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Technology and economics of electric vehicle power transfer: insights for the automotive industry

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Abstract

Battery-based electric vehicles (BEVs) in the United States (U.S.) set a new sales record in 2022, driven by technology, policy, environmental, and economic objectives. However, the rapid deployment of BEVs and charging infrastructure without a careful review of their integration with the electric grid can have negative economic impacts on reliable and resilient electricity supply. Bi-directional power transfer (Bi-Di) vehicle-grid integration technologies and services such as vehicle-to-home or building (V2H/B) and vehicle-to-grid (V2G) can potentially lower local and system peak demand, improve economics for grid operators, and benefit BEV customers. Original equipment manufacturers (OEMs) in the automotive industry are exploring technologies and economics (techno-economics) for Bi-Di services. The study conducted a literature review of eleven case studies in the U.S. and Europe that featured Bi-Di demonstrations from 2005 to 2022 to highlight insights and techno-economic opportunities and challenges for OEMs. The findings should motivate the OEMs to prioritize technology innovation and business models to increase BEV sales and gain continuous revenue from Bi-Di services, which can potentially transition "car makers" to "technology solution" companies.

Keywords: Electric Vehicle (EV), Vehicle to Grid (V2G), Vehicle to Home (V2H), Smart charging, EV charging infrastructure, Vehicle Grid Integration (VGI) Technologies, Electricity markets, Economics

Introduction

Driven by sustainability goals, favorable federal and state policies, high oil prices, and declining battery and vehicle technology costs, plug-in battery electric vehicles (EVs) with batteries to power vehicles set a new sales record. According to the U.S. Department of Energy's (DOE) Argonne National Laboratory (ANL), in 2022, the U.S. will have achieved 32% year-over-year (YoY) growth in BEV sales, the largest YoY growth in history (U.S. DOE and ANL 2022).[1] The automotive original equipment manufacturers (OEM) and industry are committing to the transition from internal combustion engine

[1] The total PEV sales include cars, light trucks (LT), and light-duty vehicles (LDV).

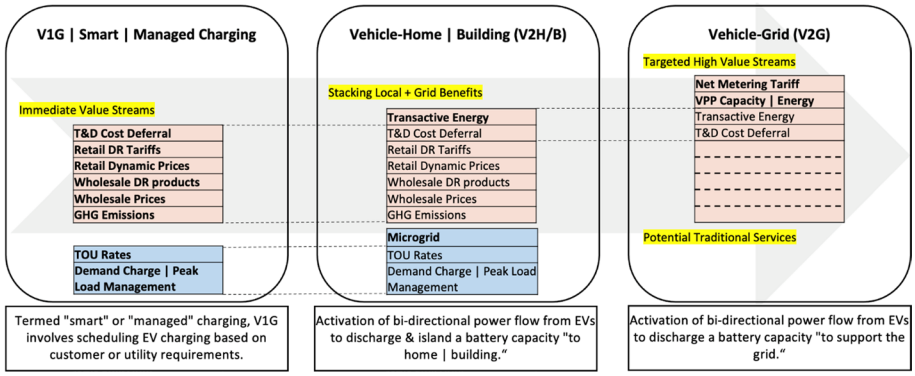

Fig. 1 Vehicle-grid integration services, terms, and energy value chain

vehicles to a BEV future. For example, General Motors (GM), one of the largest global automotive OEMs, plans to invest $35 billion in EV and autonomous vehicle product development between 2020 and 2025 and to be fully electric by 2035 (General Motors, 2022). An exponential rise in BEVs and charging infrastructure deployment without a careful review of their integration with the electric grid can have adverse economy-wide impacts on reliable and resilient electricity supply in the U.S. Studies show 8% to 9% demand growth by 2040, resulting from 27% adoption of BEVs (Bloomberg New Energy Finance 2022). While this macro-level growth may seem modest and manageable, the locational or regional micro-level growth is higher based on the time a BEV charges. For example, California, which has the most aggressive zero-emission vehicle mandates in the U.S., projects an excess of 5.4 gigawatts (GW) of demand at midnight from eight million BEVs by 2030 (Alexander et al. 2021).

The public and private sectors comprising research, advocacy, and the automotive industry have touted BEVs as distributed energy resources (DER) that can alleviate grid impacts by enabling energy flexibility with demand response (DR) and virtual power plant (VPP) services, which are collectively termed vehicle-grid integration (VGI) or vehicle-to-everything (V2X). Demand response and VPP services are offered by BEVs when they are aggregated and managed for flexible charging and bi-directional power transfer (Bi-Di) such as vehicle-to-home or building (V2H/B) and vehicle-to-grid (V2G), for services like centralized large power plants, and motivated by economic incentives. Such VGI services for DR and VPP are based on the latent ability of the BEV and synergistic DERs through flexible charging or Bi-Di services in a grid-friendly manner, i.e., improving the reliability and resiliency of the grid and customer. Using VGI technologies, a BEV can provide value-added services to a BEV owner, a campus, the grid, and society by proactively engaging electric grid and automotive industry stakeholders.

Without delving into all the VGI services, the study focuses on the role of BEV potential for Bi-Di power transfer. Figure 1 describes the VGI terms "managed charging," "V2H/B," and "V2G" in the context of the EV value chain model (EVVC). The EVVC model is adapted from an electricity value chain, which defines a portfolio of options that value energy customers' (e.g., BEV owners') EV flexibility to the electric grid at various time scales (McKane et al. 2008; Piette et al. 2014). The EVVC options can be time-of-use (ToU) rates, demand charges, DR tariffs for capacity and energy, electricity prices,

Fig. 2 Study methodology

etc., for reliable and resilient grid operations. Bi-Di services can also support emerging value chains such as transmission and distribution (T&D) cost deferrals and transactive load management, where an economic value motivates a customer to buy or sell electricity from an energy resource (Incentive-signals and to Manage Energy-consumption (TIME) 2018).

Note that a BEV's Bi-Di services are also used to power electric loads and EVs (termed, V2L and V2V), which are not focused. Similarly, managed EV charging using telematics, which is demonstrated by the automotive OEMs for utility DR programs, is not focused on either (Open Vehicle-Grid Integration Platform 2015; Guidehouse, and National Grid EV and PHEV Demand Response Evaluation 2022).

