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Vehicle-to-Anything (V2X) Energy Services, Value Streams, and Regulatory Policy Implications

Andrew W. Thompson^{abc} and Yannick Perez^{cd}

Abstract

Vehicle-to-Anything (V2X) is an umbrella term to explain the use of Electric Vehicle (EV) batteries to derive additional value during times of non-use. V2X services generate revenue from the battery asset through dynamic (V1X) or bi-directional (V2X) charging to provide benefits to the electric grid, to reduce energy consumption of buildings and homes, or to provide back-up power to loads. While relatively unknown and still regarded as a nascent technology, V2X exhibits low capital costs and enabling costs have decreased by 90% since 2014.

We present the V2X Value Stream Framework as a means to better communicate and categorize its full economic potential. A meta-analysis of Value Stream potential gives results contradictory to the literature and indicates that Bill Management, Resource Adequacy, and Network Deferral are more valuable than Energy Arbitrage and Spinning Reserves. We distinguish between Energy and Power Value Streams and show how the latter cause less battery degradation and allow for greater stacking of services. Finally, energy policy recommendations are given to better integrate V2X. While we concur that development is of and by the market, we emphasize that V2X will develop within the constraints of the regulatory environment; therefore regulators have an enabling role to play.

Keywords: Vehicle-to-Anything (V2X); Vehicle-to-Grid (V2G); Ancillary Services; Lithium-Ion Battery Degradation Costs; Lithium-Ion Battery Degradation Modeling

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1 Introduction

In 2017 the global electric vehicle (EV) stock surpassed 3 Million units, which follows a nearly 60% continuous growth rate since 2015. Sustained exponential growth is expected for the near future and will result in an estimated 130 – 220 Million EVs worldwide by 2030 (International Energy Agency, 2018). Also in 2017 the Electric Vehicle Initiative (EVI) whose members account for the large majority of the global EV stock have adopted the EV30@30 campaign which sets a shared goal to obtain a 30% EV sales share of all vehicles by 2030 (Electric Vehicles Initiative, 2019). Along with growing electric transport will come increased electricity demand. For example if all light-duty vehicles in the US were replaced with EVs, they would require about 1,000 TWh of additional electricity per year or an increase of about one-quarter of the current annual US electricity demand (Nelder et al., 2016). In 2016, the global EV electricity demand was 54 TWh which is approximately the annual energy demand of Greece. The question of electricity demand driven by EV charging will largely depend on EV penetration levels. A recent simulation study in New England showed that a 25% EV penetration would cause a 19% increase in peak demand which would require significant investment in new generation, transmission, and distribution capacity (Nelder et al., 2016). It is clear that unmanaged EV charging is not an economic option in the long-term therefore development of Vehicle-to-Anything (V2X) technology can be a solution to what will become a serious problem in a future with large penetrations of EVs.

V2X however is still a developing technology area and is virtually unheard of in public and policy spheres. Even among professionals and academics working in the electro-mobility domain V2X remains relatively unknown (Kester et al., 2018). This results in research which only looks at one facet of the V2X concept and usually only considers one market product to draw conclusions about the viability of V2X as a whole without considering the full range of potential value nor the full operational capabilities (Bishop et al., 2013; Mullan et al., 2012). Additionally the scientific literature is rife with misuse of V2X terminology which conflates meaning, confuses technical audiences and policy-makers alike, and undoubtedly highlights the need for clearer communication.

Therefore in this paper we present a thorough definition of the V2X concept to clarify the literature, we present the Value Stream Framework to better communicate the full economic potential of V2X, and explain the relevant regulatory policy context. We begin with the 2 V2X Concept Explained section where we describe the four main topologies/operating modes. We break from previous work in that we highlight lesser researched topologies and present each in the order of increasing scale and complexity. Next we introduce the 3 V2X Value Stream Framework and present results of a meta-study of economic potential and further develop the V2X concept with the introduction of the Power vs Energy services distinction. Finally we enumerate and discuss various energy policy issues in the 4 V2X Regulatory Issues section where we present a methodology to assess energy market adaptability to V2X services and provide final remarks in the 5 Conclusions and Policy Implications section.

