Electric Vehicles as Electric Energy Storage for a Zero Emission Grid

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Abstract

Electric Vehicles, especially electric vehicles with bidirectional Vehicle-to-Grid (V2G) connectivity, can serve as electric energy storage assets. Following the dramatic increase in electric vehicle registrations in 2022 there can be little doubt that electric vehicles will become a major portion of the entire light duty personal transportation fleet.

This paper endeavors to project the growing electric energy storage capability of this asset. It shows that the storage available from the EV fleet may grow to match the daily output of projected solar PV generation in the 2025-30 time period, and greatly exceed the requirements of the EV fleet itself..

This presents the possibility of a massive renewable generation capability, levelled and controlled by an even more massive electric vehicle fleet energy storage capability which can offset its intermittent and uncontrolled nature, as a future zero emission energy grid.

Introduction

Battery storage of electric energy is highly advantageous, and with the advent of high performance lithium ion batteries at a reasonable cost, it is becoming a reality.

There are several applications of this new-found capability:

- Load shifting and energy arbitrage
- Avoiding renewable energy curtailment
- Resiliency against outages
- Demand Charge management
- Participation in Demand Response (Capacity) markets
- Regulation Service to the grid

In load shifting, energy is purchased when it is cheap, say in the early morning hours, and used or sold when it is most valuable, say at 6 PM.

Renewable energy is available when the sun shines and the wind blows, not necessarily when it is needed. Storage can bridge this gap and avoid curtailment of renewable output by storing the energy until it can best be used.

Stored energy can also provide resiliency when the grid is not providing any energy at all during a power outage.

Commercial and industrial electric service is billed as Energy and also as Demand. Spikes in demand for power require the utility to build physical capacity to serve the peak not the average, and they charge for the highest fifteen or thirty minutes demand in a month to compensate for this investment. This provides a substantial incentive to level the load, which batteries can do.

At the grid level, administered by independent system operators/regional transmission organizations (ISO/RTOs) like PJM in the Mid-Atlantic, ERCOT in Texas, and CAISO in California, there is a need for to increase capacity (or reduce load) when the system load is excessive or when other generation fails, and those who are able provide that extra capacity are rewarded for it.

Also at the grid level there is a need to balance load and supply from second to second to maintain frequency and voltage stability. A battery, which can shift from charging to discharging instantaneously, is especially suitable for this service, and can be rewarded even more generously.

The conventional solution to this opportunity is to provide stationary battery banks tied to the grid by an inverter/charger, which can take AC energy from the grid to charge the battery or take DC energy from the battery to supply the grid or a local load. The inverter/ charger is controlled remotely via the internet to accomplish the objectives listed above.

Typically such a battery installation will cost in the neighborhood of $500 per kWh of capacity (per the REopt optimization program for renewable energy systems by the National Renewable Energy Laboratory). Round trip efficiency of rectification to DC and inversion back to AC is approximately 90%. The consequence of these factors is that the added cost associated with stored energy is in the neighborhood of $60/MWh. Battery stored electricity is roughly twice as costly as the original energy, due primarily to the cost of the battery installation.

Electric Vehicles as Storage

A major reason that battery storage is even conceivable is the advent of lithium ion battery technology with a high enough specific energy to give electric vehicles a useful range from a battery of acceptable mass. Lithium ion technology also provides the freedom from maintenance and the long life necessary to make battery storage practical and economic. The gigantic size of the automotive market has called into being an equally gigantic lithium ion battery manufacturing capacity, even at the present low penetration of electric vehicles. The economies of mass production have driven the cost of automotive lithium ion batteries down to its present level of $100-200 per kWh.

These considerations prompt the investigation of the use of the vehicle batteries themselves for grid storage. This is feasible because the electric vehicle can be charged any where at any time. It cannot be reenergized in a few minutes at a gas station as an IC vehicle can, but it can be reenergized at any time that the vehicle is not actually moving, and at any place with a connection to the grid and internet access for control purposes. The use of EV batteries for storage eliminates the cost of the battery as a factor in the cost of stored energy because the battery is already paid for as transportation. The question then becomes whether the battery capacity of the vehicle fleet is adequate to provide utility scale storage.

The magnitude of EV storage capacity is estimated in the following table.