Goals and objectives

With a goal of economy-wide decarbonization and higher sales of BEVs enabled by Bi-Di services, the study's objectives are to:

- Conduct case studies and literature reviews of projects that demonstrate Bi-Di services.
- Review the technology and business motives for broader adoption of Bi-Di services.
- Develop a techno-economic evaluation framework and conduct analyses to identify its value to the automotive OEM industry.
- Provide opportunity and challenge insights for necessary Bi-Di technological developments and service offerings.

Methodology

Figure 2 illustrates the study's methodology. A retrospective case study analysis was conducted that is aligned with the study's goals and objectives. A techno-economic evaluation framework was developed to analyze findings, provide insights, and list opportunities and challenges for the automotive industry. A final set of conclusions was summarized from the analyses.

Featured case studies

A longitudinal review of publicly available demonstration projects with Bi-Directional (Bi-Di) was conducted as the featured case study. The featured case studies were selected based on the knowledge of the authors, publicly available information, and Bi-Di service demonstrations that included either technical or economic analysis, or both. A total of eleven case studies in the U.S. and Europe, spanning from 2005 to 2023, with Bi-Di

demonstrations, were reviewed. Focusing on the U.S., three European demonstrations were featured to review technology and economic similarities with European OEMs and EVVC options. The analyses included integrated technologies such as hardware, software, data, standards, network architecture, and economics (costs and revenues).

The Bi-Di services, as defined, offer unique value streams to the customers and grid. E.g., V2H/B is used in the context of a microgrid, which is a "group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid." A microgrid can connect and disconnect from the grid to enable it to operate in either grid-connected or island-mode (Ton and Smith 2012). "For V2H/B services, an inverter's grid-forming or grid-following technical capabilities, interconnection functions, etc., are needed to safely connect and disconnect from the grid. For V2G, a home or building is not landed, and the grid offsets the power supply beyond what a BEV can support. While the V2H/B value is mostly from customer cost reductions and local resiliency, the V2G value is from customer and grid cost reductions and grid reliability using no-grid export (BEV partially powers a home or building) or grid export, where BEV powers the grid. As a key distinction from V2H/B, V2G services can be provided outside a facility network (e.g., a shopping mall). In either of the services, environmental benefits from emission savings can improve overall revenues.

Case study summaries

The study reviewed the featured case studies for a key set of information while recognizing that not all case studies reviewed all the information. Table 1 summarizes case studies' information, in chronological order of demonstration date (starting with the earliest). For each featured case study, three core sets of information are summarized—*BEV & infrastructure (OEM role), bi-directional service and markets (power system and customers), and revenues (economics)*. The case studies are further described with *description; Bi-Di technologies; and economic*s. The fixed costs for a fully installed and commissioned hardware and software, and the recurring costs to provide Bi-Di services are not included since they were not assessed across the case studies.

Figure 3 illustrates min, max, and average revenues for each of the featured case studies. The analysis highlights three key distinctions: (1) Lower revenue analysis by public studies relative to vendor analysis; (2) Multi-stacking of EVVC options yields higher revenues; and (3) The U.S. demonstrations have slightly higher revenues relative to the European analysis.

Case study descriptions

The section reviews the featured case studies for detailed information for further analyses, in chronological order of demonstration date (starting with the earliest).

The University of Delaware and Nuvve (2005–22)

Leading from the front from early 2000, the University of Delaware has conducted a series of demonstrations to develop and assess the value of V2G technologies (Multi-lab EV Smart Grid Integration Requirements Study 2015; Ghatikar 2016).The demonstrations led to the first commercial participant in the PJM wholesale markets in 2013 using

Table 1 Summary of featured case studies: BEV, infrastructure, Bi-Di services, and revenue

Featured Case Study	BEV and Infrastructure	Bi-Directional Service and EVVC Option(s)	Revenue (BEV/Yr.)
Univ of Delaware & Nuvve (2005–22) (Multi-lab EV Smart Grid Integration Requirements Study 2015; Ghatikar 2016; Parkison 2020)	Multiple LD- and MD-BEVs and EVSE configurations; onboard and off-board inverter demonstrations	Individual & fleet V2G (typical 10 kW grid export) for many EVVC options & PJM market commercialization	$1200 to $3400 $2300 Avg
LBNL LA-AFB (2012–16) (Marnay et al. 2013; Black et al. 2017)	Forty-one mixed-duty BEV fleet (cars, trucks, and vans); 40 EVSEs; off-board inverters (limited data)	Fleet V2G (export) of ± 15 kW for CAISO Regulation markets, & V2B microgrid	$1500 Avg
U.S. Army Ft. Carson (2013–14) (Multi-lab EV Smart Grid Integration Requirements Study 2015; Kazbour 2014)	7 BEV trucks with 60 kW onboard inverters; 5 DC EVSEs with ± 60 kW Bi-Di power capacity	Multi-stacked V2G—reactive power (export), peak shaving (non-export), & regulation services (export)	$4320 to $7200 $5760 Avg
PG&E EPIC (2016–18) (Pacific Gas and Electric Company (PG&E) 2018)	Fleet BEV truck w/ 5 kW DC discharge rate; V2H capable EVSE and supporting software	V2H for resiliency and islanding for capacity-bidding and CAISO supply-side pilot	$1400
EPRI UCSD (2016–19)(Chhaya et al. 2018)	5 LD BEV fleet with onboard bi-directional charger; four ± 7.2 kW Level 2 AC EVSEs	V2G services for many EVVC options – peak, ± renewable generation & ramping, & CAISO market participation	$450 to $1850 $1150 Avg
LBNL Miramar MCAS (2020–22) (Black and Yin 2022)	6 BEVs passenger and cargo vans with onboard inverters; a total of 6 AC EVSEs of 19 kW each	Fleet V2G (non-export) of ± 15 kW for SDG&E retail DR program, local de mand management, and V2B (microgrid)	$1525
Fermata Energy and Partners* (2019–22)(Empower Innovation 2019; N.C. Clean Energy Technology Center (NCCETC) 2021; Fermata Energy, Electric Vehicle Generates Revenue 2022; Fermata Energy Vehicle-to-Everything (V2X)2022)	LD-BEVs Bi-Di charger with an off-board inverter, mostly for Nissan Leaf CHAdeMO standard	V2G (non-export & export) for DR, system peaks, and demand charge mitigation	$1900 to $4200 $3050 Avg
Peak Power & Partners* (2019–22) (Peak Power, Peak Drive Pilot Project 2019)	Software & data platform for LD-BEVs & third-party Bi-Di chargers with off-board inverter; Nissan Leaf BEV & CHAdeMO	V2G (non-export) to lower peak demand; Utility bill savings from demand charge reduction	$8000
Parker Denmark (2016–2019) (Parker Project https://parker-project.com/)	50 CHAdeMO Bi-Directional DC EVSEs, Nissan Mitsubishi, and Peugeot V2G-enabled BEV fleets	V2G services for frequency regulation and GHG emissions; A total of 13,000 h of Bi-Di services per BEV in frequency regulation	$2046
Sciurus UK (2018–21) (Cenex, Project Sciurus Trial Insights 2020; Cenex 2020; Commercial Viability of V2G 2023)	325 CHAdeMO Bi-Di DC EVSEs with 6 kW charge & discharge; Residential (single phase) V1G and V2G Nissan Leaf BEVs with 30 kWh or more battery capacity	Residential V2G; a total of 750 MWh of V2G energy export through participation in the UK's spot market prices, frequency, and dynamic containment services	$906
Federal Ministry, Germany BDL (2021–2023) Munich (https://www.ffe.de/projekte/bdl/; Kern et al. 2020, 2022)	30-nos commuter and 20-nos non-Commuter MD- fleet BEVs with different battery capacities, charge/discharge rates; 50 Bi-Di DC EVSEs	± 11 kW for V2G service in day-ahead & intraday spot markets; V2H & V2G services for PV self-consumption and price arbitrage	$550 to $1430[a] $990 Avg

