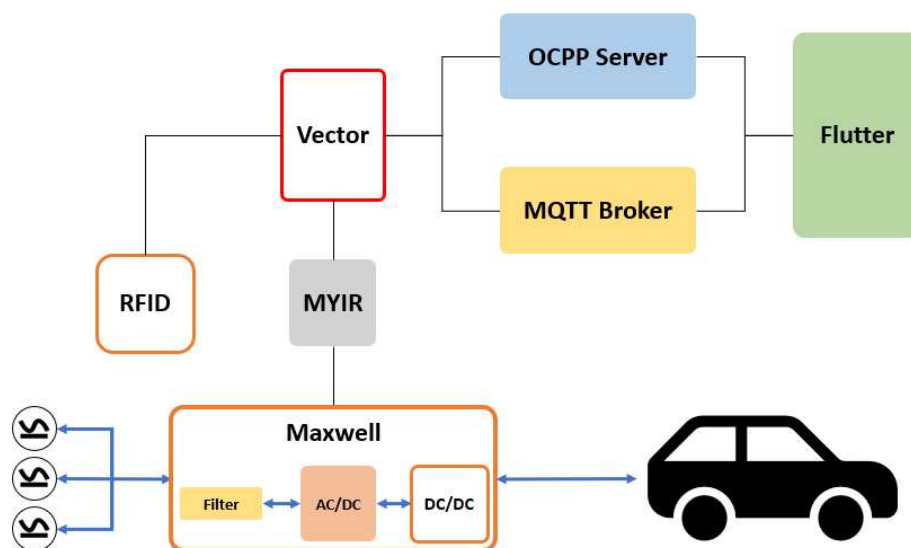


Figure 7.9: SEED 2 Architecture Block Diagram

The MYIR Linux board serves as the central controller, running the charging algorithm, hosting the micro OCPP server, and managing all communication interfaces. It exchanges data with the Vector vSECC single for vehicle communication, sends control signals to the Maxwell module via CAN bus, and processes OCPP messages internally through the micro server. This architecture ensures coordinated operation across all system components while maintaining autonomy from external cloud services.

7.3.3 User Interface and Authentication

To enable intuitive user interaction with the bidirectional charging system, a custom application was developed using the Flutter framework. Flutter, Google's open-source UI toolkit, enables cross-platform development for windows, iOS and Android from a single codebase, ensuring consistent user experience across devices while minimizing development effort.

The Flutter application serves as the primary user interface for the charging station, providing real-time information and control capabilities. Users can monitor key charging parameters including instantaneous charging or discharging power, cumulative energy transferred, battery state of charge, session duration, and estimated cost or revenue. The interface also displays grid connection status and allows users to select operating modes such as charging only, V2G enabled, or V2H priority.

The application is connected to the Vector Broker, a message broker that facilitates real-time data exchange between the user interface and the charging system. The Vector Broker acts as a middleware layer, routing messages between the Flutter app, the MYIR Linux board running the control algorithm, and the Vector vSECC single communication controller. Through this broker-based architecture, the Flutter application receives live status updates from the charger and sends user commands, such as start charging, stop charging, set target state of charge, and charging time, back to the control system. The broker ensures reliable, low-latency communication essential for responsive user interaction.

RFID authentication is integrated into the charging system to authorize users and manage access to the charging station. Each user is assigned a unique RFID card or tag. When the user taps their RFID tag on the charging station's reader, the system verifies the credentials against an authorized user

database. Upon successful authentication, the charging session is initiated according to the user's predefined preferences or the current system mode. RFID authentication serves multiple purposes: it prevents unauthorized use of the charging station, enables session tracking for billing purposes, and provides an audit trail of charging events.

The Flutter application interface, shown in Figures 7.10 through 7.12, provides intuitive control and monitoring of the bidirectional charging system. Figure 7.10 illustrates the authentication workflow: before RFID authentication, the start button is greyed and inaccessible; after successful authentication, the button turns green and becomes enabled, allowing the user to initiate a session. Figure 7.11 displays the main screen during operation, with two variants showing charging mode and discharging mode, which were made available as toggle options for testing purposes. In both modes, the charging box presents key real-time information including instantaneous power (kilowatts), cumulative energy transferred (kilowatt-hours), battery state of charge (percentage visualized as a circular progress indicator), and estimated time remaining to reach full state of charge. Figure 7.12 shows the settings screen, where users can configure charging parameters, and selecting charging time and target state of charge.

