White Paper

Fundamentals and Applications of Bi-Directional Charging

Contents

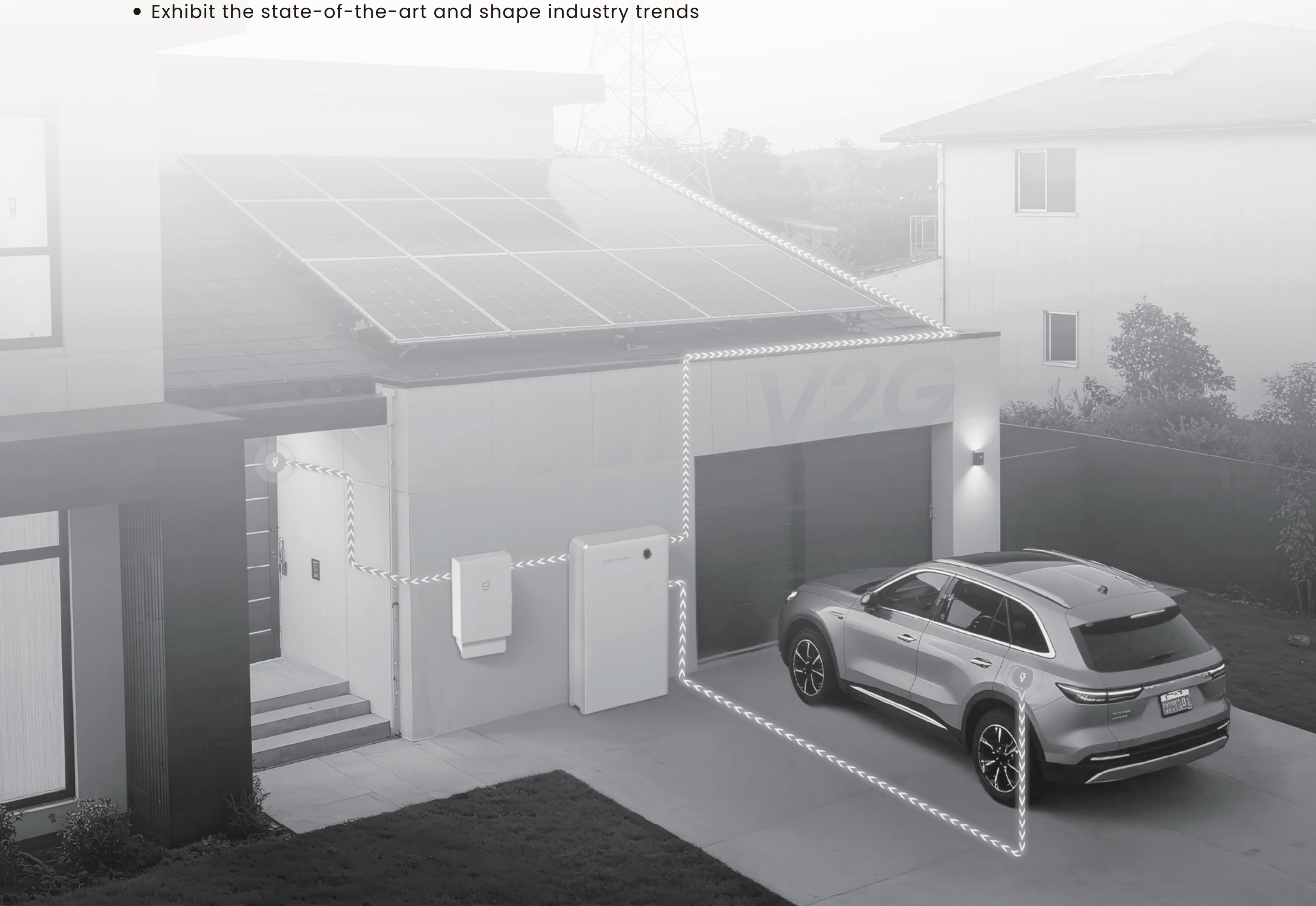
1.Executive Summary

The role of EV (electric vehicle) is becoming increasingly important across all countries, particularly in the most important EV markets like Australia, Europe (especially Germany), China, and the U.S. The increasing number of EVs represents a challenge for power networks in many countries of Europe and states of the U.S, particularly in the context of the energy transition and carbon reduction, but also an opportunity. Load peaks and thus grid instabilities can be induced by EV charging, but can also be compensated for example in the case of volatile electricity generation from renewable resources, such as wind generators and PV power plants.

With the continuous growth in EV adoption, V2G is gaining increasing recognition across the energy industry and is being consistently highlighted as a transformative grid solution. Drawing from Sigenergy's and The Mobility House Energy's first-mover experience in commercial V2G deployments, we both observed persistent challenges, emerging opportunities and critical unresolved issues simultaneously.