2 V2X Concept Explained

2.1 V2X Topology

Vehicle-to-Anything (V2X) is an umbrella term to explain the use of Electric Vehicle (EV) batteries to provide energy services and derive additional value from the battery asset during times of non-use. V2X services aim to generate revenue from the battery asset through dynamic or bi-directional charge control to provide benefits to the electric grid, to reduce/flatten/shift peak energy consumption of buildings and homes, or to provide back-up power to a load. Energy services refer to selling this dynamic charge control in the form of aggregated flexible capacity in Wholesale and Ancillary Services markets to provide much needed flexibility to System Operators and other relevant parties for technical operation of the electric grid. V2X topology refers to both the electrical connection involved and the operation mode employed and can be classified as Vehicle-to-Grid (V2G), Vehicle-to-Building (V2B), Vehicle-to-Home (V2H), Vehicle-to-Load (V2L).

While most research efforts to date have focused on the well-documented and defined Vehicle-to-Grid concept, V2X should be understood to represent all topologies of which V2G is one. A few studies have referenced Vehicle-to-Vehicle (V2V) but as this nomenclature is redundant to V2L it has fallen into disuse. Additionally, (Noel et al., 2019) have identified a Vehicle-to-Community (V2C) topology where aggregated EVs are connected at the distribution grid to serve a residential community, analogous to community storage or community solar; however we do not incorporate V2C here leaving it to future evolutions in Vehicle-to-Anything (V2X) research. Finally, (Pearre, 2019) provide a succinct review of V2X technology which further delves into infrastructure considerations that we do not address presently.

When referring to V2X it is implicit that any service would be provided in addition to and apart from the primary purpose of mobility i.e. when the vehicle is parked, which has been proven to be more than 90% of the asset life (Wu et al., 2010). The energy capacity of a V2X resource is dependent on a number of factors, namely the EV battery pack capacity and the effective charge rate which is determined by a combination of the Electric Vehicle Supply Equipment (EVSE) and the onboard charger in the vehicle. In the case of an aggregated V2X resource the other key parameter is the number of vehicles needed to provide a given energy capacity with certainty.

2.1.1 Energy Capacity

Energy capacity in contemporary battery packs in commercial vehicles range from 16 – 100 kWh with gravimetric energy densities ranging from 89 – 260 Wh kg⁻¹ at the battery cell level (Ding et al., 2019). Technological developments aim to increase gravimetric energy densities to 350 Wh kg⁻¹ in the near future and potentially upwards of 800 Wh kg⁻¹ for new lithium-air technology, which would result in potential battery packs of up to 230 kWh if pack weights remain the same (Cano et al., 2018)⁵. However, as EV battery development is focused primarily on vehicle range and energy efficiency and not on total

⁵ Rationale for 230 kWh battery pack: Curb weight is a crucial parameter for EV range, therefore assuming battery pack weight does not change from leading gravimetric energy density technology (2017 Tesla Model 3) from (Ding et al., 2019). The calculation is as follows: 75 kWh/260 Wh kg⁻¹ = 288.5 kg (current leading edge pack weight not including wiring, mounting, or packaging). To find potential future battery pack capacity, 288.5 kg * 800 Wh kg⁻¹ = 230.8 kWh ~ 230 kWh.

energy capacity, future battery pack capacity will be largely dictated by customer driving needs. Therefore we expect a maximum optimal battery capacity for each consumer driving segment which will result in an upper practical limit on individual V2X capacity, however this limit will only slightly impact the number of vehicles parameter needed for most V2X services.

2.1.2 Effective Charge Rate

The effective charge rate is determined by the limits of the combination of the Electric Vehicle Service Equipment (EVSE) which provides electricity to the vehicle, and the onboard charger within the EV which provides electricity to the battery. EVSE have become standardized by charging power where in the U.S. Level 1 = 1.44 – 3.3 kW on-board single phase AC, Level 2 = 3.3 – 14.4 kW on-board single or 3-phase AC, and Level 3 = 14.4 – 240 kW off-board direct DC charging. In Europe standards have developed along similar lines and have designated three charge levels where Normal = 3.7 kW single phase AC, Medium = 3.7-22 kW single or 3-phase AC, and High = greater than 22 kW with an additional two distinctions, one for 3-phase AC and another for DC connections (Falvo et al., 2014).

