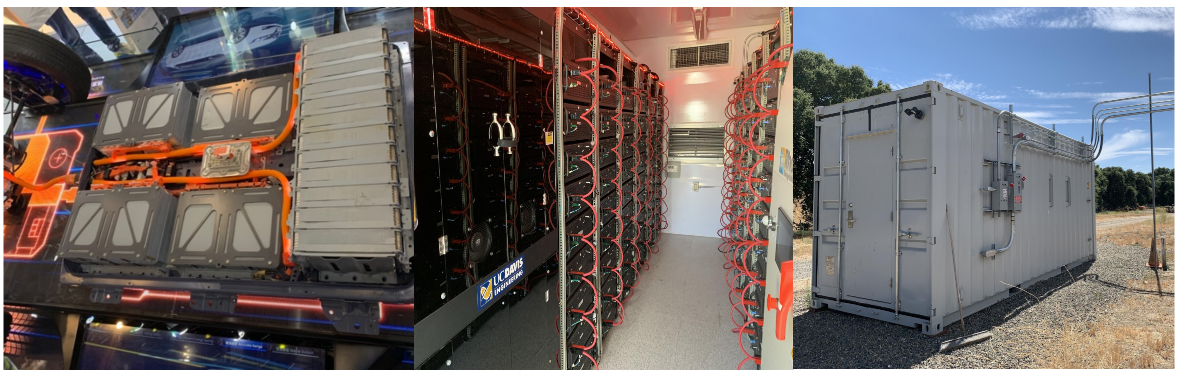

Battery Second-life: Unpacking opportunities and barriers for the reuse of electric vehicle batteries

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INTRODUCTION

After use in a vehicle, lithium battery packs in modern electric vehicles (EVs) are likely to retain more than two thirds of their usable energy storage capacity, and could deliver an additional 5-8 years of service in a stationary application. The economic potential for battery second-life could help to further decrease the upfront costs of EV batteries by increasing the value of a used EV. Given the growing market for EVs, second-life batteries could also represent an important resource for utilities and electricity consumers. Current pilots and case studies offer early lessons learned, potentially point towards best practices, and highlight challenges. In order to enable widespread reuse, policy will play an important role in reducing barriers and ensuring responsible, equitable, and sustainable reuse. This document describes the current industry landscape and explains the current and potential future use cases for second-life EV lithium ion batteries (LIBs).

TECHNICAL POTENTIAL FOR SECOND-LIFE

The ability of a battery to retain and rapidly discharge electricity degrades with use and the passing of time. For an automobile, this means that the car will no longer be able to drive as far on a single charge (loss of range), nor will it be able to accelerate as quickly (loss of performance). EV batteries will be retired from their primary application either when the vehicle itself is physically damaged (i.e. in a car accident), or when the range and/or performance is no longer acceptable to the driver. In the first instance, the battery may retain enough of its original capacity to be remanufactured and reused in another EV. When retired normally, EV batteries are expected to retain as much as 80% of their initial capacity, though the actual condition will vary from vehicle to vehicle.[1]

The performance of a new or used battery is a function of battery impedance, accessible capacity, and physical condition; the battery's state of health (SOH) is often used as a convenient metric to quantify the degradation of battery performance. How many times a battery can deliver its stored energy at a specific rate is a function of degradation. In general, there are three primary pathways for degradation in a lithium ion battery: temperature, cycles, and time. Repeated utilization of the maximum storage potential of the battery, rapid charge and discharge cycles, and exposure to high temperatures are all likely to reduce battery performance.