This joint V2X white paper’s objectives are:

- Provide a comprehensive understanding of V2X technology
- Drive industry collaboration and stakeholder engagement
- Exhibit the state-of-the-art and shape industry trends

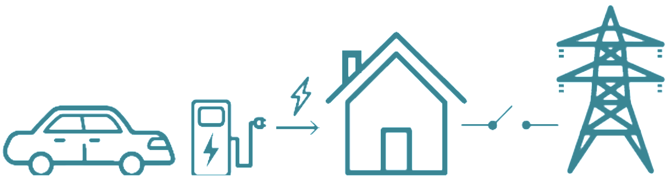


2.What is V2X technology?

Vehicle-to-Everything (V2X) bidirectional charging systems can discharge from the Electric Vehicle (EV) battery to serve a customer's onsite load or export to the grid while providing for mobility service.

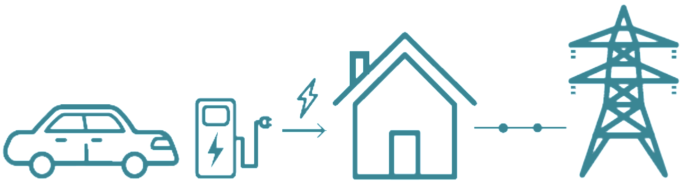
The typical control modes of V2X bidirectional charging systems are:

A.Islanded mode for backup (off-grid)



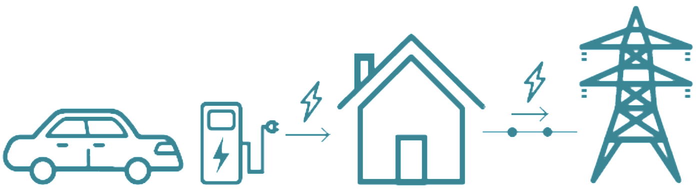
Discharged power matches onsite load. Therefore, operation is similar to a fossil-fuel backup generator or home battery system.

B.Grid-interconnected mode (on-grid), non-export to the grid



Discharging power of EV battery < onsite load, therefore no net positive power export to the grid is observed on the main meter.

C.Grid interconnected mode (on-grid) with export to the grid



Discharge power of EV battery > onsite load, and a net export of power to the grid can be observed on the main meter. This turns the EV into a dispatchable power source for various grid services such as enhanced Demand Response (DR), participation in a VPP for a variety of applications such as participation in wholesale energy markets.

The use cases of V2X bidirectional charging systems are differentiated in target scenarios and their control schemes. Control logic can be handled locally within the charging equipment or other local devices such as a Home Energy Management System (HEMS) or centrally e.g. energy regulation side, such as DSO, VPP aggregator, or CPO. The technical requirements and the applicable standards can differ for each use case and for several use cases, there exists no standardization yet at all.

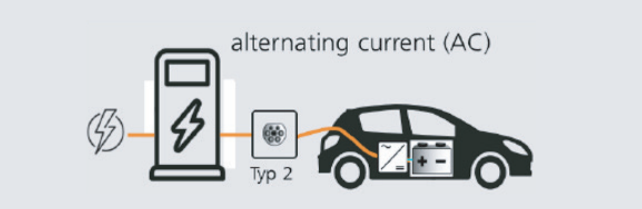
The use cases can be generally grouped into the following categories:

- V2H: Vehicle-to-Home
- V2G: Vehicle-to-Grid
- V2B: Vehicle-to-Building
- V2L/V2V: Vehicle-to-Load or Vehicle-to-Vehicle

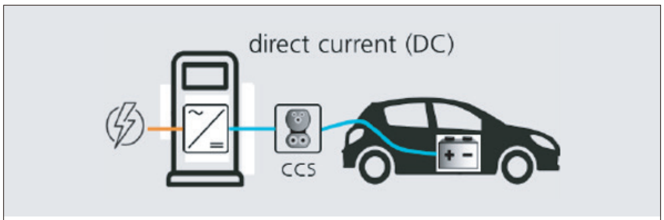
Use case group	case description	Target User
V2H	Optimization of self-consumption	Home owner/residential
V2H	Tariff-optimized charging and discharging	Home owner/residential
V2H	Island mode operation	Home owner/residential
V2G	Wholesale trading (ex. intraday or day-ahead)	Home owner, Commercial or fleet operator
V2G	Frequency regulation	Home owner, Commercial or fleet operator
V2G	Demands response	Home owner, Commercial or fleet operator
V2B	Peak shaving	Commercial building
V2B	Fleet charging management	Business/fleet customer
V2L/V2V	Vehicle to load and to vehicle	Personal use

Regardless of the use case, V2X bidirectional charging system technology can be either V2X DC (stationary inverter in charger) or V2X AC (inverter function in a vehicles' onboard charger). Both approaches have their technical and practical differences, but also share some dependencies. The main difference is that in the DC charging configuration, the inverter moves from the EV to the EV charger. As the most important starting point to enable V2X in either configuration, the EV manufacturer has to adapt the BMS (battery management system) and EVCC (EV charge controller) to enable the functionality of discharging to the vehicle's plug.