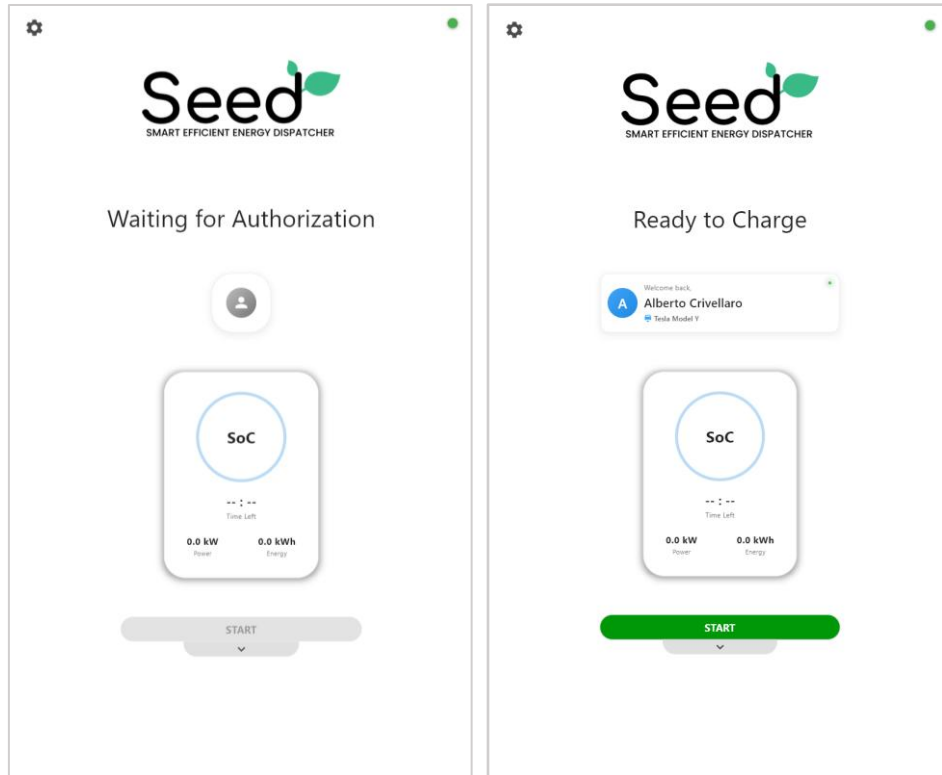


Figure 7.10: SEED 2 User Interface: Before and After Authorization

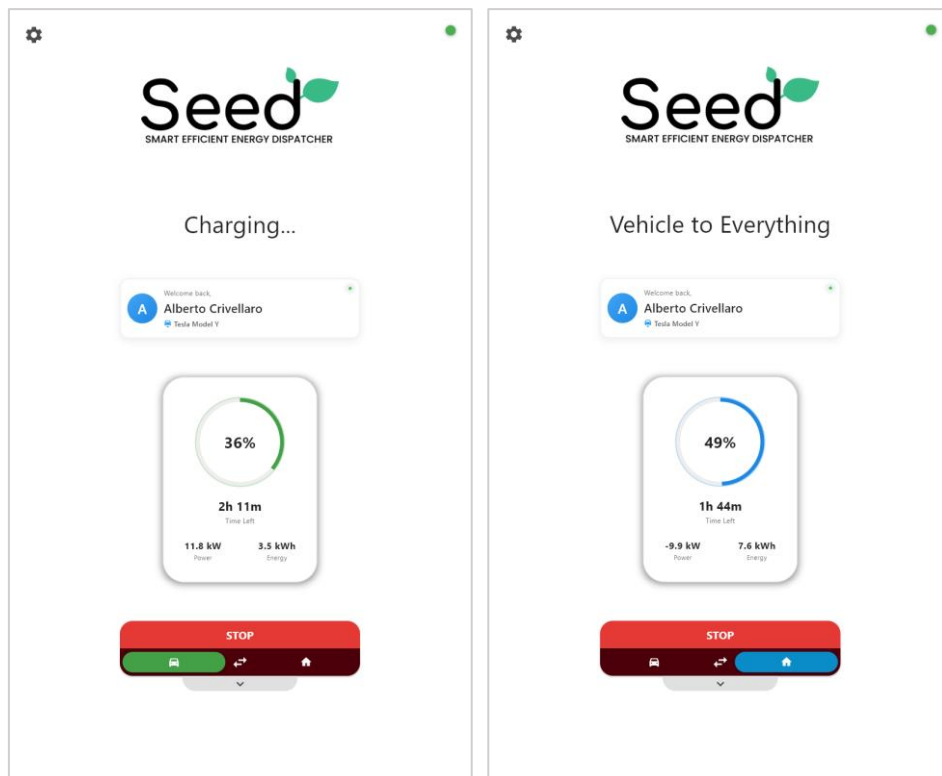


Figure 7.11: SEED 2 User Interface: Charging vs. Discharging

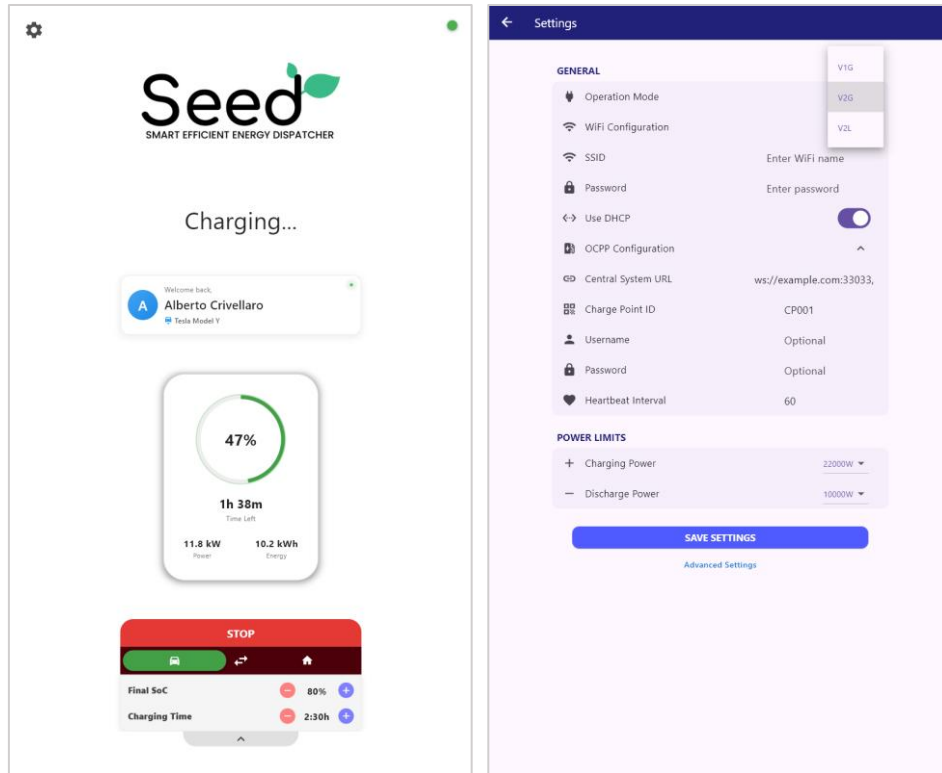


Figure 7.12: SEED 2 User Interface: Options and Settings

7.4 Charger Prototype Assembly & Inner Connections



Figure 7.13: SEED 2 Prototype Assembly

Figure 7.13 shows the fully assembled charger prototype with all internal connections (power, communication, and control wiring) integrated. Validation and testing involved attempting to charge a vehicle and reading system logs, followed by iterative adjustments and fixes until reliable operation was achieved.

7.5 Standards and Protocols (IEC, ISO)

Bidirectional EV charging must comply with international standards to ensure interoperability, safety, and regulatory acceptance. The following standards are relevant to the prototype, and Table 7.3 summarizes their specific contributions to bidirectional operation.

IEC 61851-1 [11] establishes the fundamental safety and functional requirements for EV conductive charging systems. This standard matters because it defines the control pilot function that enables basic communication between the vehicle and charger before higher-level protocols take over. Without compliance with IEC 61851-1, a charging station cannot receive safety certification for grid connection.

ISO 15118 is the most critical standard for SEED 2 implementation because it specifically enables bidirectional communication between the EV and the charging station. The standard is divided into multiple parts. ISO 15118-2 defines the communication protocol for basic V2G functions including authentication and charging schedules. ISO 15118-20 extends this to full bidirectional power transfer, adding requirements for AC and DC reverse power flow, real-time power limit negotiation, and secure certificate management. Vector vSECC single controller implements both parts, which is why it can support V2G operation.

Table 7.3: Standards Summary

Features	IEC 61851-1	ISO 15118-2	ISO 15118-20
Basic safety and control pilot	✓		
Plug & Charge authentication		✓	✓
TLS encryption		✓	✓
Bidirectional power transfer (V2G/V2H/V2L)			✓
AC bidirectional operation			✓
DC bidirectional operation			✓
Real-time power limit negotiation			✓
DER / smart grid integration			✓

Summary for SEED 2 prototype: The Vector vSECC single communication controller implements ISO 15118-2 and ISO 15118-20, providing the core bidirectional communication capabilities required for V2G operation. These standards enable Plug & Charge authentication, TLS encryption for secure data exchange, and real-time power limit negotiation between the vehicle and charging station. IEC 61851-1 provides the underlying safety framework, defining the control pilot function and basic protection mechanisms that ensure safe connection and disconnection of the vehicle. Together, these standards form a complete compliance stack: IEC 61851-1 for safety, and ISO 15118-2/20 for application layer bidirectional power transfer functionality. This combination allows the charger to operate legally, securely, and integrate within existing EV charging infrastructure.

7.6 New EV Models Supporting Bidirectional Charging

The publication of ISO 15118-20 in April 2022 marked a turning point for bidirectional EV adoption. Prior to this standard, bidirectional charging relied on proprietary implementations, which limited compatibility across brands. ISO 15118-20 provides a unified communication framework for bidirectional power transfer using the CCS, enabling Plug & Charge authentication, TLS encryption, and real-time power negotiation between any compliant vehicle and charging station.

Since the standard's release, major automakers have significantly expanded their bidirectional offerings. The European Commission has mandated that all new public and private chargers support EN ISO 15118-20 by January 2027, creating regulatory certainty for manufacturers. Several manufacturers now offer or have announced bidirectional-capable models, including the Nissan Leaf (transitioning from CHAdeMO to CCS for 2026), Ford F-150 Lightning (V2H and V2G), Hyundai Ioniq 5 and Ioniq 9 (V2L and V2G pilots), Kia EV6 and EV9, and Tesla Cybertruck (first Tesla V2G program launched 2026). The Renault Scenic E-Tech and the upcoming Renault 5 also support V2G through ISO 15118-20 compliance.

8 System Modeling and Simulation Framework

8.1 Simulation Objectives and Assumptions

The simulation framework is designed to determine the optimal charging schedule for electric vehicles under a time-of-use tariff structure with photovoltaic generation. The primary objective is to minimize the total monthly electricity cost, including energy consumption, peak power penalties, and applicable taxes, while guaranteeing a full final state of charge. The simulation assumes a fixed number of EVs recharged daily between 09:00 and 18:00, excluding weekends. Each EV has a constant initial state of charge, a battery capacity of 59 kWh, a maximum charging/discharging power of 22 kW, and a charging efficiency of 0.95. The grid connection allows bidirectional power flow, enabling vehicle-to-grid operations. All time intervals are discretized into 15-minute resolution.

8.2 Network Model Description

The network topology consists of two buses: a slack bus representing the grid connection and a local bus where all consumption and generation assets are connected. The two buses are linked by a feeder line with a user-defined length, per-kilometer resistance of 0.3 ohms, per-kilometer reactance of 0.15 ohms, and a maximum thermal current rating of 0.4 kiloamperes. The grid is modeled as an infinite slack bus with a fixed voltage of 1.0 per unit. The nominal voltage level is set to 20 kilovolts. Load consumption and solar photovoltaic production are treated as predefined time series parameters from actual measurements, implemented respectively as a load element and a static generator at the local bus. The electric vehicle is modeled as a controllable battery storage element at the same local bus.

8.3 Optimization Model

This mixed-integer linear programming model, implemented in Pyomo, determines the optimal charging schedule of an EV by controlling the charging power at each time interval and the intensity of power delivered by the charger. The model minimizes the total energy cost while ensuring that the final state of charge reaches the target level.

8.3.1 Problem Definition

Considering, to have a different number EV to recharge daily, from 09:00 till 18:00, except weekends; with a constant initial state of charge, battery capacity $59kWh$, maximum charging/discharging power $22kW$, and battery efficiency 0.95.

- **Sets**

T	Daily index	$15min$
-----	-------------	---------

T_c	Charging window	$15min$
-------	-----------------	---------

- **Parameters**

L_t	Load consumption	MW
-------	------------------	------

PV_t	Solar panel production	MW
--------	------------------------	------

BC_t	Energy buying cost	$Euro/MWh$
--------	--------------------	------------

SC_t	Energy selling cost	$Euro/MWh$
--------	---------------------	------------

P_{max}^{charge}	Maximum charging power	MW
--------------------	------------------------	------

SoC_o	Initial state of charge	%
---------	-------------------------	---

E	Battery energy capacity	MWh
-----	-------------------------	-------

SoC_{target}	Final state of charge	%
----------------	-----------------------	---

- **Fixed Constants**

MC	13.10	$Euro/Month$	Monthly charge
------	-------	--------------	----------------

PP	4.44	$Euro/kW$	Power peak penalty
------	------	-----------	--------------------

GSC	58	$Euro/MWh$	General system cost
-------	----	------------	---------------------