However the EVSE charge power can be limited by the onboard charger within the EV as is usually the case. The onboard charge power is also known as the acceptance rate which can range from 3.3 – 19.2 kW in current EVs. For example a vehicle may be connected to a Level 2 ESVE which can provide 7.7 kW of power to the vehicle, however the onboard charger within the vehicle can only charge/discharge the battery pack at a maximum of 6.6 kW, therefore the effective charge rate is limited to 6.6 kW. Conversely the onboard charger may accept up to 19.2 kW but if it is connected the same Level 2 charger, the effective charge rate will be limited by the EVSE to 7.7 kW. Therefore effective charge rate is important to understand when choosing both the vehicle type and EVSE for a V2X resource.

Figure 1 is a comprehensive visualization of the V2X concept which highlights each topology, where they operate within the energy system, and the connections with other grid elements. We classify Microgrid operation as a special use-case of the V2B topology as evidenced by the color overlap. In the following sections we present each topology starting from smallest scale and least complex to largest and most complex.

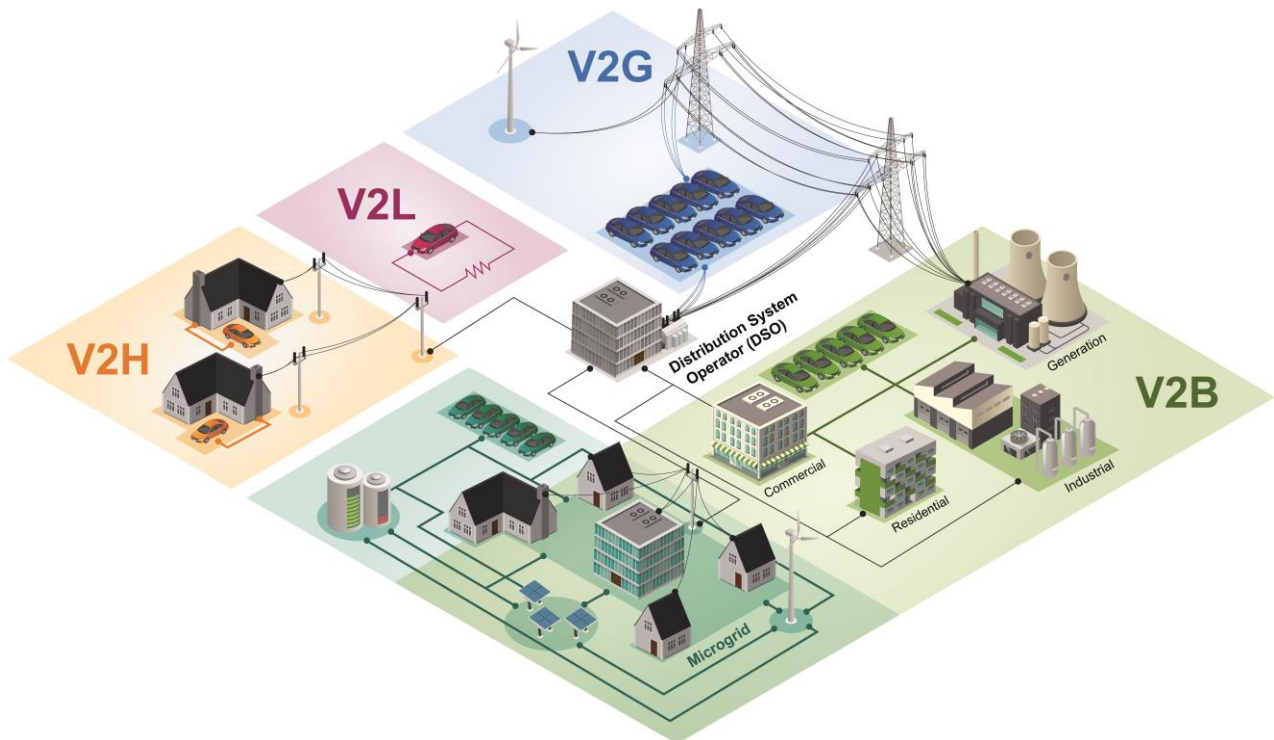


Figure 1: V2X Topology Explained

Where V2G = Blue, V2B = Green, V2H = Orange, and V2L = Red. We classify microgrid operation as a special use-case of the V2B Topology expressed by the color overlap of green shades. Colored connections indicate interactions within the topology whereas black connections indicate connections/interactions with other grid elements. We feature the Distribution System Operator (DSO) as a central figure due to the unique role of the distribution system in enabling much of V2X capability.