A schematic setup of V2X AC system with an OBC (onboard charger) and V2X DC system with an off-board charger is shown in the figure. It also shows the main advantages and disadvantages of both solutions. AC connection requires an IEC AC type2 plug in European countries, IEC AC type1 or NACS (North American charging standard) AC in North American countries. A DC connection requires a CCS2 (combined charging system) plug in European countries, CCS1 or NACS DC plug in North American countries that can be used for AC charging as well. In all cases, the V2G communication protocol between EV and AC chargers or DC chargers is moving towards the same standard, ISO15118-20.



↑ Charger hardware cost is lower
↓ Grid code requirements are challenging
↓ Grid certification needs to be done in combination of OBC and AC charger (proprietary solutions)
↓ V2X AC interoperability is not matured
↓ EV eventually slightly more expensive due to bidirectional OBC
↓ No standardized grid codes in EU



↑ (Dis-)charge power can be higher
↑ Higher interoperability with different EV models
↑ Grid interconnection and grid protection is simpler
↓ Hardware cost of a DC charger is considerable higher due to more power electronics

Status quo of the core V2X standards

As one of the grid interconnection technologies, V2X is quite similar to PV inverters with respect to grid interconnection requirements implementation.

AS 4777 is the primary standard in Australia and New Zealand for grid-connected distributed energy resources such as photovoltaic (PV) systems, battery storage and electric vehicles. Part 2 (AS/NZS 4777.2) deals specifically with inverter grid-connection requirements, including vehicle-to-grid (V2G) technology. Since that, V2G is first time to be required to fulfill the grid interconnection compliance, saying ‘grid code’ in PV industry.

The V2G relevant equivalent of Australia’s AS 4777.2 in Germany is VDE-AR-N4150, EN50549 in other European countries and UL1741 in North American countries. All of these pertain to the grid interconnection of distributed energy resources (DERs) (e.g., PV inverter, BESS (battery energy storage system) and V2X bidirectional charging systems), but they differ in technical details (power quality, anti-islanding protection, active/reactive power control, voltage/frequency response), testing methods, and other regulatory requirements. VDE-AR-N 4105 is a German-specific, stricter version of EN 50549. Besides this, the regional standards are not interchangeable with each other, so product variants specific to each market are required to comply with each standard.

Standards	Applicable Region	Core Scope	Regulatory Body
UL1741	USA, Canada	Inverters, energy storage, V2G (with SA + SB supplements)	UL (USA), CSA (Canada)
VDE-AR-N 4105	Germany	≤30 kW distributed generation (including V2G)	VDE/BDEW (Germany)
EN 50549	Pan-European countries	DER grid connection (all power ranges)	CENELEC (Europe)
AS/NZS 4777.2	Australia, New Zealand	Grid-tied inverters ≤200 kVA (including V2G)	Standards Australia

The charging interfaces between EV and EV charger are different types used in different regional markets. Similar to the regional variety in domestic sockets, their physical dimensions are different. CHAdeMO is a Japanese standards, it was at the forefront of the market but nowadays has been phased out of many global markets except for Japan.

Besides CHAdeMO, the other interfaces types (CCS1, CCS2 and NACS) are homologous. All of them combine AC and DC together, simplifying the inlet-socket for the whole-car design. Although their physical dimensions are different, the communication between EV and EV charger are compliant with the same ISO15118 family of standards and based on the well-known and highly industrialized TCP connectivity technology.

Physical interface*				
Most applicable countries	U.S, Canada, South Korea, Mexico	European countries, Australia	U.S, Canada, Mexico	European countries, U.S, Japan
Application level	ISO15118-2, ISO15118-20, DIN 70121, SAE J2847/2			CHAdeMO spec.
Underlying level	HomePlug GreenPHY and PWM pilot control signal (IEC61851-1 Annex A , SAE J1772 and SAE J3400)			CAN2.0B + Pilot control signal (CHAdeMO spec)
Security feature	TLS1.2 is optional in ISO15118-2, TLS1.3(mutual authority profile) is mandated in ISO15118-20			No
Bidirectional power transfer	BPT (bidirectional power transfer) feature is only defined in ISO15118-20: schedule control mode and dynamic control mode			CHAdeMO V2H spec.