IVA	22	%	Tax rate
-------	----	---	----------

μ	0.95		Charging efficiency
-------	------	--	---------------------

Δt	0.25		Time scaler
------------	------	--	-------------

M	1000		Large scaler
-----	------	--	--------------

- **Variables**

P_t^{charge}	$\in \{0, P_{max}^{charge}\}$	$t \in T$	Charging power	kW
$P_t^{discharge}$	$\in \{0, P_{max}^{discharge}\}$	$t \in T$	Discharging power	kW
SoC_t	$\in \{0, 100\}$	$t \in T$	Charging dynamic	%
P_t^{g+}		$t \in T$	Positive grid power	MW
P_t^{g-}		$t \in T$	Negative grid power	MW
$IsBuying$	$\in \{0, 1\}$	$t \in T$	Power Direction	<i>binary</i>
$IsCharging$	$\in \{0, 1\}$	$t \in T$	Charging Mode	<i>binary</i>
$IsDischarging$	$\in \{0, 1\}$	$t \in T$	Discharging Mode	<i>binary</i>
P_{peak}^{grid}			Peak power	MW

8.3.2 Objective Function

The model objective is to minimize the final monthly cost, taking into account all the factors that affect the monthly electricity bill, eq. 1;

$$\min \left(\sum_{t \in T} (P_t^{g+} * (BC_t + GSC) - P_t^{g-} * SC_t) + (P_{peak}^{grid} * PP * 1000) + (TAX) \right) \quad (1)$$

$$TAX = \left(\sum_{t \in T} (P_t^{g+} * (BC_t + GSC)) + (P_{peak}^{grid} * PP * 1000) + MC \right) * IVA$$

8.3.3 Constraints

- Power balance eq. 2,

$$P_t^{g+} - P_t^{g-} = L_t - PV_t + P_t^{charge} - P_t^{discharge} \quad (2)$$

for $\forall t \in T$

Model must respect the charging window eq. 3;

$$P_t^{charge} - P_t^{discharge} = 0 \quad (3)$$

for $\forall t \in T_c$

Model must never simultaneously buy and sell energy eq. 4, and 5;

$$P_t^{g-} \leq M * (1 - IsBuying) \quad (4)$$

$$P_t^{g+} \leq M * IsBuying \quad (5)$$

Model must never simultaneously charge and discharge energy eq. 6, 7, and 8;

$$P_t^{charge} \leq P_{max}^{charge} * IsCharging \quad (6)$$

$$P_t^{discharge} \leq P_{max}^{discharge} * IsDischarging \quad (7)$$

$$IsCharging + IsDischarging \leq 1 \quad (8)$$

- Hourly peak power, holds the highest hourly grid consumption eq. 9;

$$P_{grid}^{peak} \geq \sum_{i=0}^3 (L_{t+i} - PV_{t+i} + P_{t+i}^{charge} - P_{t+i}^{discharge}) \quad (9)$$

for $\forall t \in T$

- State of charge dynamics, when charging and discharging eq. 10,

$$SoC_t = \left[SoC_{t-1} + \frac{(P_t^{charge} - P_t^{discharge}) * \Delta t}{E} * 100 \right] * \mu \quad (10)$$

for $\forall t \in T$

NOTE: since the battery energy is in *kWh*, and the charging power is in *kW15min*, when computing the SoC progress one must insure to take into account this change, and scale the energy accordingly.

Final state of charge must fulfill the target, eq. 11,

$$SoC_t = SoC_{target} \quad (11)$$

for $t \geq \max(T_c)$

Full Python optimization function in **Appendix A**

9 Simulation Results and Analysis

A number of simulations is conducted for each model. Each simulation considers two EVs being plugged in daily, with an initial state of charge of 35%. The results are based on the full year and are divided per season.

To quantify the impact of such technology the following values were computed:

- Grid Consumption (MWh): amount of energy consumed from the grid.
- Peak Grid Power (MWh): maximum hourly energy consumption per month.
- Net EV Energy (MWh): difference between energy consumed and injected by EV.
- PV Generation (MWh): monthly energy produced by PV.
- PV Used (MWh): PV energy used locally.
- PV Sold (MWh): PV energy sold to grid.
- Energy Bought (€): cost of energy bought from grid.
- Energy Sold (€): revenue from energy sold to grid.
- Net Energy Cost (€): difference between the cost of energy bought and sold.
- Peak Charge (€): monthly charge due to highest power consumption.
- TAX (€): taxes to net energy cost, and peak charge.
- Cost (€): final cost which includes the sum between net energy cost, peak charge, and taxes; minus the revenues due to energy sold.

9.1 Model 1: V1G – Traditional Charging Scenario

9.1.1 Seasonal Consumptions, and Cost

Table 9.1: V1G (Traditional) – Winter (December, January, and February)

Grid Consumption	Peak Grid Energy	Net EV Energy
95.21 MWh	0.22 MWh	5.81 MWh
PV Generation	PV Invested	PV Sold
8.20 MWh	7.61 MWh	0.59 MWh

Energy Bought	Energy Sold	Net Energy Cost
19444.10 €	73.60 €	19370.50 €
Peak Charge	TAX	Cost
3783.01 €	5118.61 €	28272.13 €

Table 9.2: VIG (Traditional) – Spring (March, April, and May)

Grid Consumption	Peak Grid Energy	Net EV Energy
46.94 MWh	0.21 MWh	5.72 MWh
PV Generation	PV Used	PV Sold
30.74 MWh	22.55 MWh	8.19 MWh
Energy Bought	Energy Sold	Net Energy Cost
9521.12 €	1028.52 €	8492.60 €
Peak Charge	TAX	Total Cost
3183.29 €	2803.61 €	14479.50 €

Table 9.3: VIG (Traditional) – Summer (June, July, and August)

Grid Consumption	Peak Grid Energy	Net EV Energy
56.64 MWh	0.29 MWh	5.72 MWh
PV Generation	PV Used	PV Sold
39.78 MWh	31.75 MWh	8.03 MWh
Energy Bought	Energy Sold	Net Energy Cost
11319.55 €	1012.39 €	10307.17 €
Peak Charge	TAX	Total Cost
3437.00 €	3255.09 €	16999.25 €

Table 9.4: VIG (Traditional) – Autumn (September, October, and November)

Grid Consumption	Peak Grid Energy	Net EV Energy
66.85 MWh	0.20 MWh	5.72 MWh
PV Generation	PV Used	PV Sold
15.76 MWh	12.70 MWh	3.06 MWh
Energy Bought	Energy Sold	Net Energy Cost
12493.56 €	388.99 €	12104.57 €
Peak Charge	TAX	Total Cost
3338.77 €	3491.76 €	18935.10 €

Total:

Total grid yearly consumption: 265.64MWh	Total peak charge: 13742.07€
Total PV Used: 74.60MWh	Total Taxes: 14669.07€
Total PV Sold: 19.86MWh	Total Cost: 78685.98€

9.1.2 Year Summary

The total annual expenditure of **78,685.90 €** is presented in Figure 9.1, where a detailed breakdown of costs for the year is illustrated.

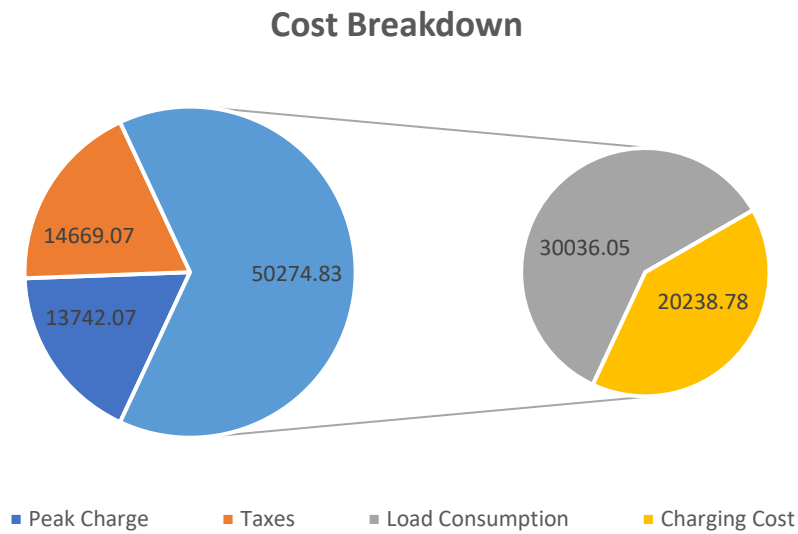


Figure 9.1: VIG (Traditional) – Annual Cost Breakdown

The total annual PV production of **94.47MWh** is illustrated in Figure 9.2, where a seasonal breakdown for the year is shown.

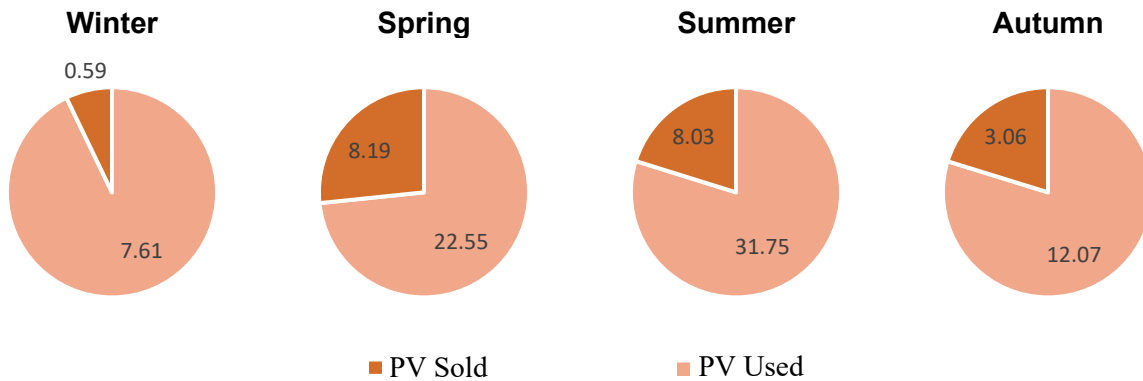


Figure 9.2: VIG (Traditional) – Annual PV Investment Breakdown

9.1.3 Observation

Under the VIG model, the peak demand charge directly affected both taxes and the final cost. With no optimization algorithm in place, the model did not actively reduce peak demand; consequently, peak-driven taxes and overall costs remained substantial, underscoring the value of optimization for peak shaving.