[a] €200 to €1300 revenue range with a USD ($)/Euro (€) conversion rate of 1.10; higher revenue results from non-commuter BEVs with higher battery capacities and charge/discharge rates

* It should be noted that the review for these case studies is based on vendors' media and public information. Data with detailed analyses were not available to validate the revenues and EVVC options

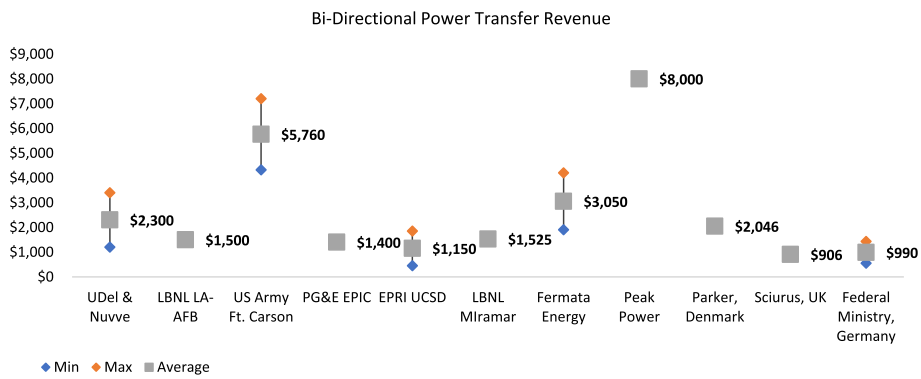

Fig. 3 Bi-Di revenue summary from case study demonstrations

BMW's Mini E BEV, which had an onboard inverter and battery charger (The University of Delaware 2013). In 2017, the University of Delaware gave exclusive global rights to its V2G software to Nuvve Corporation and commercialize V2G-enabled EVSEs (Scout 2016; Roberts 2017).

The review of many studies shows that V2G participation in the PJM wholesale markets in 2013–14 resulted in daily revenue of $5 per BEV (Multi-lab EV Smart Grid Integration Requirements Study 2015; Ghatikar 2016). Extrapolating this to a monthly participation of 21 days, an annual revenue of $1250 per BEV can be achieved. The review of revenue potential from latest information is significantly higher and varies widely, depending on the VGI service and EVVC options such as energy (ToU and DR programs), capacity (demand charges, retail, and wholesale markets), etc. (Parkison 2020). The annual revenue estimates for 100 kW V2G bid are, as follows: $500 to $3000 (energy arbitrage), up to $2500 (demand charges), $3000 to $7000 (capacity arbitrage), $5000 to $18,000 in regulation markets (capacity and energy), and $2500 to $4000 in spinning reserve markets (capacity and energy). If BEVs can leverage all these EVVC options and are available to participate, total revenue can range from $11,500 to $34500 or $1200 to $3450 per BEV with a discharge capacity of 10 kW.

LBNL LAAFB V2G (2012–16)

With funding from the California Energy Commission (CEC), Lawrence Berkeley National Laboratory conducted one of the earliest V2G demonstrations at Los Angeles Air Force Base (LA-AFB) from 2012 to 2016 (Marnay et al. 2013; Black et al. 2017). The demonstration used a fleet of 41 mixed-duty BEVs (cars, vans, and trucks) to assess the feasibility of V2G technologies to participate in California Independent System Operator's (CAISO) Regulation Up and Down markets, and for microgrid resiliency.

Limited data is available for the EVSE infrastructure other than a mention that up to 40 EVSEs customized with off-board inverters were used for the demonstration. The technology was unique at three levels: (1) develop V2G technology capability to charge or discharge a BEV based on CAISO's market rules; (2) use of advanced modeling tools that preemptively identified BEV charge and discharge schedules for day-ahead bidding; and (3) use of open standards, OpenADR and, potentially Open Charge Point Protocol

(OCPP) to efficiently integrate V2G technologies with retail (Southern California Edison) and wholesale (CAISO) market systems.

Simulated data from a fleet of 18-BEVs show an operational cost of $0.72/BEV is recognized by the energy charges in the ToU tariffs. A BEV can generate a revenue of $112/month or $1345/year by participating in the CAISO regulation markets for 21 days a month.