*As this white paper is primarily intended for non-Chinese markets, GBT (China National Standard) is not listed in the tables.

In ISO15118 family, DIN 70121 and SAE J2847/2 are mutually equivalent that just ‘simplifies’ the application messages based on ISO15118-2 on the application level. They are not fundamentally different than ISO15118-2.

In 2022, ISO 15118-20 (Gen 2) Amendment 1 was published and co-exists with ISO15118-2 in the ISO15118 standards system. ISO15118-20 enables communications for bidirectional power transfer, but the accompanying testing protocol development and uptake of ISO 15118-20 (Gen 2) have been slower than anticipated. Amendment 2 is expected to replace amendment 1 in 2026 and also to improve some relevant features.

Although some manufacturers use proprietary protocols for discharging an EV battery via the CCS system currently and SAE J2847/2 describes the application of ISO 15118-2(Gen 1) for DC V2H/V2G in U.S market, the widely recognized and accepted V2G protocol in the industry remains ISO 15118-20. This is because its characteristics are best to adapt to future-proof V2X bidirectional charging application scenarios and it includes built-in features to de-risk V2X operations compared to the previously mentioned methods.

3.The promise of V2X bidirectional charging: Drivers and Barriers

Currently V2X is in the testing phase in many countries across Europe, U.S and Asia. Most of the piloted activities still aim to prove the concept according to v2g-hub data base.

The map above shows V2G project across the globe. It provides insight into which locations are hotspots for V2G activity. By zooming in the world map, you can highlight the projects in that region in the list below. Go to the filters page to further narrow down the dataset used in this chart.

The availability of EVs capable of V2X is still limited in all markets including Europe, the U.S and Asia. Several V2X EV models have recently been announced or are already available in the EU, however, only for specific V2X applications. Tesla has realized bidirectional charging (V2L, V2H) with the Cybertruck in the U.S, but the developments for further models and EU market are not yet clear.

OEM	Model	V2X Capability	Introduction in Europe	Charging Standard
Audi	Q4	V2H and V2G announced	2023	CCS
BYD	Atto 3	V2L	2023	CCS
BYD	Dolphin	V2L	2024	CCS
BYD	HAN	V2L	2023	CCS
BYD	SEAL 82.5 kWh	V2L	2023	CCS
Cupra	Born (with 77 kWh and VW-Software 3.5)	V2H	2023/2024	CCS
Cupra	Tavascan	V2H and V2G announced	2024	CCS
Dacia	Spring	V2L	2024	CCS
Ford	F-150 Lighting	V2H	2023	CCS
Genesis	GV60, GV70, G80	V2L	2022	CCS
Hyundai	IONIQ 5/6	V2L	2022/2023	CCS
Hyundai	Kona Electric 65 kWh	V2L	2023	CCS
Kia	EV9 AWD/GT-Line	V2L, V2H, V2G	2023	CCS
Kia	Niro EV	V2L	2022	CCS
KGM	Torres EVX	V2L	2024	CCS
Lucid Air	Grand Touring	V2L and V2H and V2G announced	2023	CCS

OEM	Model	V2X Capability	Introduction in Europe	Charging Standard
Lucid Air	Pure RWD	V2L and V2H and V2G announced	2024	CCS
MG	MG4, MG5, Marvel	V2L	2022	CCS
Mitsubishi	Outlander[1], eMIEV[1]	V2G	2010	CHAdeMO
Nissan	Leaf	V2G	2013	CHAdeMO
Nissan	Leaf e+	V2H, V2G	2022	CHAdeMO
Nissan	eNV200[1]	V2G	2020	CHAdeMO
Peugeot	e-3008/5008	V2L	2024	CCS
Polestar	3	V2L and V2H and V2G announced	2022	CCS
Polestar	4	V2L	2024	CCS
Renault	5 E-Tech	V2L and V2H and V2G announced	2024	CCS
Volkswagen	ID.3, ID.4, ID.5, ID.7, ID Buzz (with 77 kWh and VW—Software 3.5)	V2H and V2G announced	2022-2024	CCS
Volvo	EX90	V2L and V2H and V2G announced	2022/2023	CCS
XPENG	G6/G9 RWD	V2L	2024	CCS

According to these pilot projects, the social-economic benefits are summarized:

1.The key benefits that have been identified are integrating a higher share of intermittent renewable energy resources

2.V2G can reduce peak loads at both transmission and distribution system level as well as congestion at distribution grid level

3.V2H can increase the self-consumption of photovoltaic power and thereby also reduce the amount of electricity needed from the grid, also reducing unwanted PV supply peaks (the Duck Curve)

4.The revenues of V2X can be substantial for EV users but differ depending on the different use cases. V2G can achieve higher revenues than V2H as electricity is fed back to the grid leveraging arbitrage opportunities in power markets. However, the revenue of V2G highly depends on price expectations on day-ahead and intraday power markets and regulatory conditions allowing participation on these markets. As more renewable energy production is rolled out over all countries, the number of negative price times per year are increasing, which improves the economic viability of V2G services.