9.2 Model 2: VIG – Smart Charging Scenario

9.2.1 Seasonal Consumptions, and Cost

Table 9.5: VIG (Smart) – Winter (December, January, and February)

Grid Consumption	Peak Grid Energy	Net EV Energy
93.29 MWh	0.11 MWh	5.33 MWh
PV Generation	PV Used	PV Sold
8.20 MWh	7.79 MWh	0.41 MWh
Energy Bought	Energy Sold	Net Energy Cost
18829.54 €	37.48 €	18792.06 €
Peak Charge	TAX	Cost
1543.10 €	4490.63 €	24825.79 €

Table 9.6: VIG (Smart) – Spring (March, April, and May)

Grid Consumption	Peak Grid Energy	Net EV Energy
45.05 MW	0.16 MW	5.25 MW
PV Generation	PV Used	PV Sold
30.74 MW	24.56 MW	6.17 MW

Energy Bought	Energy Sold	Net Energy Cost
8434.23 €	729.18 €	7705.06 €
Peak Charge	TAX	Total Cost
1157.95 €	2118.93 €	10981.93 €

Table 9.7: VIG (Smart) – Summer (June, July, and August)

Grid Consumption	Peak Grid Energy	Net EV Energy
54.75 MWh	0.29 MWh	5.25 MWh
PV Generation	PV Used	PV Sold
39.78 MWh	33.81 MWh	5.97 MWh
Energy Bought	Energy Sold	Net Energy Cost
10412.01 €	707.30 €	9704.71 €
Peak Charge	TAX	Total Cost
1642.47 €	2660.63 €	14007.81 €

Table 9.8: VIG (Smart) – Autumn (September, October, and November)

Grid Consumption	Peak Grid Energy	Net EV Energy
64.96 MWh	0.15 MWh	5.25 MWh
PV Generation	PV Used	PV Sold
15.76 MWh	13.67 MWh	2.08 MWh
Energy Bought	Energy Sold	Net Energy Cost
11775.43 €	244.13 €	11531.30 €
Peak Charge	TAX	Total Cost
1658.21 €	2964.05 €	16153.56 €

Total:

Total grid yearly consumption: 258.05MWh	Total peak charge: 6001.73€
Total PV Used: 79.83MWh	Total Taxes: 12234.23 €
Total PV Sold: 14.64MWh	Total Cost: 65959.09€

9.2.2 Year Summary

The total annual expenditure of **65,959.09€** is presented in Figure 9.3, where a detailed breakdown of costs for the year is illustrated.

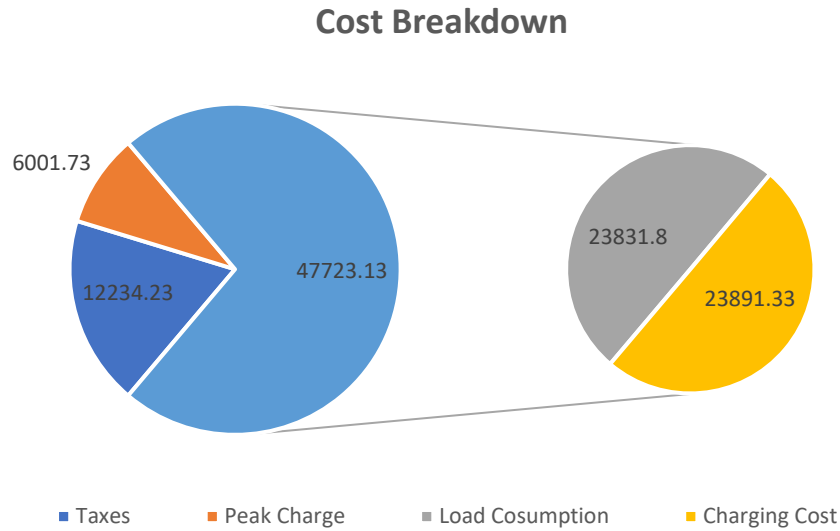


Figure 9.3: VIG (Smart) – Annual Cost Breakdown

The total annual PV production of **94.47MWh** is illustrated in Figure 9.4, where a seasonal breakdown for the year is shown.

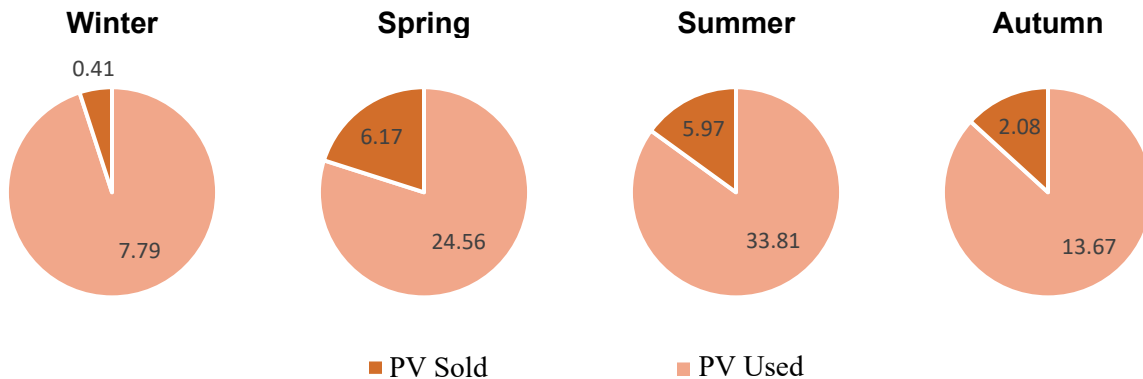


Figure 9.4: VIG (Smart) – Annual PV Investment Breakdown

9.2.3 Observation

The model successfully reduced the annual cost, an improvement primarily attributed to the increased investment in PV capacity and the implementation of peak shaving. It is worth noting that charging costs increased relative to the previous model. While this could be misinterpreted as a drawback, it actually reflects the model's prioritization of monthly peak shaving over low-cost charging. This trade-off is justified, as peak charges have a substantially greater impact on overall energy costs than the marginal savings from off-peak charging.

9.3 Model 3: V2G – Smart Charging Scenario

9.3.1 Seasonal Consumptions, and Cost

Table 9.9: V2G (Smart) – Winter (December, January, and February)

Grid Consumption	Peak Grid Energy	Net EV Energy
93.29 MWh	0.35 MWh	5.33 MWh
PV Generation	PV Used	PV Sold
8.20 MWh	7.79 MWh	0.41 MWh
Energy Bought	Energy Sold	Net Energy Cost
18834.09 €	47.49 €	18786.60 €
Peak Charge	TAX	Cost
1542.33 €	4491.46 €	24820.38 €

Table 9.10: V2G (Smart) – Spring (March, April, and May)

Grid Consumption	Peak Grid Energy	Net EV Energy
45.11 MWh	0.22 MWh	5.26 MWh
PV Generation	PV Used	PV Sold
30.74 MWh	24.29 MWh	6.44 MWh
Energy Bought	Energy Sold	Net Energy Cost
8495.87 €	808.81 €	7687.06 €
Peak Charge	TAX	Total Cost
987.74 €	2095.04 €	10769.85 €

Table 9.11: V2G (Smart) – Summer (June, July, and August)

Grid Consumption	Peak Grid Energy	Net EV Energy
54.83 MWh	0.23 MWh	5.27 MWh
PV Generation	PV Used	PV Sold
39.78 MWh	33.85 MWh	5.93 MWh
Energy Bought	Energy Sold	Net Energy Cost
10429.14 €	700.46 €	9728.67 €
Peak Charge	TAX	Total Cost
1018.53 €	2527.13 €	13274.33 €

Table 9.12: V2G (Smart) – Autumn (September, October, and November)

Grid Consumption	Peak Grid Energy	Net EV Energy
64.99 MWh	0.26 MWh	5.25 MWh
PV Generation	PV Used	PV Sold
15.76 MWh	13.68 MWh	2.08 MWh
Energy Bought	Energy Sold	Net Energy Cost
11792.26 €	243.80 €	11548.46 €
Peak Charge	TAX	Total Cost
1174.14 €	2861.25 €	15583.85 €

Total:

Total grid yearly consumption: 258.23MWh	Total peak charge: 4722.74€
Total PV Used: 79.61MWh	Total Taxes: 11974.88€
Total PV Sold: 14.86 MWh	Total Cost: 64448.41€

9.3.2 Year Summary

The total annual expenditure of **64,448.41€** is presented in Figure 9.5, where a detailed breakdown of costs for the year is illustrated.