Electric Vehicle Energy Storage 2020-2050

Total fleet	253,000,000	Light duty vehicles in US		Total US Gen.	4116	Million MWh/2021
Growth rate	1%					1%
Year	**% EV**	**Number of EV Millions(1)**	**Battery cap. kWh, each(2)**	**EV storage cap. kWh, Millions**	**EV Power cap. MW at disc. rate**	**US Capacity MW(3)**
2020	1	3	55	138	68,750	456,308
2022	1.4	4	60	214	107,111	465,480
2025	3	8	80	631	315,303	479,585
2030	10	28	100	2,762	1,380,778	504,048
2035	25	73	120	8,707	4,353,634	529,760
2040	50	153	150	22,879	11,439,282	556,783
2050	75	253	150	37,908	18,954,125	615,035

1 Estimated from Bloomberg News EV sales forecast.
2 Estimated based on current capacities and trends.
3 US EIA Annual Energy Outlook, 2022, total generation/8766 hours growing at 1%.

The analysis starts with estimates of the size of the EV fleet year by year based on the 2020 Bureau of Transportation Statistics light duty automotive fleet of 253 million vehicles and EV sales projections supplied by Bloomberg News. These show a roughly 40 % per year compound growth rate, which has been characteristic since 2018. The results in the 2030s are speculative, but the end years are probably fairly reliable since a number of companies like General Motors plan to produce nothing but electric vehicles starting in 2030-2035.

The growth in EV battery capacity is a rough estimate of current averages and it plateaus at an estimated 150 kWh, equal to a range of 500-600 miles, the most likely choice even with very cheap batteries.

The number of EVs times their battery capacity gives the storage capacity of the total EV fleet in millions of kWh, and a conservative discharge rate of 0.5 C (one half their capacity per hour) gives the power capacity that they can provide in MW. This grows to an amount equal to the total US grid capacity in the 2025-2030 time period, showing that EVs can be expected to scale up to become a major factor in the utility system.

Solar Capacity vs. EV Storage

The following table compares the planned solar capacity, (nameplate MW and actual production MWh), with planned stationary battery storage and the potential for storage in EV batteries. The planned stationary storage is smaller than the daily solar generation by a factor of ten or more. On the other hand, the EV storage capability can be expected to match the solar output in 2025 and exceed it by a factor of fifteen in the far future.

Solar capacity. MW(4)	**Solar gen./day MWh (5)**	**Planned Storage MWh (6)**	**EV Storage MWh**	**EV Usage/day MWh**	**Year**
80,000	263,014	10,000	137,500	20,548	**2020**
120,000	394,521	40,000	214,221	29,345	**2022**
200,000	657,534	60,000	630,606	64,788	**2025**
280,000	920,548	100,000	2,761,555	226,977	**2030**
375,000	1,232,877	135,000	8,707,270	596,388	**2035**
420,000	1,380,822	160,000	22,878,560	1,253,620	**2040**
580,000	1,906,849	230,000	37,908,250	2,077,164	**2050**

4 US EIA Annual Energy Outlook, 2022, planned utility and small scale, namepl
5 At 1200 hours average actual production per year/365
6 US EIA Annual Energy Outlook, 2022, planned battery storage, approximaely half hybrid, half stand alone.

The results are shown in the next chart in which the logaritm of the various quantities is plotted to keep the various capacities comparable in size.

Figure 1. U S Projections 2020-2050. Solar generation and EV energy consumption, MWh/day. Planned stationary energy storage and potential EV energy storage, MWh.

Interestingly the solar production and the EV usage in MWh per day come together at around 2040 and then rise together. Planned stationary storage in MWh is far from adequate to store the solar output at any time, but potential EV storage rises rapidly above solar output after 2025 and provides more than ample storage capacity as the EV revolution matures.

Utilization

It is not adequate to have available storage. In addition, we need a way to get the energy into the batteries, and back out again.

V1G involves controlling the one-way flow of energy to the EV battery. For all of the applications listed above, except resiliency, some service can be provided by simply controlling the rate of charging of the EVs by their onboard chargers. Primitive load shifting and renewable energy optimization can be done by turning the EV chargers on only when energy is cheap, or when renewables are in surplus. Demand charge management and demand response can be achieved by turning the chargers off during peak periods, either locally or on the grid as a whole. A limited form of frequency regulation can be achieved by modulating the charging rate to match the need of the grid for more or less power second to second.

V2G is the <u>bidirectional</u> flow of energy from and to the grid from a vehicle battery. Provision of resiliency and a robust response to the other opportunities listed above, as provided by stationary batteries, will require true bidirectional V2G in which the energy can be both provided to and extracted from the EV batteries under control. This has been a subject of active discussion and demonstration for the last twenty years, but despite the obvious economic incentives, it has yet to be commercialized.