Negative price time per year is increased year by year.

Unit: hours per year

Year	Germany	Sweden	Netherlands	UK	Data source
2019	211	48	89	5	EPEX Nord Pool
2020	298	72	132	12	
2021	276	91	158	8	
2022	346	117	201	23	
2023	389	145	255	31	
2024(1-6)	240	98	180	22	

https://mobilityhouse-energy.com/int_en/knowledge-center/article/which-cars-are-v2g-capable

Barriers to large-scale adoption persist, such as:

1.The willingness of EV drivers to participate in bidirectional charging is the most critical aspect. Potential revenue or electricity cost savings are typically the most important factors for EV owners, along with concerns about battery degradation.

2.Regulations vary across regions/countries and set the boundary conditions for V2X deployment. They can either represent a barrier or a driver. Some crucial elements of regulation related to V2X are:

- The general rules and directives of the electricity market for V2X adoption
- The technical specifications and requirements of V2X charging equipment and EVs,
- V2G tariffs and taxation structure
- V2G grid codes requirements

3.Interoperability between EVs and bidirectional EV chargers blocks V2X scaling. Vehicles supporting the ISO 15118-20 standard are only starting to enter the market. Some vehicle OEMs have developed proprietary protocols or versions of widely used protocols, limiting which hardware is compatible with the EV. Widespread interoperability is crucial for the deployment of V2X across use cases and market segments.

- **ACER’s amendment proposals for the European Grid Codes. The homologation is crucial for V2G adoption in EU.**

Harmonized European Grid Codes for EV + EVSE by 2028/2029

2023	2025-2026	3 years	2028-2029
Amendment proposal by ACER	Entry into force of the amendment proposal by European Commission	Implementation of measures to ensure Grid Code conformity by stakeholders	Application of Grid Codes by EV + EVSE

The following segment is brought to you by our featured aggregation and trading partner The Mobility House Energy GmbH

4.The role of aggregators and the retail energy market participation

V2X gives EV users the ability to have their vehicle participate in the home energy ecosystem and to integrate with the electrical grid and power markets. Simple control based on basic rules and/or a home energy management system gives EV owners the tools to integrate their EVs into their home to accomplish tasks such as optimizing the use of solar power to avoid using power imported from the grid.

However, to achieve the maximal financial benefit for an EV owner and to maximize the positive impact on the overall grid, some additional features are helpful or even necessary.

Dynamic Electricity Tariffs

Traditional electricity tariffs have generally achieved what consumers needed: a simple and risk-managed electricity rate. This has been the industry standard as it provides little variability in month-to-month cost and for many households it was not a topic of frequent thought or discussion.

When an EV enters the picture, this traditional tariff structure is no longer such a great fit. The introduction of an EV can drastically increase household electricity consumption, and increase the potential for instantaneous power consumption. EVs can often consume energy at the worst time for the grid, which both retail energy suppliers and grid operators must account for in the fees that end up with the consumer. This becomes even more of a disadvantage in a V2X context as most traditional tariffs have no concept of the house putting power back onto the grid, except limited exceptions to facilitate rooftop PV installations.

What is to be done? EV's have a key difference to the majority of household devices: they can be made to shift the timing and magnitude of energy consumption. By understanding the needs of the driver, this can even be automated to align consumption with the needs and opportunities of the grid – such as charging when wholesale electricity prices are negative and in V2X discharging when prices are sky high.

As the electricity tariff is the link between the electricity market and the consumer, the savvy EV owner must sign up for a tariff that reflects the benefit of charging at the right time instead of the wrong time. While there are pure pass-through tariffs which give consumers a price at or similar to the wholesale market price, some tariffs are even more advanced and when paired with a control system or aggregation can give the consumer upside from grid-beneficial charging and V2X while limiting downside with a price cap or similar mechanism.

EV Flexibility Aggregation and Trading

A single V2G EV can only have so much impact on the electrical power system as it will have a power level in the 10s of kWs, smaller than the minimum trade size for most electricity markets. Additionally, a single EV user may come and go at their own free will and therefore may not be around when electricity has been bought or sold on their behalf.

This problem is solved by introducing a concept called EV Aggregation. When combined, the power of many EV's combined forms an aggregated portfolio which is able to participate on electricity markets and in many balancing mechanisms, and is more predictable than any individual EV driver. The technology layer to achieve this aggregation is critical and requires advanced software platform capabilities, data analytics and short term algo trading.