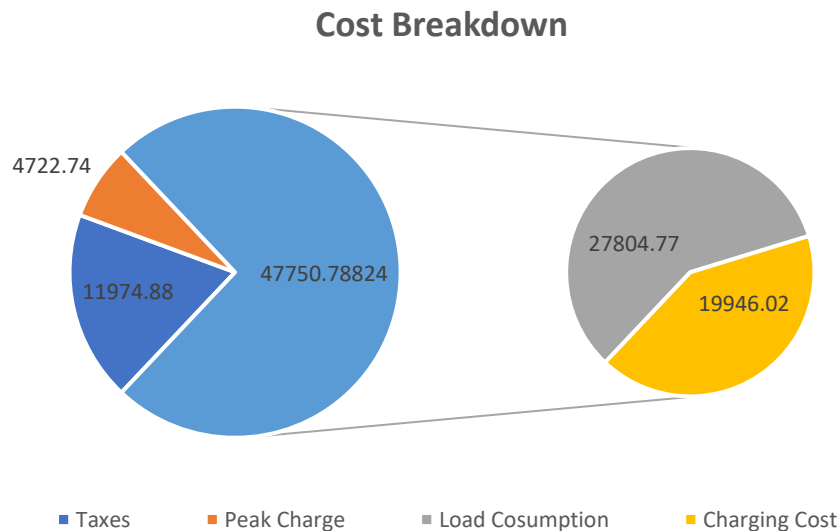


Figure 9.5: V2G (Smart) – Annual Cost Breakdown

The total annual PV production of **94.47MWh** is illustrated in Figure 9.6, where a seasonal breakdown for the year is shown.

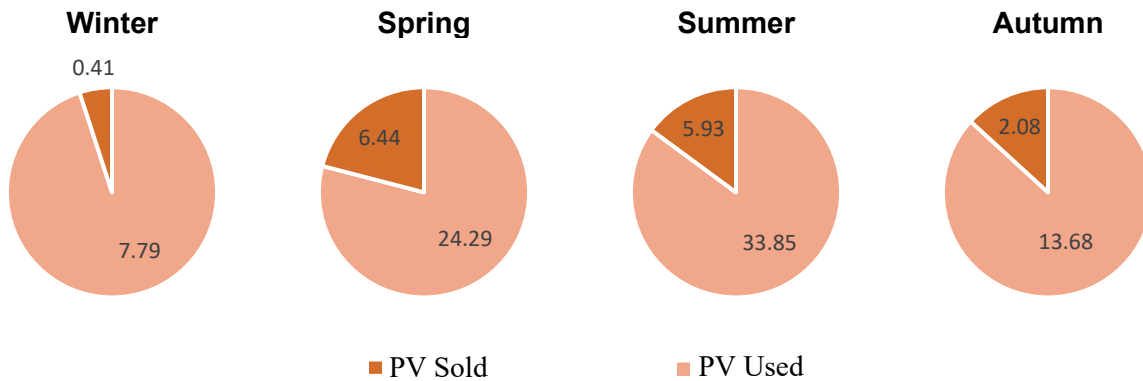


Figure 9.6: V2G (Smart) – Annual PV Investment Breakdown

9.3.3 Observation

Compared to the significant improvement seen when moving from traditional V1G to smart V1G, the smart V2G model delivered only a minor additional gain. PV consumption improved by just a fraction, while peak shaving showed a more noticeable enhancement. This suggests that the majority of cost and performance benefits were already captured by smart V1G alone.

9.4 Comparative Analysis

9.4.1 Peak Shaving

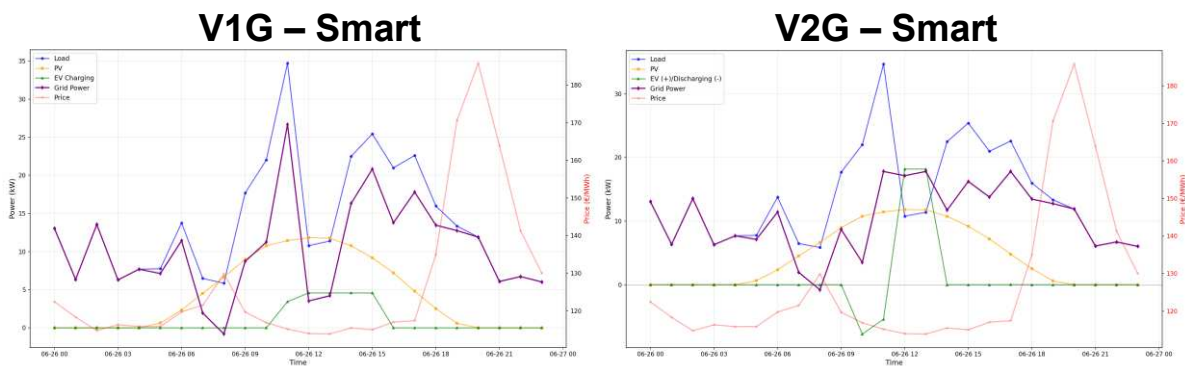


Figure 9.7: V1G (Smart) vs. V2G (Smart) Peak Shaving; June 26/2025

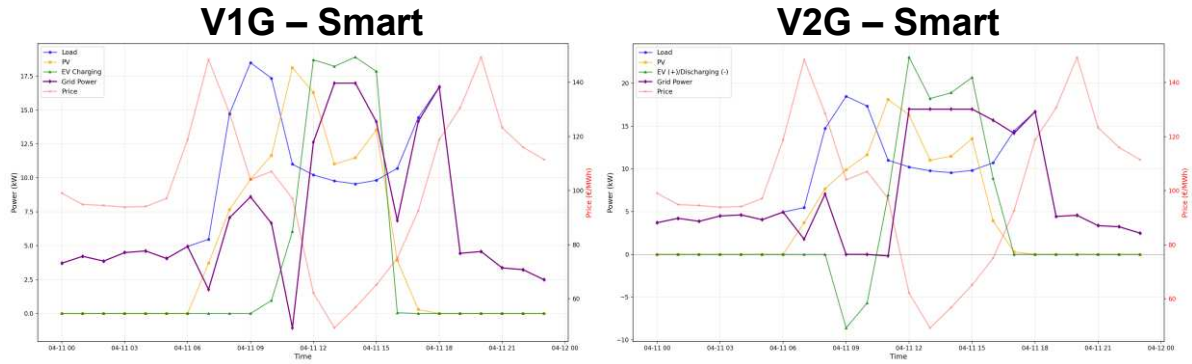


Figure 9.8: V1G (Smart) vs. V2G (Smart) Peak Shaving; April 11/2025

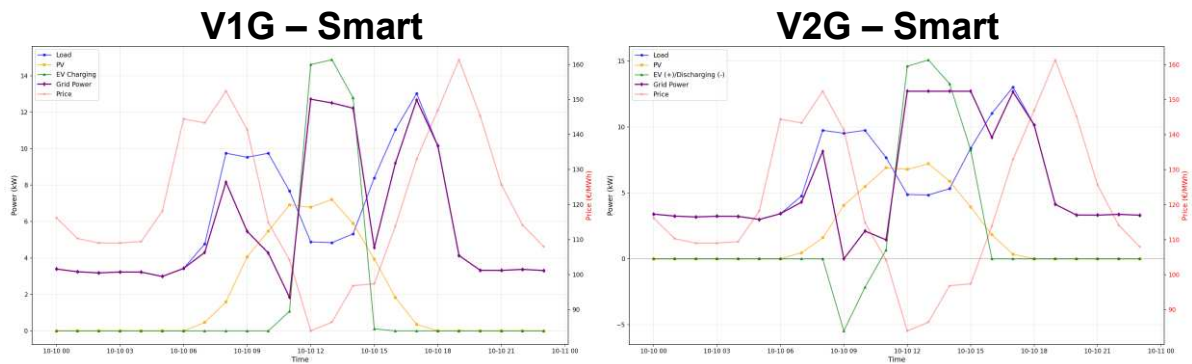


Figure 9.9: V1G (Smart) vs. V2G (Smart) Peak Shaving; October 10/2025

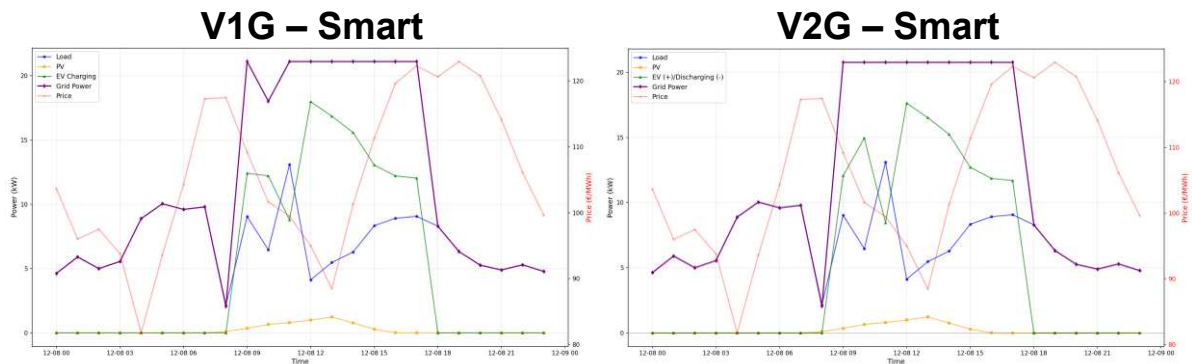


Figure 9.10: V1G (Smart) vs. V2G (Smart) Peak Shaving; December 08/2025

A key strength of the smart V2G model lies in its superior peak shaving capability compared to smart V1G, as illustrated in Figure 9.7. Taking a random day in June as an example, the V1G model fails to actively reduce the peak; instead, it shifts the charging schedule away from the peak period. In contrast, V2G actively reshapes the power flow profile and significantly decreases the peak by discharging power back into the grid. This same behavior is observed in Figures 9.8 and 9.9. However, in Figures 9.10, due

to low PV production combined with high demand, the bidirectional charger has no choice but to function effectively as a unidirectional charger. Notably, even when both models adopt the same underlying technology, their outputs differ. This discrepancy stems from the realism embedded in the problem formulation, which minimizes cost on a monthly basis rather than daily. Consequently, the model prioritizes long-term monthly peak/cost reduction over short-term daily optimization, a distinction that becomes particularly evident under constrained generation and high demand conditions.