Part of the reason for this is that it requires an expensive stationary inverter/charger to do high rate (20-30 kW) charging from widely available AC to EV battery DC and high rate inversion from the 350 V DC EV battery to useable 208/240 V AC. Inverters of this kind have been available and demonstrated in V2G service for ten years, but they cost roughly $0.50 per Watt, which is very hard to justify. Princeton Power Systems, a pioneer in this field, went out of business in 2021.

Now, however, a new day is dawning with the advent of on-board inverters from major manufacturers. Ford is leading the way by providing 10 kW of AC power from the F-150 Lightning EV pickup truck for operating tools and camping gear. They claim that this feature has helped accumulate the hundreds of thousands of orders they have received for delivery, starting in 2022. The electric Chevy Silverado is doing the same for delivery in 2023. VW is rumored to have a bidirectional model in development.

This is not a new idea. Twenty years ago, AC Propulsion of San Dimas, CA, published

Figure 2. Variable frequency AC drive by AC Propulsion with integrated recharge capability.

an extensive study of a high-power V2G vehicle [1] in which the charger/inverter used the same Insulated Gate Bipolar Transistors (IGBT) and motor windings as the variable frequency AC drive that the company invented and showed off in its T-Zero electric sports car. This vehicle had extraordinary performance, and the drive was incorporated into the early Tesla Roadsters.

In the above drawing from the 2002 report, the Traction Inverter and the Traction Motor constitute the AC Propulsion variable frequency drive which is based on a network of high power (150 KW) Insulated Gate Bipolar Transistors. The IGBTs convert 350 V battery DC into variable frequency, three phase AC to drive an induction traction motor at whatever speed the vehicle is travelling. This was a major improvement over previous DC variable speed drives in cost and reliability.

By adding the components for “integrated recharge capability” (costing only about $300), two of the three phases were controlled to permit rectification of an AC input to provide 20 kW of recharging capability using the existing IGBTs and two windings of the motor as the heavy, high cost, high power components. The result is an almost zero-cost, on-board high-power battery charger

By elaborating the control package to make the two phases function as an inverter, the system can be made completely bidirectional providing 20 kW or more of 60 Hz AC output at any desired voltage and at virtually no additional cost.

Ford and others may be using this system now, and the advantages of a bidirectional world are so compelling that it is almost certain that someone will. The bottom line here is that not only is it possible to create a high-power, bidirectional flow of electric energy from an EV battery, but by intelligently using the components that are already on board, it can be done at almost no cost.

Implications

The availability of EV battery storage along the lines predicted above imply that some of the services described in the introduction can be implemented quite soon. Load shifting, energy arbitrage and renewable utilization are already practiced. Existing EVs can easily be programmed to charge only in the early morning hours to avoid peak load hours and charge at the lowest rate where time-variable pricing is in effect. Programs to take advantage of the availability of renewable energy already exist for those EV owners willing to pay a premium.

Because of the enormous size of the automotive fleet, which consumes 28% of the entire energy budget of the US [2], even these straightforward V1G technologies can provide a very significant storage resource to the grid. Specifically, controlled EV charging can improve the utilization of renewable energy with very minimal additional technology and investment.

EV batteries to address resiliency will have to wait until high power V2G is available in quantity, but charge rate modulation for demand charge management, demand response participation and frequency regulation can be started now. The latter two require aggregation of enough capacity under control to make it worthwhile to the grid operator, normally 100 kW. As the advent of high-power V2G accelerates, all of these applications become more attractive and achieve a higher impact.

An assessment of the growth of V2G-capable vehicles is shown below. It is based on the likely sales of the big pickups that are leading the way, and assumptions about the number of other vehicles that will follow based on past experience and present knowledge. One of the assumptions is that the V2G-enabled market will grow at 20 % per year, only half the growth rate for EVs as a whole. It could well be more.

V2G Growth 2020-2040

	CAGR Sales		20%	Vehicles, thousands				
Year	**Ford**	**Chevy**	**VW**	**Nissan**	**Others**	**Total Sales**	**Total EV**	**MWh**
2020	Sales							
2022	200					200	200	20,000
2025	346	150	100	100	100	796	1,693	169,340
2030	860	373	249	249	200	1,931	8,510	850,959
2035	2,140	929	619	619	498	4,805	25,348	2,534,837
2040	2,140	2,311	1,541	1,541	1,238	8,771	59,287	5,928,663

The total of V2G-enabled vehicle energy storage in 2040 is 15% of the total projected electric vehicle storage, which, as we have seen, grows to twenty times the total solar energy available per day and a similar multiple of what is used by the EV fleet per day. In other words, there will probably be ample bidirectional V2G capacity in the relatively near future.