5.About the author: the V2X solutions of Sigenergy

Thanks to the state-of-art DC coupling architecture, the bidirectional DC charging module seamlessly integrates with PV system and Battery energy system. This industry-leading technology delivers unparalleled competitive differentiation compared to conventional V2G market solutions, generating exceptional ROI for stakeholders through:

- **Higher energy-efficiency**

Minimized power conversion stages enable direct PV surplus transfer to vehicle battery, delivering 100% renewable energy. Thereby ensuring the self-consumption rate, while simultaneously enabling the use of vehicle batteries or storage batteries to provide 100% pure green electricity for household loads at night, thus reducing household electricity expenses.

- **Effortless grid interconnection for V2G in system**

By leveraging existing PV inverter technology in the system, the EVDC seamlessly integrates with bidirectional energy controller (AC/DC converter), enabling vehicle batteries to ultimately feed power back to the grid and/or household loads through these components. The solution complies with grid code certification requirements worldwide, facilitating seamless vehicle-grid integration for grid interaction and electricity trade market participation. This further enhances revenue streams while lowering the technical threshold for V2G implementation.

- **Priority control of PV, V2G and Battery in system**

Through the Sigenergy APP or remote communication interfaces, users can customize priority levels and power limits for PV, energy storage, and vehicle batteries. This enables more precise management of energy flow control for PV energy, battery storage energy and EV batteries energy, while providing flexible adaptation to energy usage habits across different regions/countries - ultimately enhancing the user energy experience.

- **V2G integration with Battery for VPP service**

The system's built-in EMS interface and VPP interface enable EV batteries to participate directly in regional/national VPP services and ancillary service of grid operators in electricity energy trade markets - just like battery storage systems and PV systems. This requires minimal effort for rapid V2G deployment on customer site across all countries.

- **PV and Battery boosted quick charging**

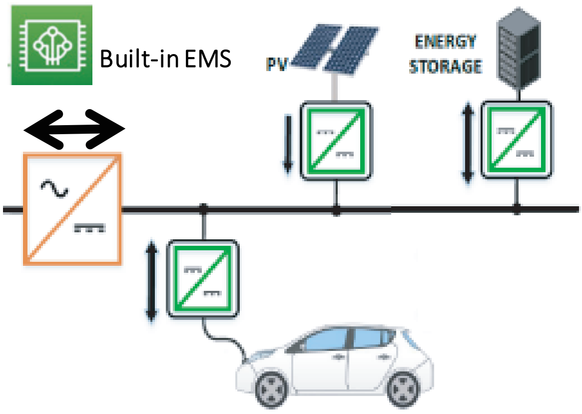
In power-deficient regions, the system combines PV and battery storage with minimal grid input to deliver high-power 25kW fast charging for vehicles at home - meeting residential quick charging demands in emergency cases. Simultaneously, through the Sigenergy App's scheduled charging feature, users can set peak-off timer. The system automatically initiates precise grid-power charging only during these optimal rate windows, significantly reducing EV charging electricity costs.

Fulfill the different voltage levels across all countries

The modular architecture with rapid-stack installation capability allows seamless integration of EVDC with different PCS variants adapting to the different voltage levels across all countries. Because EVDC is compliant with global charging standards, this all-in-one system architecture facilitates the rapid V2G deployment worldwide.

Black start capability

Unlike conventional bidirectional DC chargers employing CCS systems - which inherently lack black start functionality - the EVDC leverages integrated PV and battery energy storage systems to deliver native black start capability. This critical advantage enables uninterrupted V2G-powered home backup services during grid outages, eliminating the need for additional external device that other available solutions uses in the market.



Energy Controller

3.8-11.5kW, split phase | 3-12kW, single phase | 5-30kW, three phase

Bi-directional Charging (kW):