How quickly the second-life battery reaches a SOH threshold is affected by how many times the battery is charged and discharged ("cycling"), and depth of discharge (DoD) requirements (i.e. how completely the battery is discharged compared to its overall capacity). Given the duty cycles experienced by EV batteries, calendar degradation (i.e. time) and thermal conditions are likely the main determinants of battery longevity during the initial (vehicle) application.[2]

The technical potential of a repurposed battery is mainly determined by its SOH at the onset of second life, and the characteristics of the targeted second life application. As SOH gets lower, degradation accelerates until the battery is no longer functional and must be permanently retired. For context, some

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[1] https://www.uscar.org/guest/article_view.php?articles_id=659

[2] https://www.nrel.gov/docs/fy15osti/63524.pdf

literature assumes 60% SOH to be an appropriate retirement threshold to avoid accidents or high rates of failure (Lacey et al., 2013; Casals et al., 2015; Bobba et al., 2018).

The specific second life application, therefore, affects the battery's technical potential because it determines the cycling and DoD requirements. For example, Tong et al. found that a repurposed battery energy storage system lasted 5.5 years supporting a photovoltaic (PV) system. Contrastingly, Casals et al. find that when simulating a transmission deferral application, where cycling and DoD requirements are lower, the battery lasts up to 11 years (Casals et al., 2019).

Retired battery systems are likely to enter a range of applications based on their physical characteristics, SOH, and performance. Some modules with minimal degradation and absent defects or damage could likely be refurbished and reused directly as a replacement battery packs for the same model vehicle. Major automakers, including Nissan and Tesla, have offered rebuilt or refurbished battery packs for purchase or warranty replacement of original battery packs in EVs.[3]

Market Potential

The market potential of repurposed battery storage depends on the supply of retired EV batteries, and demand for stationary storage applications. Predicting the future availability of second-life batteries depends on the adoption rates and expected lifetime, with some percentage of unusable products discarded due to certain modes of failure. Forecasts from academic studies and industry reports estimate a range of 112-275 GWh per year of second-life batteries becoming available by 2030, surpassing forecasted demand for utility-scale LIBs according to Bloomberg NEF (Engel et al., 2019; Jiao et al., 2019). By 2027, an estimated 45,000 EV batteries will be retired just in California.[4] Assuming a conservative capacity for each of these batteries (20 kWh) this amounts to over 900 MWh/year of available capacity; with both the individual battery capacity and the amount of batteries retiring poised to increase into the projected future. For context, the state of California added 120 MWh of battery storage capacity in 2018.[5]

[3] https://www.greencarreports.com/news/1116722_nissan-begins-offering-rebuilt-leaf-battery-packs
[4] https://ww2.energy.ca.gov/2018publications/CEC-500-2018-024/CEC-500-2018-024.pdf
[5] https://www.eia.gov/electricity/data/eia860/