This means that all of the applications for electric energy storage described in the introduction can be met by bidirectional EV charging at very low cost. The growth of free-standing storage installations should be very limited as indeed the current projections show them to be. In the face of low-cost, ubiquitous, and ample EV storage capacity, they will be even harder to justify.

It also means that there will be ample storage to achieve all of the grid storage objectives fully. The storage requirements for optimum use of renewable energy by flattening the “duck curve” can be met. The intermittent output of wind and solar can be stored for later use. A gigantic storage capability will be available to stabilize the grid. In many ways an ideal energy supply. And to make up for the occasional lapses in grid service, resiliency requirements can be met to a large degree, as complemented by distributed renewable generation. All of the other load-flattening requirements can be met, both locally behind the meter for demand charge management, and in conjunction with grid operators (ISO/RTOs and utilities) for management of the grid as a whole.

While the literature in this field is slim compared to that for V2G and the use of end of life EV batteries, both of which are extensive, this development was foreshadowed by a prescient article in Forbes Magazine in 2020 [3]. A recent article from the University of Delft reaches similar conclusions to this study. [4]

Requirements

The missing link in realizing the advantages listed above is demonstrated technology to integrate bidirectional EV charging into the customer’s electric service and into the grid. Up to the present, V2G technology has focused on a DC link to the vehicle. Now the automotive industry is handing us an AC link at virtually no cost, and we need to learn how to use it.