9.4.2 PV Investment

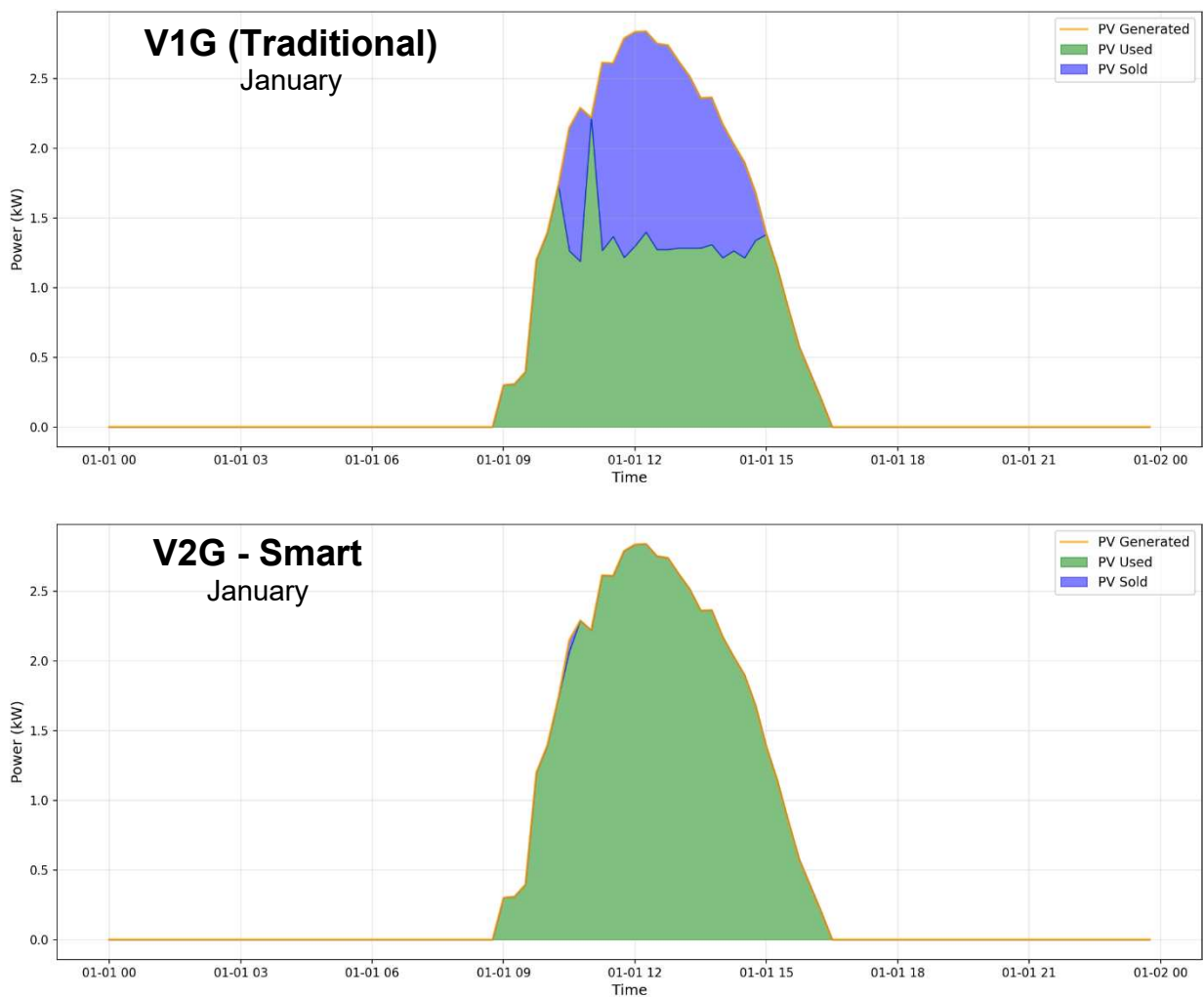


Figure 9.11: V1G (Traditional) vs. V2G (Smart) PV Usage; January 01/2025

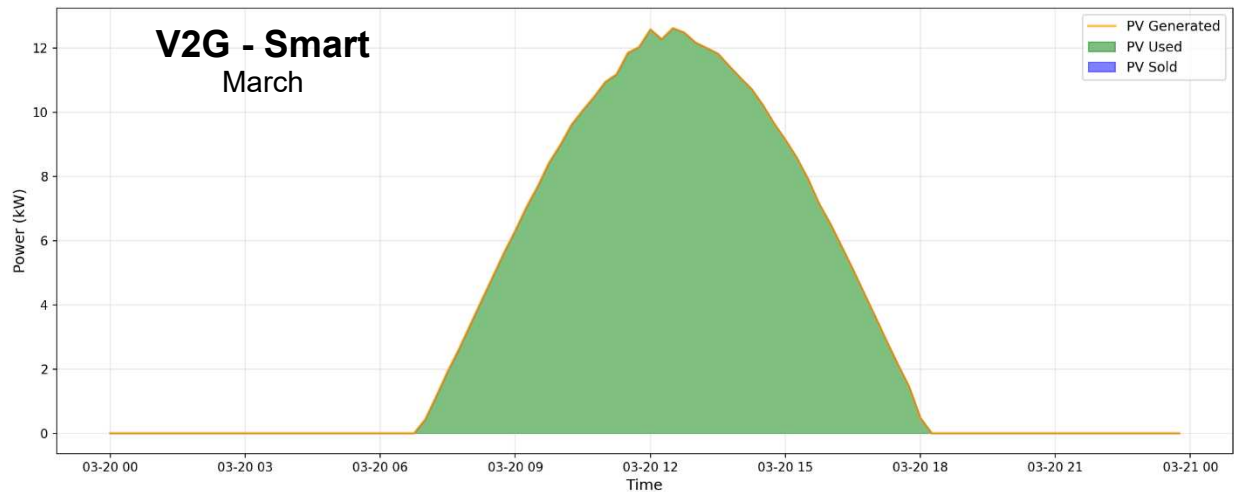
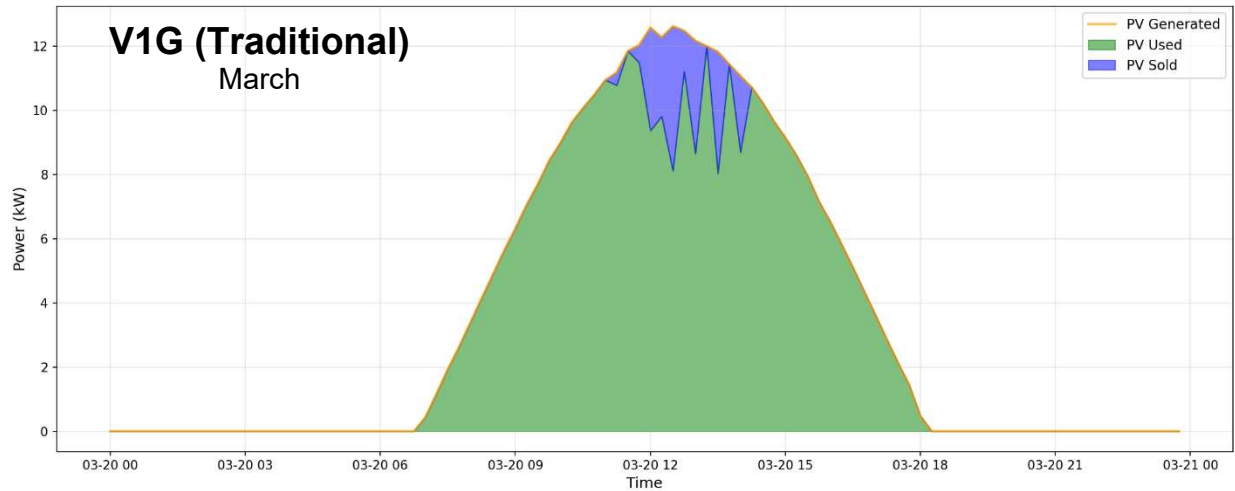


Figure 9.12: V1G (Traditional) vs. V2G (Smart) PV Usage; March 20/2025

Figures 9.11 and 9.12 highlight an advantage of V2G technology: enhanced PV self-consumption. Unlike the traditional V1G model, the V2G model actively stores excess solar energy in the vehicle battery and, when needed, discharges it either to meet household demand or for grid services.