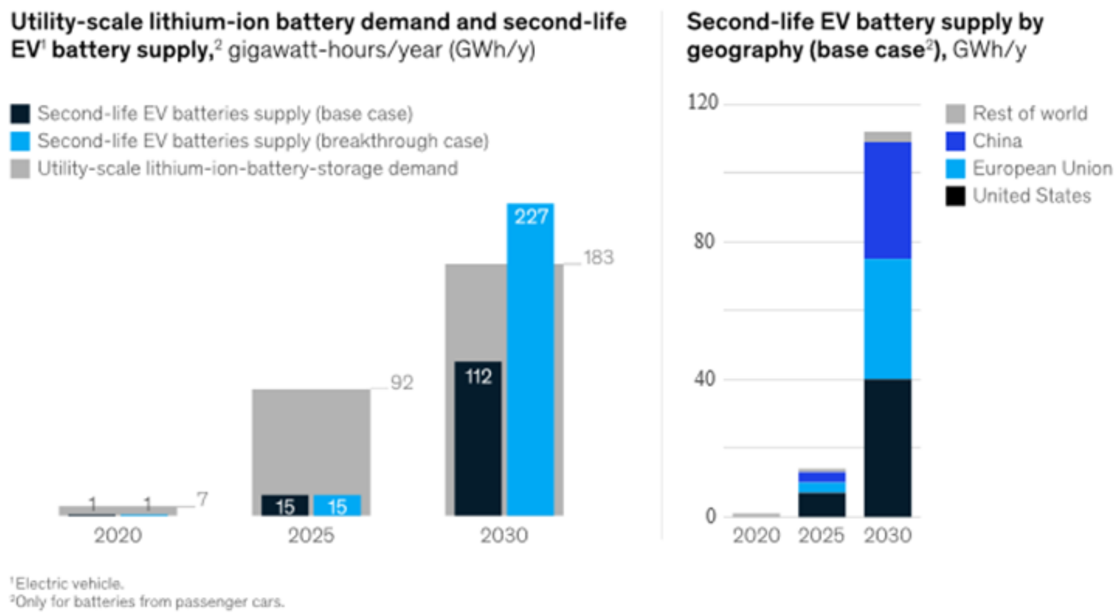

FIGURE 1 BATTERY SECOND-LIFE MARKET POTENTIAL (BLOOMBERG, 2019)

Within the stationary storage landscape, the primary markets for second-life batteries will be:

- wholesale independent systems operators (ISOs),
- transmission/distribution and utility companies,
- and customer markets, or private consumers (Atcitty et al., 2013; Parra, 2019).

Distributed energy storage offers the greatest economic benefit when battery systems provide stacked services, i.e. multiple services at the same time (Fitzgerald et al., 2015). For example, a consumer customer might install so-called behind the meter storage primarily to reduce electricity costs by avoiding demand charges but also value resilience in a power outage. Both behind and in front of the meter, distributed storage can provide a range of services for electric utilities including resource adequacy, frequency regulation, demand response, and other forms of energy arbitrage.[6] A key challenge for battery storage (new or used) in a commercial market is how to capture each of these value streams.

The economics of second-life battery storage also depend on the cost of the repurposed system competing with new battery storage. To be used as stationary storage, used batteries must undergo several processes that are currently costly and time-intensive. Each pack must be tested to determine the remaining state of health of battery modules, as it will vary for each retired system depending on factors that range from climate to individual driving behavior. The batteries must then be fully discharged, reconfigured to meet the energy demands of their new application; in many cases, packs are

[6] See https://rmi.org/wp-content/uploads/2017/03/RMI-TheEconomicsOfBatteryEnergyStorage-FullReport-FINAL.pdf

disassembled before modules are tested, equipped with a battery management system (BMS), and re-packaged.

Depending on the ownership model and the upfront cost of a second-life battery, estimates of the total cost of a second-life battery range from from 40-160 $/kWh (Madlener et al., 2017; Martinez Laserna et al., 2018). This compares with new EV battery pack costs of $157 /kWh at the end of 2019.[7] The National Renewable Energy Laboratory has also created a publicly available battery second-use repurposing calculator that accounts for factors such as labor costs, warranty, and initial battery size and cost. Figure 2 illustrates the potential cost structure of a repurposed battery in a second-life application where the buying price is the maximum value paid for the used battery. If this value could be passed through to the original owner, it could help to defray the upfront costs of EV batteries.