2.2 Vehicle-to-Load (V2L)

V2L is the least complex and smallest scale topology and constitutes any instance of an individual EV battery providing energy to a load. The primary envisioned operation of V2L is in providing emergency back-up energy in the case of an electric grid outage or serving as a source of energy in rural areas with limited grid connections. V2L can provide energy to critical equipment in hospitals or research centers, power external electronics, or even operate in recreational non-emergency usages as a generator for camping, construction sites, concerts, parties, and other areas where there are limited grid connections.

While V2L provides the most easily accessible and recognizable value, it paradoxically has garnered the least amount of academic research which highlights a large opportunity for future work.⁶ One of the key areas of inquiry will be the economic valuation of V2L. Willingness-to-Pay (WTP) and Willingness-to-Accept (WTA) studies are the norm in electric power systems design and energy economics for determining the Value of Lost Load (VoLL). VoLL is a socioeconomic indicator which measures the

⁶ A recent scientific publication search of top rated energy journals with keywords “Vehicle to Load V2L” yielded a total of 3 publications: Applied Energy (Robledo et al., 2018), IEEE Xplore (Wang et al., 2018), Journal of Power Sources (Thompson, 2018), Energy Policy (0), Energy Economics (0), Renewable Energy (0).

monetary damage arising from loss of economic activity due to a power outage, or stated differently, a measurement of the maximum electricity price customers are willing to pay to avoid an outage (European Commission, 2017; Schröder et al., 2015).

Research on VoLL indicates a heterogeneity of value across segments with the industrial/commercial sectors ranging from a few €/kWh to more than € 250/kWh and a large variation between countries from few €/kWh for EU member states to more than € 250/kWh for the USA and New Zealand. For private users in the residential sector the values range from a few €/kWh up to € 45/kWh (Schröder et al., 2015). It is clear though that even the lowest estimations of VoLL constitute a significant price gap and thus value potential of V2L when compared to the US average residential electricity price of 0.13 \$/kWh (€ 0.11/kWh) with EU member state household electricity prices ranging from € 0.10/kWh to € 0.31/kWh (Eurostat, 2019; US Energy Information Administration, 2019a).

Recent work which uses more granular socioeconomic data has noted that a higher than average VoLL is exhibited among the fuel poor, early adopters of EVs, and those living in rural locations (Electricity North West, 2018), areas where V2L is a natural fit. V2L technology may develop faster in rural areas or where diesel generators are still heavily relied upon as in Alaska, Hawaii, and other islanded electric grids where even expensive technologies are made competitive due to the high cost of diesel fuel and the associated shipping costs (IRENA, 2015; NREL, 2013). V2L remains an area of promise for future research as technical barriers are largely absent and development will be focused on application of existing capabilities.

2.3 Vehicle-to-Home (V2H)

V2H is the next least complex topology and consists of optimizing home energy consumption or using one or several EVs as emergency back-up power for residential homes. V2H will operate with a connection to a central hub/home energy controller, likely in conjunction with rooftop solar and potentially with small-scale battery storage as seen most notably in the Tesla Powerwall and in Nissan's V2H ecosystems (Nissan Motor Corporation, 2018; Tesla Inc., 2019). As an illustration, a single fully charged Tesla Model S with a 100 kWh battery pack even with a very low effective charge rate of 2 kW could provide over 70 hours of electricity consumption of an average residential home in the US and approximately 10 days of electricity for an average home in the European Union⁷, a clear value which explains the existence of several commercial products today.

V2H value derived from energy optimization is largely dependent on locational aspects such as residential tariff structures and electricity prices. Electricity tariffs can be characterized as being either Volumetric (with and without net-metering) or Capacity based. Both structures can either be applied uniformly throughout the 24 hour day or may vary depending on the hour, such as with the Time-of-Use

⁷ From (Enerdata, 2016) Annual US average electricity usage = 12305 kWh, Annual EU average electricity usage = 3600 kWh. US average hourly electricity usage: 12305 kWh / 8760 h = 1.41 kW, EU average hourly electricity usage: 3600 / 8760 h = 0.41 kW. Hours of V2X electricity provision from 100 kWh battery pack for US: 100 kWh / 1.41 kW = 70.92 h, Hours of V2X electricity provision for EU: 100 kWh / 0.41 kW = 243.90 h