Acknowledgement

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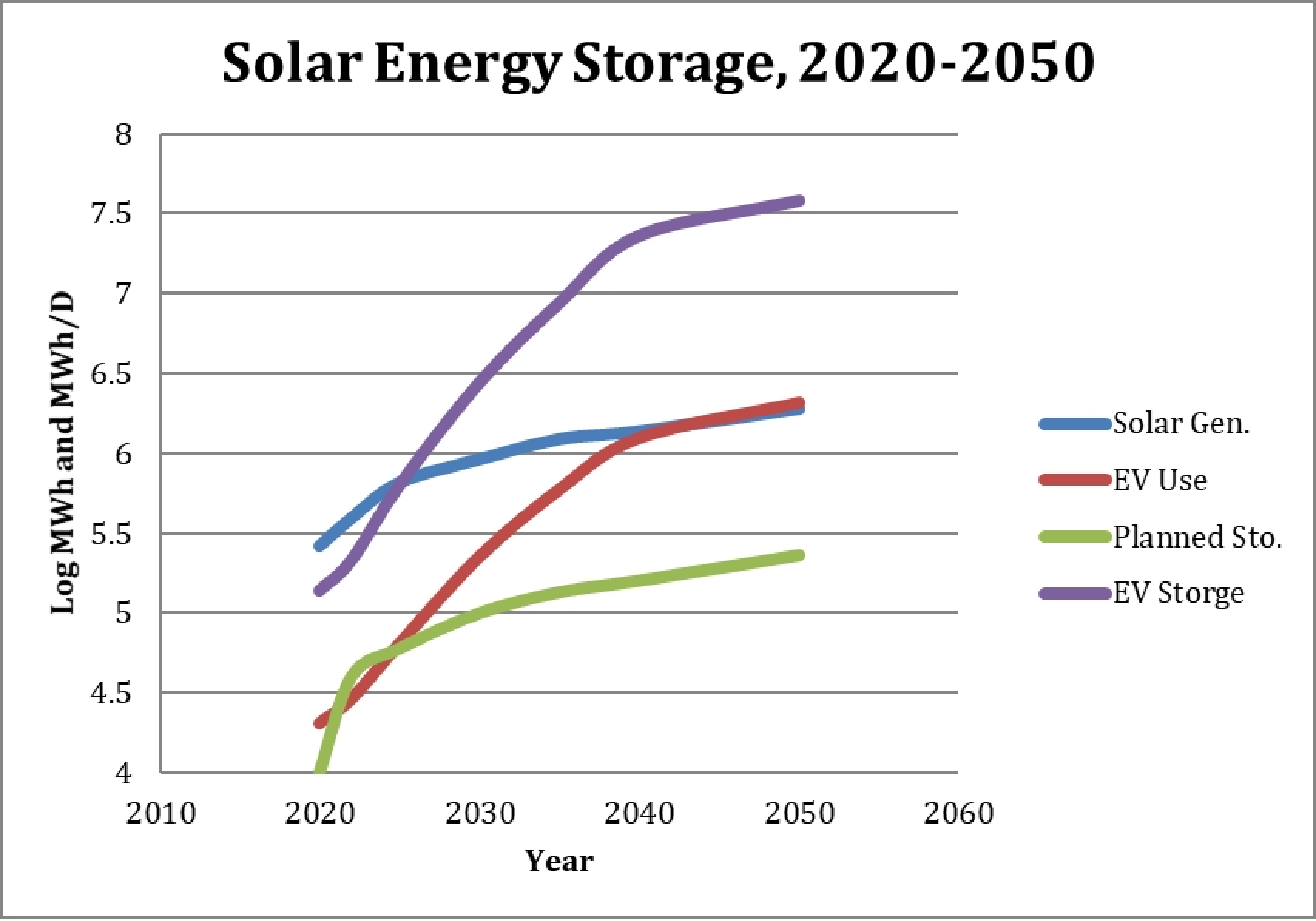
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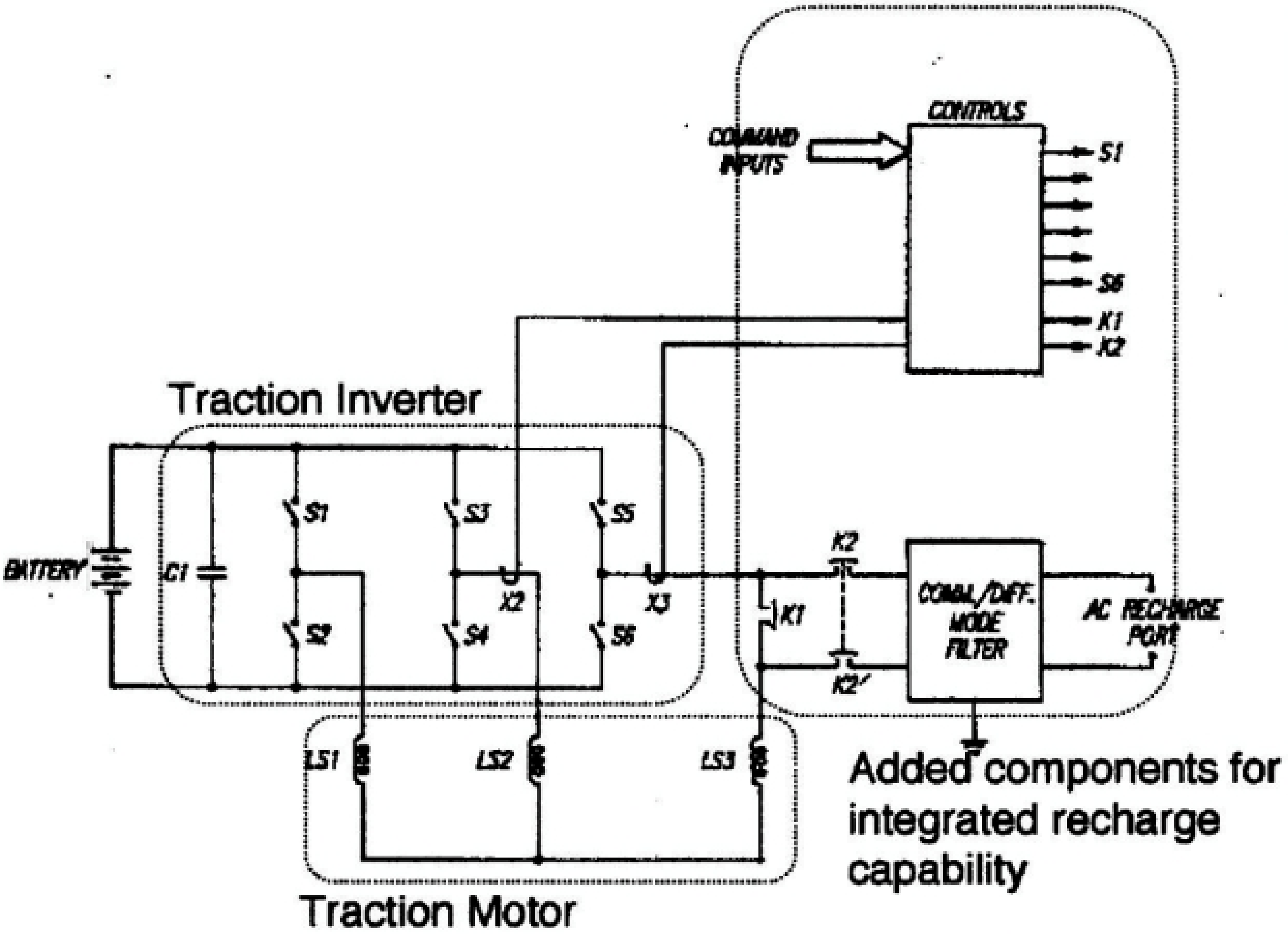

Traction Inverter

Traction Motor

Added components for integrated recharge capability

Figure