12.5 | 25

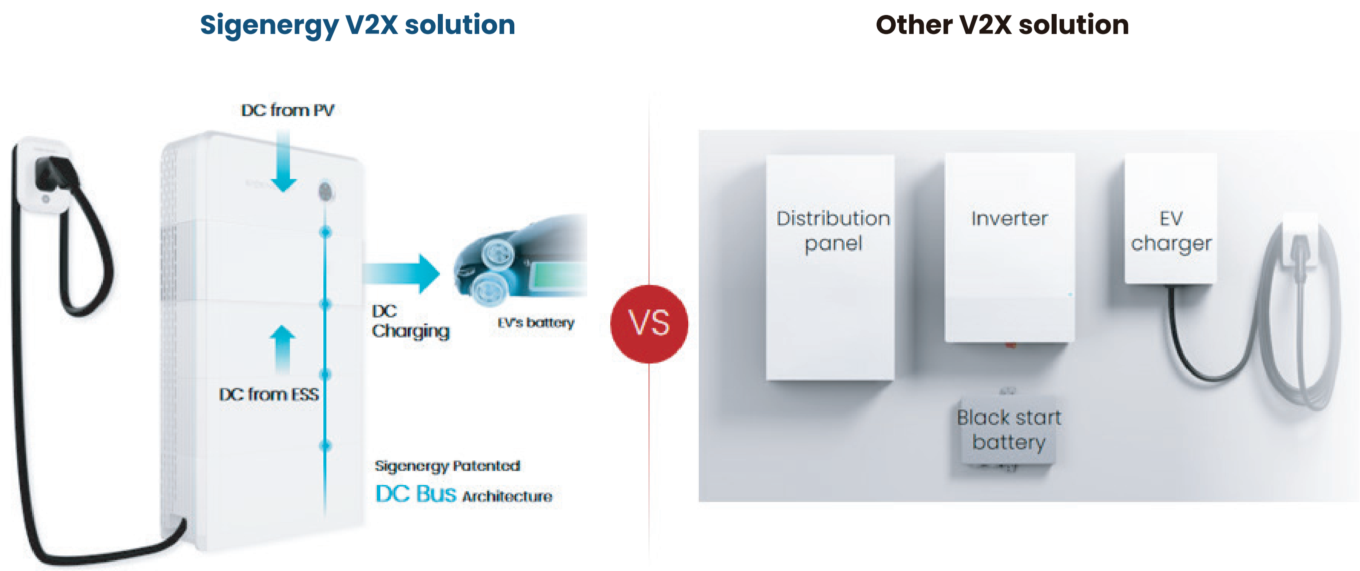
Charging interfaces:

CCS1 | NACS | CCS2

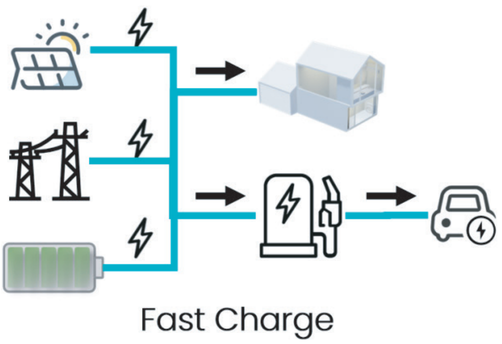
Sigen Battery Module:

6.0 | 10.0

Max. 6 batteries supported
Max. 54.24 kWh Battery capacity excluding V2X module



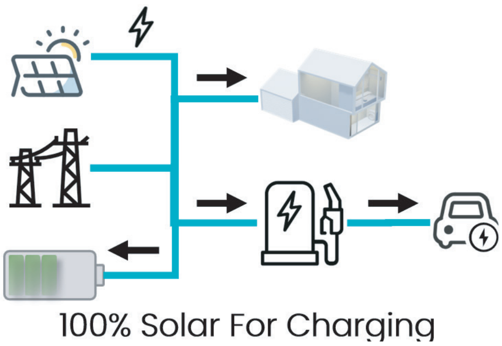
6.The available control modes of V2G in system



Fast charge mode

PV energy and Battery energy are integrated with the input power from grid to maximize the EV charging power at home.

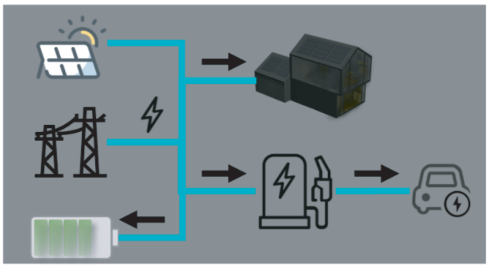
It requires less input power from grid, but boost the charging power by PV and battery storage system together for virtual expansion.



PV surplus charging mode

PV energy powers the residential load in highest priority, the excess power are transferred to EV batteries through the internal DC-link.

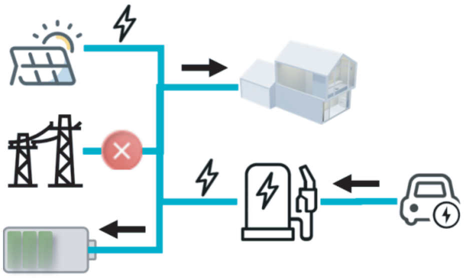
In the meantime, battery energy can be integrated with PV power because of the weak sunlight.