(TOU) or Peak/Off-peak designs (Schittekatte et al., 2018). Thus V2H can optimize energy expenditure in two ways: 1.) by flattening the home consumption curve to reduce peak electricity demand thus reducing capacity charges or 2.) by taking advantage of TOU structures along with electricity price and adapting home energy consumption to minimize energy costs. Additionally, there is discussion of developing special EV electricity tariffs which encourage charging in the evening hours when electricity demand is low to reduce wind curtailment and thermal plant shutdowns (King and Datta, 2018). In summary, V2H offers a clear value proposition which has already garnered industry support and is the second most commercially developed V2X topology to date.

2.4 Vehicle-to-Building (V2B)

V2B operates much like that of V2H but at larger scale which may employ only a few EVs or aggregate entire fleets to optimize building or site (micro-grid) energy consumption. As V2B is aimed at commercial and industrial buildings, benefits are more pronounced and V2B technology can reach grid-significant capacity through aggregation which opens other avenues that V2H cannot access. Industrial and Commercial consumers not only are subject to much higher capacity charges but are also charged for line phase imbalances caused by large inductive loads which increase line power losses and require expensive corrective actions.

These capacity charges, additionally referred to as demand charges, can comprise over half of a monthly commercial/industrial electricity bill yet are induced by only a few brief spikes in building load. US average annual commercial electricity bills range from \$6,671 - \$11,647 (€ 5.857 – € 10.226) and US average annual industrial bills range from \$40,680 – \$491,749 (€ 35.715 – € 431.729) from most recent 2017 data (US Energy Information Administration, 2019b). Therefore a V2B resource that can reduce these peaks by even a few kW can deliver significant cost savings, thus providing a valuable service for a low capacity and time commitment (Ghaderi and Nassiraei, 2015; Pearre, 2019).

Power Factor Correction (PFC), Reactive Power Control (RPC), and Voltage Regulation (VR) are all corrective actions employed to improve power quality and thus minimize line losses in power systems. While passive methods such use of capacitor banks are simple but expensive, active methods employ power electronics to dynamically adjust reactive power output. EVs can provide these services by operating EVSEs with different goals: by providing reactive power to achieve a reference power factor (PFC), by providing or absorbing reactive power to/from the grid (RPC), or by providing/absorbing reactive power in response to grid conditions to improve node voltage levels (VR) (Tan et al., 2019). Research indicates however that Voltage Regulation may be the most impactful service to offer and that EV charging can be effectively operated with minimal influence on the distribution grid (Knezovic et al., 2014).

These expanded benefits are not limited to customers alone since, due to the scale, grid operators also reap benefits from reduced industrial/commercial peak loads and improved power factors. Additional considerations such as reduction of carbon emissions, infrastructure capital cost deferment, and reduction of operational costs have been reported by V2B integration (Koh and Lim, 2016). These direct

and derivative benefits come at the cost of increased complexity as fully capable V2B services will require connection to building or central energy system controls which may or may not have communication capabilities with the greater electric grid. V2B offers substantial and tangible financial benefits through Industrial/Commercial cost savings and by providing grid-significant capacity resources which can access energy markets as elaborated further in the 3 V2X Value Stream section.

2.5 Vehicle-to-Grid (V2G)

V2G is the most well-known V2X topology and refers to using EV batteries to interact with and provide value to the electric grid in the form of one or more energy services (Kempton and Tomić, 2005). While V2G is understood to mean bi-directional charge/discharge capability, V1G entails mono-directional charge control and is also referred to as Smart Charging. Both operating modes require sophisticated telecommunication and controls which can receive signals and respond to real-time grid conditions by either varying charge power (V1G) or by varying both charge and discharge power (V2G). V2G presents the largest overall revenue potential with direct access to wholesale energy and ancillary services markets, however it constitutes the most complicated topology due to the need for grid-significant capacity acting in response to real-time grid conditions. V2G services therefore are provided by an Aggregator coordinating a multitude of individual vehicles or by operating a fleet of vehicles.