9.4.3 SEED 2 As a Business Model

To assess the robustness of the proposed model across varying conditions, 150 simulations were conducted under different scenarios, including variations in PV generation, demand profiles, and pricing structures. The average cost reduction was then computed for each season, as summarized in Table 9.13. Overall, the model achieved a total average annual saving of €2,169.80 compared to the baseline case.

This value represents the mean saving across all simulated scenarios, providing a reliable indication of expected performance under real-world variability.

Table 9.13: Average Cost Reduction Per Season

Season	Cost Reduction
Winter	112.02 €
Spring	404.65 €
Summer	875.16 €
Autumn	777.97 €

Figure 9.13 presents a comparison of annual cost savings between the smart V1G and smart V2G models for the year 2025. Across the entire year, V2G consistently outperformed V1G in terms of cost reduction, with maximum savings observed during summer and autumn. As illustrated in Figure 9.14, these seasonal cost savings are closely linked to peak demand reduction.

During summer and autumn, V2G achieved the most significant peak shaving compared to V1G, directly translating into lower demand charges and, consequently, greater overall cost savings. The correlation between Figures 9.13 and 9.14 confirms that the primary driver of V2G's superior economic performance is its ability to actively reshape the load profile through bidirectional power flow, rather than merely shifting charging events as in V1G.

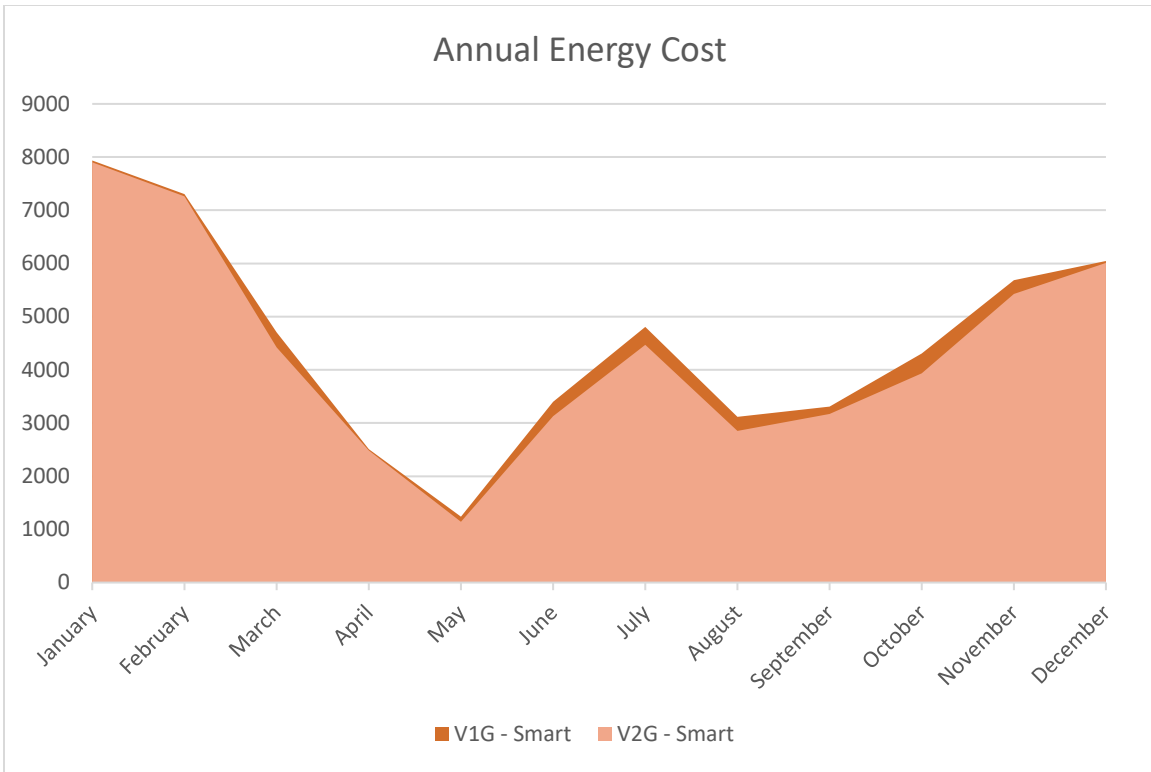


Figure 9.13: V1G (Smart) vs. V2G (Smart) Cost Saving; 2025

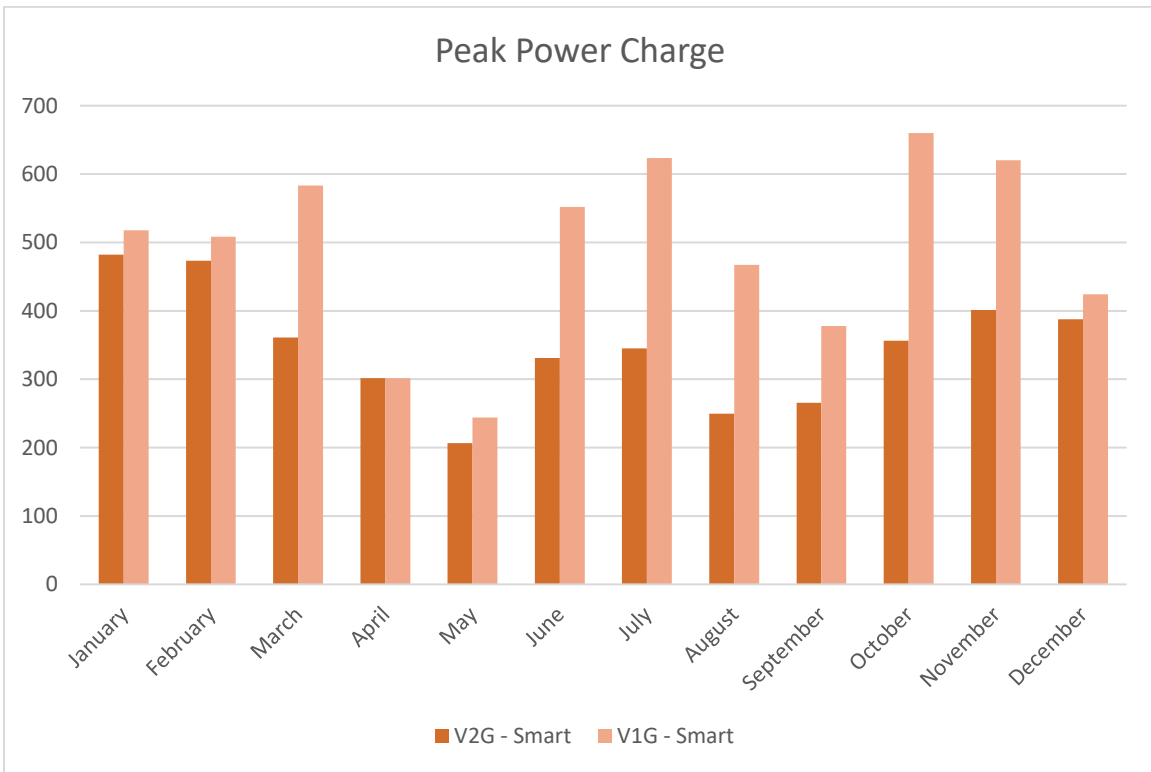


Figure 9.14: V1G (Smart) vs. V2G (Smart) Peak Saving; 2025

9.5 Discussion of Results

As a business model, SEED 2 with an estimated cost of approximately €5,000 can recover its initial investment within two to three years under typical operating conditions. This payback period positions SEED 2 as an economically viable solution for prosumers seeking to integrate bidirectional charging technology. Furthermore, the extensive simulations conducted throughout this study support all claims regarding the model's efficiency and its potential to outperform conventional approaches. The results consistently demonstrate that the proposed model delivers measurable cost savings, peak demand reduction, and enhanced PV utilization across a wide range of scenarios.

10 Conclusions and Future Work

The initial claim of this study has been validated: the income benefits derived from V2G can be similar to those of V1G depending on the operating conditions. From a PV investment perspective, both models showed comparable performance without major differences. Moreover, in the majority of simulations for both chargers, PV energy was fully consumed or stored locally.

On the other hand, V2G outperforms V1G in peak shaving and load leveling. Its spontaneous ability to switch power direction within ten seconds allows it to extract substantially more value from peak shaving opportunities than V1G, which is limited to load shifting alone.

For future work, as mentioned in Chapter 5, the primary beneficiary of bidirectional charging technology to date is the electrical grid, followed by the EV user, and finally the premises hosting the technology. This hierarchy stems from the absence or lack of clarity surrounding grid services that should be economically rewarded, such as frequency regulation, voltage fluctuation management, and reactive power support. To further motivate research and investment in this area, and to extract greater benefits from V2G technology, these services need to be clearly defined and monetized. Once properly addressed, the optimization problem can be updated accordingly, enabling practical and profitable participation in grid service markets.

From a power systems point of view, the main implementation problem is that a few bidirectional chargers scattered across a large network don't really help much. What the grid actually needs is large-scale deployment across many areas. Right now, unidirectional chargers are everywhere, and EVs that support bidirectional charging are still rare. Therefore, moving from V1G to V2G should happen gradually, starting with medium and large industries that already have renewables on site.