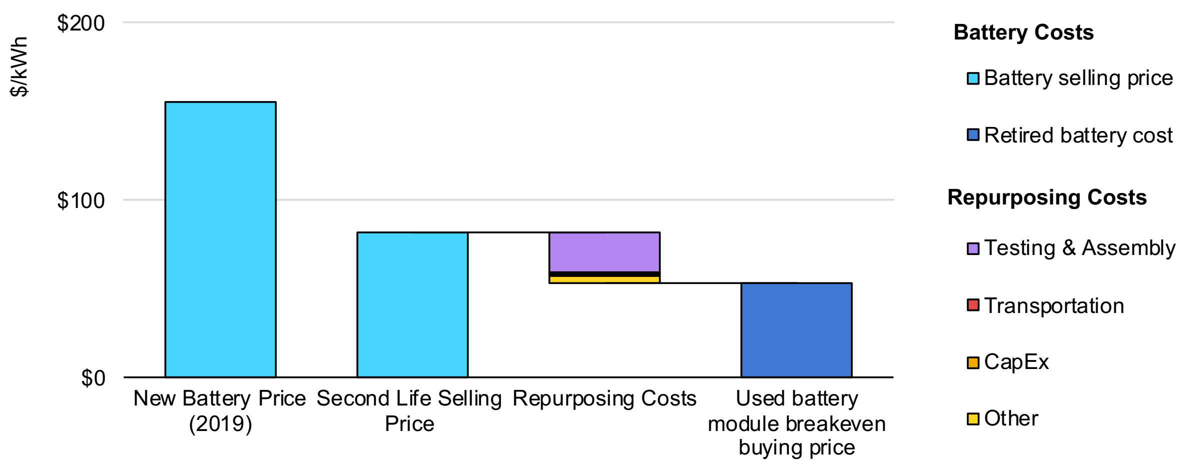

FIGURE 2 COMPARING NEW AND REPURPOSED EV BATTERY PACK COSTS[8]

Further, the major barriers will be the performance and durability of the battery after its first-life and developing fair compensation for the enhanced ability of LiBs to perform certain services within these three markets. On top of this, the value of the service provided by these batteries must be thoroughly calculated. These factors are most relevant to the market potential of second-life batteries.

SECOND-LIFE APPLICATIONS

In a stationary setting, distributed energy storage resources can provide a range of services both behind and in-front of the electricity meter. For private customers, battery energy storage can provide back-up power (e.g. resiliency), and decrease electricity costs. For utility customers, storage can provide a range

[7] https://about.bnef.com/blog/battery-pack-prices-fall-as-market-ramps-up-with-market-average-at-156-kwh-in-2019/

[8] The estimate underlying this figure was generated using the Battery Second-Use Repurposing Calculator created by the National Renewable Energy Lab, available at: https://www.nrel.gov/transportation/b2u-calculator.html

of services including frequency regulation, deferral of investments in transmission and distribution infrastructure, and energy arbitrage. The ability of storage to capitalize on certain services will be dependent on siting, energy market and generation type. Value stacking is used to refer to the bundling of grid services provide by storage to maximize the revenue potential and improve the economics of energy storage resources. In most services that the second-life LiB could provide, there would be a lot of downtime (50-95%, e.g. Fitzgerald et al., 2015). Thus, this downtime can be utilized for another service. Value stacking is another complication when assessing the economics of reused batteries.

Customer Energy Management

There are a variety of options behind the meter for customers to deploy energy storage to reduce energy costs and improve system resilience. Typical goals for storage on the customer side are optimizing time of use (TOU) billing, demand charge reduction, and to support on-site renewable electricity generation. In the case of TOU billing and demand charge reduction, these applications are directly dependent upon a customer's utility.

In California, most electric utilities offer TOU rate structures that encourage customers to shift their energy use to off-peak hours.[9] This is achieved mainly through peak pricing. For example, customers in PG&E's territory can choose a rate structure where electricity is cheaper outside the hours of 4-9pm. Capacity bidding is another market mechanism that similarly rewards commercial customers for reducing load when asked, typically on the scale of one hour.[10] The implementation of storage in these cases is to charge when electricity is cheaper, then discharge during peak hours when it is advantageous to reduce customer load (this is known as "peak shaving"). As TOU rates trend towards evening hours, utilizing second-life batteries in behind-the-meter load shifting applications provides an environmental benefit as well, since they charge from cleaner electricity during the day then displace demand for energy that would otherwise be supplied by natural gas peaker plants.

The economic and environmental benefits of storage are magnified if the location also produces energy from onsite renewables. Battery storage is used to balance the intermittency of wind and solar generation (i.e. firming). Storage enables customers to take advantage of times when onsite generation exceeds demand; energy can be stored, then discharged to fill in the "lull" periods (i.e. no wind or cloud pass; Malhotra et al., 2016). On-site storage could also provide a greater value than net-metering for some types of private systems.