U.S. Army Fort Carson (2013–14)

A subset of the U.S Federal Smart Power Infrastructure Demonstration for Energy Reliability and Security (SPIDERS) program at Fort Carson, CO, conducted a demonstration of MD-BEVs for V2G services within a microgrid. The EVVC options included reactive power export, peak shaving, and power regulation wholesale markets (Multi-lab EV Smart Grid Integration Requirements Study 2015; Ghatikar 2016). The demonstration developed BEV and EVSE hardware and software to interface BEV to a microgrid and aggregated V2G controls when the microgrid is in grid-tied mode (non-export) and frequency regulation (export) function.

The BEVs comprised 5 nos. of Smith and 2 nos. of Boulder BEV trucks with 60 kW onboard inverters and 80 kWh battery capacity. Project developed 5 nos. of DC EVSEs based on the SAE J1772 CCS standard with ± 60 kW Bi-Di power capacity and used PLC physical layer on the control pilot line to communicate with the BEV. Another mode of communication using the Home Plug Green physical layer was not tested. The demonstration captured 45% of the total connected load of two BEVs that shaved 43 kW of the measured demand. The frequency regulation signal from PJM was used for testing where a signal was sent to the microgrid controller with a 4-s sampling rate and delivered to EVSEs with a 15-s sampling rate.

The multi-EVVC options showed significant revenue opportunities if scaled for longer periods. The following annual economic values were determined: $4320 per EVSE (reactive power export), $7200 per BEV (demand charge reduction from peak shaving), and $4800 per BEV (frequency regulation markets) (Kazbour 2014).

PG&E EPIC (2016–18)

The utility, Pacific Gas and Electric Company (PG&E) conducted V2H and V2G bidirectional services demonstrations under California's Electric Program Investment Charge (EPIC) program (Pacific Gas and Electric Company (PG&E) 2018). Here, under the directive of the California Public Utilities Commission (CPUC), PG&E assessed V2H technologies to provide residential back-up for resiliency or island home to reduce grid load during DR events (Pacific Gas & Electric Company (PG&E) 2016). To assess the effectiveness of DR participation, California Independent System Operator (CAISO) Supply-Side Pilot (SSP) program was leveraged.

Albeit technically feasible, the lack of willingness by automotive OEMs (due to lack of efficacy and battery warranty) to mass produce BEVs with bidirectional charging capabilities was mentioned, as one of the key barriers to the commercialization of V2H and V2G technologies. The technologies tested included a V2H capable off-board inverter and charger that could be used to aggregate BEVs, which are assumed to provide 3.3 kW of discharge power per BEV.

The project estimated the full cost of a V2H system to be $4500, which included bi-directional EVSE and software (AC Level 2 with IEEE 2030.5), critical panel costs (transfer switch, panel equipment, switch box), and full installation that did not include V2H-capable EV. The high V2H technology cost was one of the barriers where customer interest dropped significantly with a price above $1000. Here, customers viewed the use of V2H technology for emergencies (resiliency) and not for cost savings through participation in DR programs. The project results show approximately $1400 of net benefit to incent customer participation.

EPRI UCSD V2G (2016–19)

With funding from the California Energy Commission (CEC), Electric Power Research Institute and its partners conducted a V2G demonstration at the University of San Diego from 2016 to 19 (Chhaya et al. 2018). The project demonstrated V2G technologies and integrated systems with distribution grid conditions awareness. The V2G services from five LD fleet BEVs were tested and modeled for peak management, address over- and under-generation conditions from renewables, reduce fast ramping up or down from high demand, and wholesale market participation.

System integration included ISO, utilities, and distribution transformer management system (TMS) with a residential gateway that communicated with BEVs via ± 7.2 kW Level 2 AC EVSEs. Open data standards were used to communicate between TMS, EVSE, and BEVs that were cyber-secure and included SAE J3072, J2847/3, and IEEE 2030.5. The TMS was a Virtual End Node with OpenADR 2.0b data standard for communications with an aggregator, energy service provider, utility DSO, or an ISO.

Revenues from V2G were modeled using four EVSEs and five LD fleet BEVs with a 6.6 kW onboard bi-directional charger. The modeling results that stacked numerous benefits from V2G services ranged between $450/year to $1850/year per BEV. It should be noted that V2G revenue could be, as high as $1725 when a BEV can participate in ISO markets with "no constraints on battery degradation or SOC." In certain cases, for "congested locations with both high system and distribution capacity value," a BEV can generate a V2G revenue, as high as $1100/year.

LBNL Miramar MCAS (2020–22)

With funding from the California Energy Commission (CEC), Lawrence Berkeley National Laboratory conducted a V2G demonstration at Miramar, CA's Marine Corps Air Station (MCAS) from 2020 to 22 (Black and Yin 2022). The demonstration included a fleet of 6 passenger and cargo vans with onboard inverters to review the feasibility of V2G and V1G technologies to participate in California utility, San Diego Gas and Electric's (SDG&E), DR program, assess local demand management for utility bill savings, and for microgrid resiliency.

Each V2G-enabled van was nominally rated at ± 15 kW with an onboard charger limiting the charging and discharging power to 15 kW in each direction. A total of 6 AC Level 2 (L2) EVSEs with a maximum current output of 80 A or a total 19 kW power output were used. A total of 20 kW of net discharge was achieved for demand charge management during normal building operations. An aggregated average discharge in the range of 5 kW to 12 kW was achieved for a 4-h DR event window, which resulted in each

Table 2 Utilities, partners and revenue findings from fermata energy's case studies

Utilities and partners	Annual revenue (bev/year)
Electronic Instrumentation and Technology facility, Danville, VA with Danville Utilities	$1900
Roanoke Electric Cooperative (REC)'s headquarters, Ahoskie, NC in partnership with NC Clean Energy Technology Center and REC	$2655 $3500 to $4000 (stacked EVVC estimate)
Burrillville Wastewater Treatment Facility, Burrillville, RI with National Grid	$4200
City of Boulder's North Boulder Recreation Center	$2965

BEV discharging approximately 2.5 kW power. The EVSE's advanced communications included an open standard, IEEE 2030.5, using Ethernet.