Fast charging is also gaining traction with both manufacturers and users, mainly because it's efficient and people appreciate a quick charging session. As Chapter 7 on standards and protocols makes clear, charging management and protection requirements are shifting from the EV side to the EVSE side, and

OCPP connection is becoming required (mainly in public charging). This change is really interesting, it's making charging more welcoming for different EV models, and pushing EVSE manufacturers to upgrade their hardware and software to handle that diversity. This shift is the most fundamental part of the whole technology. It reduces the complexity of charging and could eventually help move toward wider V2G adoption.

Finally, this study not only proved and quantified the cost reduction capability of V2G, it also addressed the huge growth of energy demand, and why smart applications need to be adopted to encounter this growth, in the most efficient, green, and resilient methods. There is no doubt, about V2G becoming a great solution used by many, distributed energy resources that DSOs count on to improve the behavior of the electric grid. Additionally, aggregators are also showing interest in installing their own modules inside bidirectional chargers for both data collection for future control strategies.

Appendix A

```
def optimize_daily_ev_charging(day_load, day_pv, day_price, daily_selling_price,
                               max_e_mwh, max_p_mw, min_p_mw, initial_soc, soc_target_day):

    # Convert to lists for Pyomo
    time_indices = list(range(len(day_load)))
    load_values = day_load.values.tolist()
    pv_values = day_pv.values.tolist()
    price_values = day_price.values.tolist()
    selling_values = daily_selling_price.values.tolist()

    # Create Pyomo model
    model = pyo.ConcreteModel()
    model.T = pyo.Set(initialize=time_indices)

    # Parameters
    model.L = pyo.Param(model.T, initialize=dict(zip(time_indices, load_values))) # MW
    model.PV = pyo.Param(model.T, initialize=dict(zip(time_indices, pv_values))) # MW
    model.BC = pyo.Param(model.T, initialize=dict(zip(time_indices, price_values))) # Euro/MWh
    model.SC = pyo.Param(model.T, initialize=dict(zip(time_indices, selling_values))) # Euro/MWh

    # Fixed Constants
    MC = 13.10 # Monthly Charge Euro/Month
    PP = 4.44 # Power Peak Penalty Euro/kWh
    IVA = 0.22 # Taxes %
    GSC = 58 # System Cost Euro/MWh
    CE = 0.95 # Charge Efficiency
    M = 1000 # Big-M value (larger than any expected grid power, in MW)

    # Variables
    model.p_charge = pyo.Var(model.T, within=pyo.NonNegativeReals, bounds=(0, max_p_mw))
    model.p_discharge = pyo.Var(model.T, within=pyo.NonNegativeReals, bounds=(0, min_p_mw))
    model.soc = pyo.Var(model.T, within=pyo.NonNegativeReals, bounds=(0, 100))
    model.grid_buy = pyo.Var(model.T, within=pyo.NonNegativeReals)
    model.grid_sell = pyo.Var(model.T, within=pyo.NonNegativeReals)
    model.is_buying = pyo.Var(model.T, within=pyo.Binary)
    model.peak_power = pyo.Var(within=pyo.NonNegativeReals)

    # Binary variables for charge/discharge (necessary)
    model.charging_mode = pyo.Var(model.T, within=pyo.Binary)
    model.discharging_mode = pyo.Var(model.T, within=pyo.Binary)

    def no_sell_when_buying(model, t):
        return model.grid_sell[t] <= M * (1 - model.is_buying[t])
    model.no_sell_when_buying = pyo.Constraint(model.T, rule=no_sell_when_buying)
```

```

def no_buy_when_selling(model, t):
    return model.grid_buy[t] <= M * model.is_buying[t]
model.no_buy_when_selling = pyo.Constraint(model.T, rule=no_buy_when_selling)

def objective_rule(model):
    buying = sum((model.BC[t] + GSC) * model.grid_buy[t] for t in model.T)
    selling = sum(model.SC[t] * model.grid_sell[t] for t in model.T)
    peak_penalty = model.peak_power * PP * 1000
    taxes = (buying + peak_penalty + MC) * IVA
    return buying - selling + peak_penalty + taxes
model.objective = pyo.Objective(rule=objective_rule, sense=pyo.minimize)

# Grid balance - ORIGINAL
def grid_balance_rule(model, t):
    return (model.L[t] + model.p_charge[t] - model.p_discharge[t] - model.PV[t] ==
            model.grid_buy[t] - model.grid_sell[t])
model.grid_balance = pyo.Constraint(model.T, rule=grid_balance_rule)

# Create a set of hourly window start indices
hourly_starts = list(range(len(time_indices) - 3)) # Can start windows up to len-4
model.HourlyWindows = pyo.Set(initialize=hourly_starts)

def peak_power_hourly_rule(model, start_idx):
    # Sum grid power over this 4-period hourly window
    hourly_sum = sum(model.L[start_idx + i] + model.p_charge[start_idx + i] -
                     model.p_discharge[start_idx + i] - model.PV[start_idx + i]
                     for i in range(4))
    return model.peak_power >= hourly_sum
model.peak_constraint = pyo.Constraint(model.HourlyWindows, rule=peak_power_hourly_rule)

# Charge/discharge mutual exclusivity
def mode_sum_rule(model, t):
    return model.charging_mode[t] + model.discharging_mode[t] <= 1
model.mode_sum = pyo.Constraint(model.T, rule=mode_sum_rule)

def charge_link_rule(model, t):
    return model.p_charge[t] <= max_p_mw * model.charging_mode[t]
model.charge_link = pyo.Constraint(model.T, rule=charge_link_rule)

def discharge_link_rule(model, t):
    return model.p_discharge[t] <= min_p_mw * model.discharging_mode[t]
model.discharge_link = pyo.Constraint(model.T, rule=discharge_link_rule)

# SOC dynamics

```

```

def soc_dynamics_rule(model, t):
    if t == 0:
        return model.soc[t] == initial_soc
    else:
        charge_energy = model.p_charge[t] * 0.25 * CE
        discharge_energy = model.p_discharge[t] * 0.25 / CE
        net_energy = charge_energy - discharge_energy
        soc_change = (net_energy / max_e_mwh) * 100
        return model.soc[t] == model.soc[t-1] + soc_change
model.soc_dynamics = pyo.Constraint(model.T, rule=soc_dynamics_rule)

# Final SOC constraint - ORIGINAL
def soc_final_rule(model):
    return model.soc[model.T.last()] >= soc_target_day
model.soc_final = pyo.Constraint(rule=soc_final_rule)

# Charging window - ORIGINAL
def charging_window_rule(model, t):
    timestamp = day_load.index[t]
    in_hours = 9 <= timestamp.hour < 18
    is_weekday = timestamp.weekday() < 5
    if not (is_weekday and in_hours):
        return model.p_charge[t] + model.p_discharge[t] == 0
    return pyo.Constraint.Skip

try:
    model.window = pyo.Constraint(model.T, rule=charging_window_rule)
except:
    pass

# SOLVE with HiGHS (faster) - NO buy/sell binaries!
solvers_to_try = ['cbc', 'highs', 'glpk']

for solver_name in solvers_to_try:
    try:
        solver = pyo.SolverFactory(solver_name)
        if solver.available():
            print(f" Using solver: {solver_name}")
            solver.options['time_limit'] = 30
            results = solver.solve(model, tee=False)

            if (results.solver.termination_condition == pyo.TerminationCondition.optimal or
                results.solver.termination_condition == pyo.TerminationCondition.feasible):

                p_charge_values = [pyo.value(model.p_charge[t]) for t in model.T]

```

```

        p_discharge_values = [pyo.value(model.p_discharge[t]) for t in model.T]
        p_net = [p_charge_values[i] - p_discharge_values[i] for i in
range(len(p_charge_values))]
        soc_values = [pyo.value(model.soc[t]) for t in model.T]
        grid_buy_values = [pyo.value(model.grid_buy[t]) for t in model.T]
        grid_sell_values = [pyo.value(model.grid_sell[t]) for t in model.T]
        grid_values = [grid_buy_values[i] - grid_sell_values[i] for i in
range(len(grid_buy_values))]
        peak_value = pyo.value(model.peak_power)

# Proper energy calculations
total_charge = sum([p_charge_values[i] for i in range(len(p_charge_values))])
total_discharge = sum([p_discharge_values[i] for i in range(len(p_discharge_values))])
# Check for simultaneous buying and selling
simultaneous_count = 0
for i in range(len(grid_buy_values)):
    if grid_buy_values[i] > 1e-6 and grid_sell_values[i] > 1e-6: # Small tolerance
        simultaneous_count += 1

print(f" Peak power: {peak_value:.3f} MW")
print(f" Total charging: {total_charge:.3f} MWh")
print(f" Total discharging: {total_discharge:.3f} MWh")

if simultaneous_count > 0:
    print(f" ⚠ WARNING: {simultaneous_count} time steps with simultaneous
buy/sell!")

return pd.DataFrame({
    'time': day_load.index,
    'p_charge_optimized': p_net,
    'charge_power': p_charge_values,
    'discharge_power': p_discharge_values,
    'soc_optimized': soc_values,
    'grid_power': grid_values
}).set_index('time')
else:
    print(f" Solver {solver_name} status: {results.solver.termination_condition}")
else:
    print(f" Solver {solver_name} not available")
except Exception as e:
    print(f" Solver {solver_name} error: {e}")
    continue

return None

```

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