Utility Scale Services

There are a number of services that distributed energy storage an provide for electric utilities. As mentioned previously, a key barrier for second-life EV batteries and distributed energy storage more

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[9] See https://www.smud.org/en/Rate-Information/Time-of-Day-rates/Time-of-Day-5-8pm-Rate or https://www.pge.com/en_US/residential/rate-plans/rate-plan-options/time-of-use-base-plan/time-of-use-plan.page#:~:text=

[10] https://www.sdge.com/businesses/savings-center/energy-management-programs/demand-response/capacity-bidding-program

broadly is the ability to capture these different value streams. There are four general types of grid services storage can provide:

- **Frequency regulation** broadly characterizes the need for the grid to maintain the balance between generation and load (demand), an inherently difficult task considering the freedom of consumers to use electricity without regard for schedule. Electrical systems maintain the frequency of the grid at a particular level, in the case of the United States this level is 60 hertz (Hz). Operation outside of a tight tolerance band can cause failure in the grid and lead to rolling blackouts. Frequency regulation is a service that involves counterbalancing changes in either generation or load (referred to as "regulation up" when increasing output and "regulation down" when decreasing output). The service is provided by a battery storage system bidding in (and being compensated for) a particular amount of regulation-up or regulation-down for a particular quantity. The provider of this service is also compensated based on how fast they can provide this service, which is advantageous for batteries storage systems since they much faster than traditional thermal generators.
- **Transmission and distribution** deferral refers to the grid infrastructure, which is currently inadequate to withstand future load forecasts. Considering economic growth and a push for increased electrification, plenty of nodes in the grid will have to be updated to serve this increased capacity. Upgrading this infrastructure is costly and typically forecasted peak exceeds existing capacity by only 1-3% (Fitzgerald et al., 2015). With battery storage placed downstream of node of interest, the battery can charge during non-peak hours. Another service, transmission congestion relief, is similar in principle and deployment. This option is hard to generally value, considering how spatially dependent it is.
- **Spinning Reserves -** Each operator has the obligation to maintain a certain amount of reserve in the event of unexpected drop in generation, usually an added on percentage of forecasted peak load as delegated by North American Electric Reliability Corporation (NERC). These two reserves can broadly be defined as spinning and non-spinning reserves. Spinning reserves refer to reserve that can easily be realized at a given generator in relatively short notice (i.e. increasing torque on turbine). Non-spinning reserves, typically refer to a longer time scale response and involve the initiation of a non-operating generator. In restructured electricity markets, the topology of spinning vs non-spinning is more just referencing response time.
- **Energy arbitrage** involves taking advantage of scarcity pricing inherent in the electricity wholesale market. The arbitrage is capitalizing on differences in the locational marginal prices (LMP) of electricity, and typically involve predetermined knowledge of peak pricing within a 24-hr period. Any generator registered with the Federal Energy Regulatory Commission (FERC) can perform this arbitrage, provided they are connected to the grid and a market counterpart (Fitzgerald et al., 2015). A challenge for LIBs in energy arbitrage applications are the low cycle count and long duration of high state of charge, which lowers the potential for revenues from value stacking and increases potential for parasitic losses.

CASE STUDIES AND PILOTS

There are a number of existing pilot and demonstration projects operating second-life EV battery systems in a range of applications. Table A (located in the Appendix), lists over twenty such projects designed for a range of the applications described above. This section provides additional detail on a handful of the case studies identified.

Behind the Meter

Several pilot projects exist for second-life LIBs used in customer energy management strategies, ranging from small to large-scale customers. For example, the Energy Storage Local Advanced System (ELSA) project has supported the development of a number of installations. One is located at Nissan Europe's office in Paris, France. The battery system consists of 12 second-life Nissan Leaf batteries amounting to a total energy capacity of 192 kWh and power capacity of 144kW. This system is unique in its scope among the ELSA projects, demonstrating the scalability and management of these second-life packs. This system optimizes the operation of the SLBESS to take advantage of TOU rates, storing electricity (charging) when energy is cheap and consuming stored electricity (discharging) when energy is expensive.[11]

The Robert Mondavi Institute at UC Davis is another example of a behind-the-meter system that is paired with solar PV. In a project sponsored by the California Energy Commission (CEC), a team of researchers led by Jae Wan Park built and installed a 300-kWh system comprised of 18 repurposed Nissan leaf battery packs assembled inside a shipping container. The system discharges daily on a set schedule from 4-8pm, allowing the sustainable teaching winery to claim that they use their own solar energy after the sun goes down.