In summary, the average monthly cost savings per V2G-enabled van in summer was $89 per month from on-peak demand and energy savings, plus $35 per participating 4-h SDG&E DR event, or a total $1525/year for each BEV. With an addition of 125 kWh battery installed onsite, the demand-savings achieved during grid-tied operation amount to an average range of 24 kW to 41 kW in winter and summer months, or 26% to 40% of total facility load, respectively. The demand savings result in utility bill cost savings in the range of 20% to 37% in the winter and summer months, respectively.

Fermata energy and partners (2019–22)

It should be noted that the review is based on the media and company information. Data with detailed reports were not available to validate the revenue models. Fermata Energy, a private company in the U.S., offers vehicle-to-home, building, and grid technologies, and is one of the signatories of the U.S. Department of Energy's (DOE) Vehicle to Everything (V2X) Memorandum of Understanding where an objective is to use Bi-Di charging services to benefit the customers (Fermata Energy https://fermataenergy.com; U.S. DOE 2022). With its Bi-Di chargers and a cloud software platform, Fermata Energy and its partners have conducted a series of V2G and V2B demonstrations with utilities and DR programs to mitigate peak demand that lower system-wide costs and demand charges (Empower Innovation 2019; N.C. Clean Energy Technology Center (NCCETC) 2021; Fermata Energy, Electric Vehicle Generates Revenue 2022; Fermata Energy's Vehicle-to-Everything (V2X) 2022).

Fermata Energy's Bi-Di chargers with off-board inverters are rated at 15 kW and 20 kW power capacity and are targeted for LD-BEVs where tests have focused on Nissan Leaf's CHAdeMO charging standard. It should be noted that the U.S. and European automotive OEMs use Society of Automotive Engineers' J1772 for AC and Combined Charging System (CCS) for DC EVSEs. The average discharge rate for most of the demonstrations was around 14 kW.

The revenues from Bi-Di services were promising, which are summarized in Table 2.

Peak power and partners (2019–22)

It should be noted that the review is based on the media and company information. Data with detailed reports were not available to validate the revenue models. Peak Power, a private company in Canada aggregates "battery storage, grid-interactive buildings, and bi-directional electric vehicles with a single software platform (Peak Power, About Peak Power. https://peakpowerenergy.com/about-us-net-zero-building/)." In the Peak Drive project in partnership with the Canadian government and Ontario's Independent System Operator, Peak Power conducted a V2G demonstration with twenty-one third-party Bi-Di chargers and Nissan Leaf's CHAdeMO charging standard for three office buildings in Toronto city (Peak Power, Peak Drive Pilot Project 2019).

Using the commuter and car-sharing program BEVs, the V2G service and stationary energy storage system reduced peak demand in the office buildings and thus lowered demand charges. Unique to the Toronto region, the Global Adjustment Charge (GAC) is determined based on the five highest peak hours of consumption in a given year. This charge is substantial for a peakier facility for a limited number of hours in a year. From the early demonstration results, Peak Power indicates that annual revenues of $8000 per BEV can be achieved from bill savings.

Parker, Denmark (2016–2019)

Funded by the Energy Technology Development and Demonstration Program (EUDP) of Denmark, the goal of the Parker Project was to demonstrate that BEVs can participate in advanced smart grid services using V1G and V2G services. The project partners included Nissan, Mitsubishi, PSA ID, Nuvve, Frederiksberg Forsyning A/S, Insero A/S, Enel X, and DTU (Parker Project. https://parker-project.com/).

The project utilized a fleet of BEVs from various OEMs and a CHAdeMO V2G DC charger for V2G demonstration. In addition, the project partnered with V2G hub Frederiksberg Forsyning, where BEVs provided frequency containment reserves in the Copenhagen area.

The project's vehicles and charging infrastructure have now proven technically capable of providing all frequency coordination services in use in Denmark. It was concluded that V2G technology is scalable for BEVs across multiple OEMs, participation in frequency services for wholesale markets, and longer duration with annual revenues of €1860 ($2046) per BEV.

Sciurus Project, UK (2018–21)

Innovate UK funded a V2G project, Sciurus, a demonstration from 2018 to 2021, in partnership with Cenex, Nissan, OVO Energy, Indra, and Kaluza. Among the largest V2G project demonstrations at the time, the objective was to validate the technical and economic feasibility.

Around 325 V2G-enabled EVSEs with off-board inverters were installed in homes and tested with CHAdeMO-based Nissan Leaf BEVs. Cloud optimization and phone App were used to determine the V2G schedule, manage charging, and ± 6kW energy export. The energy export was optimized for UK's spot energy market prices, frequency regulation, and dynamic containment services.

EV users received £0.30 per kWh ($0.38) of energy exported from their EVs, or £0.26 per kWh ($0.33) if they had local micro-generation. On average, a customer was paid £80 ($100) per month on their V2G credits, or £960 ($1200) annually (Commercial Viability of V2G 2023)).

Federal Ministry Germany Bi-Directional Charge Management Project (2019–2023)

Funded by Germany's Federal Ministry for Economic Affairs and Technology, the Bi-Directional Charge Management (BDL) project was initiated in 2019. Led by the BMW Group, other partners included KOSTAL Industrie Elektrik GmbH, TenneT, Bayernwerk Netz GmbH, Forschungsstelle für Energiewirtschaft e.V. Forschungsgesellschaft für Energiewirtschaft mbH, Karlsruhe Institute of Technology (KIT) and the University of Passau (Munich https://www.ffe.de/projekte/bdl/).

Testing of the first 50 BMW i3 vehicles with Bi-Di capability was launched in 2021 under real-life, everyday conditions (Munich https://www.ffe.de/projekte/bdl/). The BEV battery was used for charging or discharging at 11 kW, which significantly impacted revenue generation. For V2G services, BEV charging times are optimized for hourly electricity prices and its arbitrage in day-ahead and intraday markets.

The V2G services leverage multiple EVVC options: managed charging, frequency response, energy arbitrage, and reduction of GHG emissions. The V2G and V2H/B services were used to reduce system peaks (commercial), increase self-consumption (residential), and temporal arbitrage in markets (commercial and residential) (Kern et al. 2020). Each BEV's V2G service could generate annual revenue between €500 to €1300 ($550 to $1430) through day-ahead and intraday spot market trading. The intraday trading revenues were about twice as high, relative to the day-ahead market. Combined market participation has the revenue enhancement by 10% (Munich https://www.ffe.de/projekte/bdl/).