Scheduled Charge

Scheduled charging

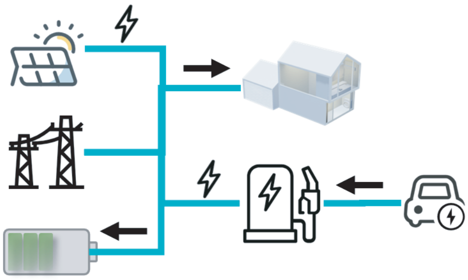
After plugged into EV, user set the timer through Sigen APP. The charging is automatically initiated when the peak-off time reaches. Convenient in the night charging to enhance user experiences.



V2H_Islanded for backup

Islanded V2H for backup

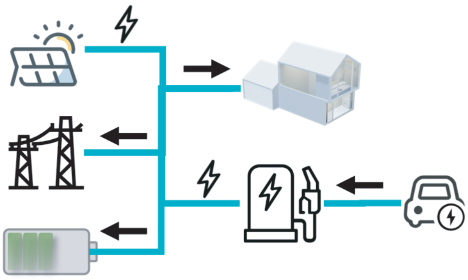
If grid outage at home, user can black start the system and use the EV batteries to energize the home loads for a long time, like the generator. Realize the home energy independent supply.



V2H_Grid-tied, non-export
(total discharge < load)

On-grid V2H mode

Without additional device, system connects with grid directly, and EV batteries can power the home load in on-grid condition without need to reversely feed power to grid.



V2G_Grid-tied, export
(total discharge > load)

V2G mode

Without additional device, system connects with grid directly, and EV batteries can power the home load and feed power to grid reversely with or without integrating PV energy and Battery energy.

Vehicle battery is used for VPP services or grid balance to participate in Flexibility market or electricity trade markets.

7.References

1. Study on the "Potential of a full EV-power-system integration in Europe & how to realise it", Study by Fraunhofer ISE & Fraunhofer ISI on behalf of Transport & Environment, 30/10/2024
2. State of the Industry Insight into the Electric Vehicle Charging Infrastructure Ecosystem, ChargeUp Europe
3. Grid Integration of Electric Vehicles A manual for policy makers, IEA(International Energy Agency)
4. Research Whitepaper - European EV Charging Infrastructure Masterplan, acea, March 2022
5. Practice Note - Smart Charging and Consumer Behavior in the United States, World Resources Institute, November 2022
6. V2X Enablers and Barriers - Assessment of the regulatory framework of bidirectional EV charging in Europe, DNV and smartEn, December 2023
7. Best practices guide for permitting and grid interconnection procedures for recharging infrastructure, Publication Office of the European Union, 2023
8. Bidirektionales Laden in Deutschland - Marktentwicklung und Potenziale, P3 automotive GmbH, e-mobil BW and NRW.ENERGY 4CLIMATE, September 2023
9. V2X Bidirectional charging systems - Best practices for service connection or interconnection, VGIC(Vehicle Grid Integration Council), August 2022
10. White Paper of Charging Interface Initiative e.V. in collaboration with P3 group, ACER's amendment proposals for the European Grid Codes, CharIN, 28/10/2024
11. Grid Integration Levels, v5.2, CharIN, 26/06/2020
12. Whitepaper of Charging Interface Intiative e.V. - DC CCS Power Classes for bidirectional charging, CharIN, 02/06/2023
13. Certificate Policy for the CharIN V2G second-generation PKI(compliant to ISO15118-20), Version 1.0, CharIN, 23/11/2022
14. CharIN BPT Survey - Insight into CharIN expert view, CharIN

About Sigenergy

Sigenergy is a global energy technology company specializing in solar, energy storage, and EV charging solutions. With a world-class R&D team, the company develops innovative products that combine simplicity in deployment, uncompromising safety, and an exceptional user experience. By integrating artificial intelligence with advanced energy storage technology, Sigenergy delivers next-generation smart energy solutions that empower the transition toward a cleaner, more sustainable future.

About The Mobility House Energy

The Mobility House Energy is a dedicated business unit within The Mobility House, a technology company shaping the future of energy and mobility. Founded in 2009, The Mobility House operates globally from Munich, Zurich, London, Paris, Singapore, and Belmont (CA).
The Mobility House Energy integrates EV and stationary batteries into the energy system – increasing flexibili-

ty, maximizing value, and reducing CO_2 emissions. Using its proprietary FlexibilityAggregator and Flexibility-Trader technologies, the company controls, optimizes, and trades storage assets across multiple markets.
In 2024, The Mobility House Energy, in partnership with Mobilize (Renault Group) and Renault, launched the world's first commercial Vehicle-to-Grid (V2G) product in France. Additional collaborations, including with Mercedes-Benz, are set to expand V2G access across multiple European countries. By 2026, the company will surpass 1 GW of flexible capacity traded across power and energy markets.