On the larger end of customer demand, a cooperative effort between Nissan, Eaton, BAM and The Mobility House has led to the installation of a hybrid first-life/second-life system at the Johan Cruijff Arena, in Amsterdam, Netherlands. This system, comprised of 148 Nissan Leaf batteries, has a 3 MW power capacity and a 2.8 MWh electricity storage capacity.[12] The primary purpose of the battery system is to decrease energy costs by shifting load. Another service is to provide back-up power to the arena for at least an hour in the event of a blackout.

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[11] https://www.elsa-h2020.eu/Nissan_Europe_Office.html

[12] https://www.mobilityhouse.com/int_en/magazine/press-releases/johan-cruijff-arena-3mw-energy-storage-system-launch.html

Regulation at Small and Large Scales

Frequency regulation is currently provided by second-life batteries on both large and small scales. An example of a small-scale demonstration is aanother ELSA project, this one in the city of Kempten, Germany.[13] In collaboration with the regional utility, Allgäuer Überlandwerk GmbH (AÜW), a development of 6 multi-family homes was erected. The homes are equipped with 37.1 kW of installed rooftop PV capacity, supported by a collection of six second-life Renault Kangoo batteries (95 kWh total). The batteries are used to store excess solar so that it can be used onsite in the evenings, as well as providing regulation to balance out the customer load and PV generation.

A more traditional representation of larger-scale area regulation, established in 2016, is located in Lunen, Germany. This collaboration between Daimler, The Mobility House, and GETEC produced an installment of 1,000 BMW i3 packs, 90% of which are second-life batteries. This installment has a total energy capacity of 13 MWh and participates in the wholesale energy market to provide ancillary services, including area regulation.[14]

Policy for Reuse

Although there are no uniform global or regional policies governing the reuse and recycling of EV batteries, there has been an increase in attention paid to the issues of end of life (EOL) management in recent years.

One key challenge for EOL management is sharing of critical data like battery manufacturer, cathode material, battery condition, and usage history down the value chain to the potential secondary market or recycler. The Global Battery Alliance was founded in 2017 as a collaboration of 70 public and private organizations with the goal of establishing a sustainable battery value chain including repurposing and recycling (World Economic Forum, 2020). The battery alliance battery passport initiative aims to improve the sharing of data along the value chain by standardizing labelling and creating a database of battery information. Sharing of battery data could decrease the costs of battery repurposing and increase the value proposition of battery reuse.

Another key challenge for battery reuse is logistics. Used batteries, once removed from a vehicle, are considered hazardous waste and are therefore governed by restrictions on the transportation of

[13] https://www.elsa-h2020.eu/City_of_Kempten.html

[14] https://www.mobilityhouse.com/int_en/magazine/press-releases/worlds-largest-2nd-use-battery-storage-is-starting-up.html/

hazardous wastes. The costs and challenges in transporting and aggregating used batteries is also a barrier to widespread reuse.

When considering the fate of EV batteries, it is useful to place them in the framework of the waste hierarchy: prevention first, followed by reuse, recycling, energy recovery, and finally treatment and disposal (European Commission, 2008). Extended producer responsibility is a common framework for promoting responsible end of life management, but it is unclear whether EPR systems will enable a robust market for battery reuse. Table 1 below provides a survey of relevant policies for second life batteries globally.