Core findings

Collectively, analyses of featured case studies show the value of Bi-Di services, as demonstrated within participating markets and relevant responses to single or multiple EVVC options. It is worth noting that for technical and economic analysis, actual discharge or charge rates, total demand, and energy reduction, time of the day, day of the week, response duration, state-of-charge, etc., also play a critical role, which is not reviewed in the study.

The average annual revenues from the U.S. case studies reviewed by the public institutions are in the range of $1150 to $5760 per BEV, where higher revenues depend on regional markets and EVVC option stacking. The U.S. case studies reviewed by the private sector show higher average annual revenue from $3050 to $8000 per BEV. The average annual revenues from the European case studies reviewed by the public institutions show a slightly lower revenue range of $906 to $2046, indicating market sensitivity to Bi-Di service revenues Aggregated studies in the U.S. also show modeled revenues of $1250 to $1400 for BEV fleets, as validation, of V2G export revenue for Up- or Down-regulation markets (Goentzel et al. 2012). More Bi-Di demonstrations have shown promising results for BEV fleets where fixed

operational schedule and high availability makes them more suitable for Bi-Di services. E.g., a fleet of BEV school buses successfully exported 7 MWh of energy to National Grid's distribution network for over 80 h (Cision 2022).

Techno-economic insights

Availability of technical solutions and economic feasibility usually form the core of corporate motive to proliferate any technology to market. As such, the section focuses on analyses of these two core business functions through a basic techno-economic framework. Case study findings are analyzed, and automotive OEM-relevant insights are listed, as opportunities and challenges.

The framework for techno-economic analysis is leveraged from the EVVC model to look at Bi-Di services, options and time scales, and the value to the grid and customer. Depending on the utility programs, Bi-Di service, and EVVC options can be stacked to maximize the value. Grid or customer value can result in technology development and business offerings from the automotive industry with a clear pathway to corporate revenues and sustainability goals. The value chain could result in Bi-Di technologies and business offerings from the automotive industry and offer energy reliability and cost-savings to the customer, and environmental benefits to society. The techno-economic metrics used to value Bi-Di services are, as follows:

1. Bi-Di Service: V2H/B service value could be derived intrinsically from the customer's local resiliency. A V2G service provides energy reliability and enables cost-arbitrage value to grid operators through customer participation.
2. EVVC Options: Options in support of the electric grid value based on electricity rate tariffs, DR programs, or other capacity or energy contracts that a Bi-Di service provider can engage with a utility and its customer. The tariffs, programs, or contracts can manifest under ToU, demand charges, DR tariffs, utility or ISO capacity and energy sales, etc.
3. EVVC Timescales: Timescales define BEV's availability for grid services. E.g., ToU rates are long-term customer contracts and can be optimized in advance for BEV operations. However, real-time electricity market prices need faster data and optimization timescales. Note that the timescales do not necessarily indicate activation of Bi-Di service, it can be specific to the telemetry of data, as a function of BEVs' response to a grid request.
4. Grid or Customer Value: Value to power system or customer from capacity (kW) and energy (kWh) services, T&D Cost Deferral ($/kW & $/kWh), VPP services ($/MW and $/MWh), Power Quality (VAR, voltage, frequency), Environmental (GHG price), and Societal (Health, Equity) can result in sustainable system-wide electricity reliability and resiliency through multiple EVVC energy market options (e.g., ToU, demand charges, and wholesale or retail capacity and energy sales).

Table 3 lists the EVVC metrics and analysis based on the findings from the case studies. It is worth highlighting that all demonstrations were within a customer's premises (e.g., a microgrid campus, commercial building, home), which are termed behind-the-meter (BtM) applications. A V2G power export service (e.g., reactive

Table 3 Electric vehicle value chain metrics and case study findings

Bi-Di service	EVVC option	EVVC time-scales	Grid and customer value
V2G	TOU rates, demand charges, energy and capacity, environment	4-Seconds*, minutes, hours	Cost Saving: ToU, demand charge, DR programs and reactive power export Revenue: Lower local and system peaks; capacity and energy sales in wholesale markets; and GHG emission reductions
V2H or V2B	Mostly for resiliency, DR tariffs, or system peak reduction	Minutes to hours	Cost Saving: DR program Revenue: Lower system peaks

*Sub-minute timescales are for data transfer and not necessarily for a BEV's response to discharge a battery

Table 4 Revenue, Business & Sustainability Goal Findings from Case Studies

Bi-Di Service	Revenue ($/BEV/year)	Business & Sustainability Goals
V2G	V2G export & non-export revenues range widely depending on EVVC options, utility regions, tariffs, and market and regulatory structures Revenue ranges average at a low of $906 to a high of $8000	Promotes BEV adoption by lowering operational and customer costs Promotes a higher share of renewable energy by addressing variability with demand flexibility (DR), and capacity and energy aggregation services (VPP)
V2H	One case study (PG&E) tested V2H for local resiliency and to bid lower demand into the ISO market Bi-Di EVSE hardware and software costs were higher ($4500) relative to revenue ($1400), OEMs should review options to lower costs and increase revenue from V2G service	Promotes BEV adoption among customers favoring V2H functionality, which can also be used to realize cost savings Encourage market development of Solar + BEV storage solutions to lower GHG emissions and increase value with DR market participation
V2B	A couple of studies used V2B and synergistic DERs for microgrids. Technology applied to V2G (export and non-export) to increase value Revenue of ~ $1500 with limited BEVs in CA markets is a positive step to evaluate options to increase revenues from fleet BEVs	*Like V2H, with a larger potential value chain due to higher energy use in buildings*

power, regulation market participation), as noted earlier, can also be exercised externally to customer's premises (e.g., shopping mall, distribution grid network), which are termed, as front-of-the meter (FtM) applications.