Table 1: Survey of Existing End of Life Policies for Electric Vehicle Batteries

Policy	Region	Enacted	Description
California Assembly Bill No. 2832	California	2018	The Secretary for Environmental Protection to assemble a Lithium-Ion Car Battery Recycling Advisory Group to advise policies for the end of life to achieve as close to 100% of reuse and recycling as possible.
New York State Rechargeable Battery Recycling Act; Minnesota Rechargeable Batteries And Products Statute; New Jersey Statutes Sale Of Certain Batteries Dependent On Battery Management Plan	USA	2010; 1991; 1991	Extended Producer Responsibility (EPR). Ban on the disposal in landfills
The Battery Directive	European Union	2006	Extended Producer Responsibility (EPR) Required 50% recycling of LIBs (categorized as “other”) by weight
The Interim Measures For The Management Of Recycling And Utilisation Of Power Batteries Of New Energy Vehicles	China	2018	Extended Producer Responsibility Implements labelling, a traceability system, and encourages standardization of the design and production
Guide For Collecting And Storing Libs	China	2019	Ministry of Industry and Information Technology (MIIT) has released a guide for collecting and storing LIBs, along with a draft mandate on the testing of batteries that will be used in a second life application

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Appendix: Table A - Existing Second-Life Pilot Projects

Lead Entity	Location	Year(s)	Capacity
United Technologies Research Centre Ireland, Ltd.	Paris, France	2017-	88 kWh (Kangoo packs number unspecified)
Gateshead College, United Technologies Research Centre Ireland, Ltd.	Sunderland, United Kingdom	2017-	48 kWh (3 Leaf packs, 50 kW PV capacity)
Nissan	Paris, France	2017-	192 kWh (12 Leaf packs)
RWTH Aachen University	Aachen, Germany	2017-	96 kWh (6 Kangoo packs)
City of Kempten, the Allgäuer Überlandwerk GmbH	Kempten, Germany	2017-	95 kWh (6 Kangoo packs, 37.1 kW PV capacity)
City of Terni, ASM Terni	Terni, Italy	2017-	66 kWh (Kangoo packs number unspecifed, 200 kW PV capacity)
Daimler, Getec Energie, The Mobility House, Remondis	Lunen, Germany	2016-	12 MW, 13 MWh (1000 i3 packs, 90% 2nd life)
Nissan, Eaton, BAM, The Mobility House	Amsterdam, Netherlands	2019-	3 MW, 2.8 MWh (148 Leaf packs, 42% 2nd life)
Daimler, The Mobility House, GETEC ENERGIE, Mercedes-Benz Energy	Elverlingsen, Germany	by 2020	20 MW, 21 MWh (1878 packs, 40% 2nd life)
Mobility House, Audi	Berlin, Germany	2019-	1.25 MW, 1.9 MWh (20 e-tron packs, 100 % 2nd life)
UPC SEAT, Endesa	Malaga, Spain	2016-	37.2 kWh (4 PHEV packs, 8 kW PV)
BMW, Vattenfall, Bosch	Hamburg, Germany	2016-	2 MW, 2.8 MWh (2600 i3 modules)
Renault, Connected Energy Ltd	Belgium	2020-	720 kWh, 1200 kW (Kangoo packs number unspecified)
Nissan, WMG: University of Warwick, Ametek, Element Energy	United Kingdom	2020-	1 MWh (50 Leaf packs)
UC Davis, California Energy Commision, Nissan	Davis, CA, USA	2016-	260 kWh (864 Leaf modules, 100 kW PV)
BMW, EVgo	Los Angeles, CA, USA	2018-	30 kW, 44 kWh (2 i3 packs)
UC San Diego, BMW, EVgo	San Diego, CA, USA	2014-2017	108 kW, 180 kWh (unspecificed number of mini E packs)
General Motors, ABB	San Francisco, CA, USA	2012	25 kW, 50 kWh (5 Volt packs, 74 kW PV, 2 kW wind turbines)
Toyota	Yellowstone National Park, USA	2014-	85 kWh (208 Camry modules)
Nuvve, University of Delaware, BMW	Newark, USA	2019-	200 kW (unspecificed number of mini E packs, integrated with V2G in addition)
Nissan Sumitoto (4R Energy), Green charge network	Osaka, Japan	2014-	600 kW, 400 kWh (16 Leaf packs)