The automotive industry's motivation to manufacture BEV hardware and software that integrate with EVSE infrastructure, electric grid, and customer systems, and scale Bi-Di services, revenues, and sustainability goals must be validated. From the limited case study findings, Table 4 lists revenues and alignment to broader business and sustainability goals.

The techno-economic analysis, albeit centered around automotive OEMs and fundamental technical and business processes of BEVs (e.g., data, software, battery), the insights are relevant for the industry, comprising of EVSE OEMs, network operators, energy aggregators, and grid operators such as either distribution or independent system operators. Together, the industry plays a key role to enable collective opportunities and address shared challenges for the mass-market adoption of Bi-Di services.

Opportunities

Two key trends that are the focus of the study—technical and economic—point to opportunities for Bi-Di services. Analyses from featured case studies should encourage the automotive OEMs to prioritize technology innovation, business models, and broader industry engagement to sell more BEVs, and at the same time, capitalize on the continuous revenue from Bi-Di services—a strategy that transitions "car makers" to "technology solution" companies. The following top-five opportunities emerge from the case studies.

Revenue Models: The automotive OEMs have a new revenue opportunity with Bi-Di services, ranging from $906 to $8000 per year per BEV, with a larger share of V2G services. With increasing outages, V2H/B technologies can support customers with cost-effective local resiliency—a service that stationary batteries can provide. V2H/B service can replace other backup sources for residential or small businesses and complement large commercial and industrial facilities. The V2H/B technologies expanded for V2G service increasing the grid and customer value with cost and GHG emission savings. Stacked market mechanisms such as ToU, demand charges, peak capacity and energy prices, DR markets, etc., can enhance economics.

Lower-Cost Solutions: The fixed cost information for Bi-Di services was not available across the case studies. However, the automotive OEMs, with scaled production and mass-market adoption infrastructure, have the potential to iteratively lower any potential high fixed costs by adopting technologies such as reliable telematics data, onboard inverter, energy management, etc. The onboard inverter approach transforms a BEV, as an energy source for Bi-Di services with any compatible EVSE infrastructure. The case studies (e.g., EPRI-UCSD) tested onboard inverter capabilities that has the potential to lower equipment costs with scaled production.

Technical Solutions: Technical solutions include hardware, software, data, and analytics that enable Bi-Di services. With BEV aggregation, as a VPP energy source, enabling the foundational features (e.g., onboard inverter, data frequency, EVSE interoperability) by the automotive OEMs can lower costs. Such a strategy can have axiomatic benefits where EVSE OEMs, energy aggregators, and grid operators develop synergistic market services to benefit a collective automotive and grid industry. Examples of such benefits can be seen from General Motors (GM) and SunPower (GM Energy, Collaborations & Projects 2022), and Ford Media Center 2022) collaborations for residential energy and Bi-Di services to support native V2H capabilities in BEVs.

Software and Data Analytics: One key area of innovation is the development of software and data analytics to maximize the value of Bi-Di services. For example, access to reliable telematics data can inform customers' driving patterns and battery SoC, which can be used to model BEV availability for a specific EVVC option. Case studies (e.g., LBNL LA-AFB, EPRI-UCSD) show the value of modeling-in-the-loop and optimization of BEVs for maximum value. The use of common data models for software and analytics can maximize available energy and capacity from a minimum number of resources, resulting in lower enrollment and operational costs.

Enhanced Fleet Services: Automotive OEMs have long-standing relationships with vehicle fleet owners and operators. In addition to the value that BEVs provide for cost

savings (operational savings) and sustainability goals (lower emissions) to fleet owners and operators, Bi-Di services can enhance the value of fleet services. A BEV fleet provides enhanced V2H/B, and V2G value to one customer due higher number of BEVs, availability, and fixed operational schedules, as highlighted by many case studies (e.g., Univ. of Delaware, LBNL Miramar).

Challenges

Case studies findings show familiar challenges or unknowns around uncertainty in the valuation of Bi-Di services by electricity markets, albeit promising cost and revenue models emerge. The transition from demonstration to commercial offerings by the automotive OEMs requires further validation of technology costs and enabling mechanisms for longer-term revenue opportunities. The following top-five challenges emerged that the automotive OEMs should address.

Fixed and Recurring Costs: Recognizing that costs can he high for early-stage technologies, the automotive industry must review fixed and recurring costs and strategies to reduce them. An assumed 1- to 2-year anticipated payback results in fixed costs between $900 to $1800 for a low range and $8000 to $$16,000 for high range of Bi-Di revenues from case studies. To procure a 40% effective profit to the automotive industry from the revenues, the recurring costs and expenses should be 60% or lower of the estimated revenues. Lower costs and higher revenues can be key motivators for automotive industry to advance Bi-Di services.

Electricity Markets: Revenues beyond customers' electricity price structures such as ToUs and demand charges are a function of retail and wholesale market design and DR tariffs that value Bi-Di services. E.g., demand charges in the U.S. vary from $20/kW to > $50/kW (National Renewable Energy Laboratory (NREL) 2017). In the U.S., the retail markets are typically managed by the utilities, and wholesale markets are managed by the ISOs/RTOs with no clear data and information coordination (Metering, Data and Information, and Telemetry 2222). Further analyses of reliability (energy or capacity commitment) and persistency (commitment when needed) of Bi-Di services by automotive OEMs would be required to motivate the electric grid stakeholders and markets to coordinate and competitively price energy and capacity offerings for EVVC options such as T&D cost deferrals, reactive power export, reduction in system peak, etc.

Regulations: Electric grid operations are one of the most regulated industries in the U.S. The transmission-level operators are regulated by a federal agency, and most distribution utilities are regulated by the public utility commissions. Coordination is prioritized mostly for the reliability of the electricity supply. Public policies to reduce GHG emissions from transportation and generation sectors are influencing energy technology development and adoption at a faster rate than ever before. Case studies show that BEVs can be used to manage peaks and Regulation-Up and Down wholesale markets. The absence of clear policies on price, energy, capacity, GHG emissions, and long interconnection queues is a challenge to scaling Bi-Di services. Automotive OEMs will have their task cut out to work closely with policymakers and regulators to ensure that today's Bi-Di technologies and services are scalable and revenue certainty for tomorrow.

Battery Degradation: The U.S. federal law requires LD-BEV car and truck batteries to last at least 8 years or 100,000 miles, which most automotive OEMs support (Doe

2016). State laws, such as California, will require at least 10 years and 150,000 miles by the model year 2030 where BEVs "maintain at least 80% of electric range (California Air Resources Board (CARB) 2022." This was not an issue in case studies that discharged limited energy from BEVs would "not be expected to add a burdensome amount of cycle life to the battery (Multi-lab EV Smart Grid Integration Requirements Study 2015)." A lack of clear understanding of battery degradation models for long-term Bi-Di services beyond mobility-use must be fully analyzed. Considering that battery degradation is a function of battery technology and chemistry in use, automotive OEMs have full visibility, and control, and are ideally placed to assess degradation issues based on the Bi-Di service offerings and metrics such as hours of discharge, discharge rate, battery cycles, etc.

Data, Integration, and Cybersecurity: Data provides visibility to prerequisite information for Bi-Di services (e.g., state, SoC, location). For case studies, data was used to model and optimize BEV charging and discharging schedules for mobility needs and cost savings (e.g., LBNL LA-AFB, EPRI-UCSD). Multi-stack Bi-Di services need communications and integration across BEVs, automotive OEMs, EVSE and home or building systems, utility/ISO markets, etc. Efficient and cost-effective data access and interoperable system integration are critical to lowering fixed and recurring costs. The case studies have used many open data standards for interoperability between electricity markets and BEV infrastructure (e.g., OpenADR 2.0, IEEE 2030.5, OCPP). Demonstrations did not address cybersecurity needs, which must be considered by design before Bi-Di service offerings become critical for reliable grid operations. There is a lack of common standards for interoperability between BEV—EVSE and EVSE—Home or Building. Automotive OEMs must work with standards organizations and BEV ecosystem stakeholders to adopt common interoperability standards and cybersecurity methods.

Conclusions

The study: (1) conducted a literature review of case studies for the role of bi-directional power transfer (Bi-Di) services from battery electric vehicles (BEV); (2) developed a framework for two of automotive OEM's core business functions, technology, and economics (techno-economic), to assess Bi-Di benefits to customers and grid; and 3) conducted analyses to highlight findings and propose opportunities and challenges for the two core business functions. A total of eight case studies were featured that conducted comprehensive Bi-Di demonstrations from 2005 to 22.

While the fixed and recurring costs were not assessed across the case studies, it should be recognized that these costs could be high for early-stage technologies. The revenues that range from $906 to $8000/year/BEV are promising. Technology analyses reveal the need to develop innovative and scalable technologies to integrate BEVs with EVSEs, DR aggregators, and electricity markets. The other techno-economic highlights are: (1) revenue and growth are linked to regulatory structure and market enablement that values Bi-Di service; (2) higher BEV battery capacity and EVSE power levels maximize revenue; (3) BEVs and EVSEs with base Bi-Di technology capabilities are difficult to procure and needs development; 4() advanced modeling techniques and data analytics play a key role in the reliability and persistency of Bi-Di services and (5) commercial projects must

consider cybersecurity and interoperable data standards that support market rules and lowers technology costs.

Abbreviations

AC	Alternating Current
ANL	Argonne National Laboratory
BDL	Bi-Directional Charge Management
BEV	Battery Electric Vehicle
Bi-Di	Bi-Directional Power Transfer
BMW	Bayerische Motoren Werke AG
CA	California State
CAISO	California Independent Systems Operator
CCS	Combined Charging System
CEC	California Energy Commission
CHAdeMO	Charge de Move
CO	Colorado State
CPUC	California Public Utilities Commission
DC	Direct Current
DER	Distributed Energy Resources
DR	Demand Response
DOE	The United States Department of Energy
DSO	Distribution Systems Operator
DTU	Technical University of Denmark
EPIC	Electric Program Investment Charge
EPRI	Electric Power Research Institute
EUDP	Energy Technology Development and Demonstration Program
EV	Electric Vehicle
EVCC	Electric Vehicle Value Chain Model
EVSE	Electric Vehicle Supply Equipment
GAC	Global Adjustment Charge
GHG	Greenhouse Gas
GM	General Motors
GW	Gigawatt
GWh	Gigawatt-Hour
IEEE	Institute of Electrical and Electronics Engineers
ISO	Independent Systems Operator
KIT	Karlsruhe Institute of Technology
kW	Kilowatt
kWh	Kilowatt-Hour
LA-AFB	Los Angeles Air Force Base
LBNL	Lawrence Berkeley National Laboratory
LD	Light-Duty
MCAS	Marine Corps Air Station
MD	Medium-Duty
MW	Megawatt
MWh	Megawatt-Hour
NC	North Carolina State
OCPP	Open Charge Point Protocol
OEM	Original Equipment Manufacturer
OpenADR	Open Automated Demand Response Standard
PG&E	Pacific Gas and Electric Company
PJM	PJM Interconnection
PLC	Power Line Communication
PV	Photovoltaic
REC	Roanoke Electric Cooperative
RI	Rhode Island State
RTO	Regional Transmission Operator
SAE	Society of Automotive Engineers
SCE	Southern California Edison
SDG&E	San Diego Gas and Electric Company
SOC	State of Charge
SPIDERS	Smart Power Infrastructure Demonstration for Energy Reliability
SSP	Supply-Side Pilot
T&D	Transmission and Distribution
TMS	Transformer Management System
TOU	Time of Use Electricity Tariff
UCSD	University of California San Diego
U. K	United Kingdom
U. S	United States

V2B	Vehicle-to-Building
V2G	Vehicle-to-Grid
V2H	Vehicle-to-Home
V2L	Vehicle-to-Load
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VA	Virginia State
VAR	Volt-Ampere Reactive
VGI	Vehicle-Grid Integration
VPP	Virtual Power Plant

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Author contributions
GG conceptualized the article, methodologies, techno-economic evaluation framework, majority of case-studies, data analysis, and conclusions, and was a major contributor in writing the manuscript. MA was instrumental in reviewing and analyzing the case studies in Europe and representing the relevant data within the manuscript's framework. All authors have read and approved the final manuscript.

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