While V2G approximately doubles the available capacity with a substantially greater revenue potential than a V1G resource, current enabling costs (mono to bi-directional EVSE infrastructure marginal costs) are significant and point to the lack of available commercial products and technological maturity (Campbell, 2014; Thingvad et al., 2017; Wang et al., 2016). Cost trends are encouraging however as V2G enabling costs have decreased by a factor of 9.4 or nearly 90% from € 44 953 in 2014 to € 4 805 in 2018 and will continue to decline as technology develops (Campbell, 2014; EVConsult, 2018)⁸. Additionally, an effective charge rate corresponding to Level 2 (6.6 kW) or higher is necessary for V2G services as lower charge rates would require too many vehicles to meet minimum capacity bids in energy markets, the few available V2G EVSE commercial products have settled in the 10 – 15 kW range.

The V2G concept also has attracted significant commercial interest and has spurred a number of start-up companies (NUUVE, EMotorWerks), large investments in hardware and ecosystem development (The Enel Group, Nissan Energy, ChargePoint), and wide participation from automotive OEMs (Renault Nissan

⁸ 2014 numbers from (Campbell, 2014) which reported the Princeton Power Systems GTIB-15 V2G EV charger price at \$55,000 compared to the ChargePoint CT4011-GW V1G Charger at \$5,000. Thus V2G enabling costs (EC_{2014}) were \$50,000 in 2014.

2018 numbers: Enel X/Magnum Cap V2G 10 1.5 charger price at € 5 500 from personal communication compared to Enel X/EMotorWerks JuiceBox Pro 32 V1G charger commercially available for € 695 within the EU (Available for \$549 in the USA), thus V2G enabling costs (EC_{2018}) were € 4 805 in Europe in 2018.

Convert EC_{2014} to USD_{2018} with average USD inflation rate of 1.48% = 53,035.20 USD_{2018}

Convert USD_{2018} to EUR_{2018} using 2018 US/EUR historical average Fx of 0.8476,

Therefore EC_{2014} = € 44 953 EUR_{2018} and EC_{2018} = € 4 805 EUR_{2018}

Mitsubishi Alliance, Groupe PSA, Honda, BMW, Transpower, Volkswagen, Toyota, among others). A recent market report identified at least 50 ongoing V2G research projects that are at the pilot or commercial phase worldwide making V2G the most commercially developed topology (EVConsult, 2018).

3 V2X Value Stream Framework

We present economic potential of V2X in terms of Value Streams where value can be derived from the **Wholesale Energy Market**, through use of products or mechanisms; through interaction with **Utilities and Network System Operators**, by providing value in terms of capital cost deferment and greater efficiency of existing network assets, or through interaction with **Customers**, by providing value to Residential/Commercial/Industrial consumers in terms of cost savings and reliability.

The term *value* has been deliberately chosen instead of *revenue* to allow for an expanded definition scope since in many instances energy market regulation has either not developed or caught up sufficiently to define adequate compensatory structures which reflect the full benefits new technology can provide. The Value Stream Framework is also intended to eventually include enviro-social aspects such as CO₂ emissions reduction, battery life prolongation, reduction in air pollution/city noise, and wellbeing. In this first iteration we focus primarily on V2X Value Streams which already have identifiable monetization avenues within the energy industry and leave enviro-social aspects for future work. In a future where carbon markets or carbon pricing in energy markets become important, this would likely constitute increased benefits that V2X can offer, however we restrict the Value Stream Framework to current regulatory environments.

Furthermore the Value Stream Framework is presented to categorize the full range of energy services V2X can provide, designate which topology can provide each service, and identify where value is derived while providing some insight to the economic scale of each Value Stream. Finally, the Value Stream Framework is not intended as an affirmation or condemnation of overall economic viability as the feasibility of each V2X topology will depend on a multiplicity of project-specific and locational factors.

3.1 Value Stream Identification

3.1.1 Assumptions

V2X energy services are defined by the technical capabilities of lithium ion batteries arranged into packs of differing sizes. As the underlying technology is the same, V2X has similar characteristics as lithium ion Battery Energy Storage Systems (BESS) albeit at reduced scale. Technical operation has been proven to be within System Operator performance requirements by several pilot projects (Black, 2014; Kempton et al., 2009), therefore the first key assumption is that that V2X can provide most of the services as BESS.

We develop the V2X Value Stream Framework drawing upon work from Lazard's Levelized Cost of Storage (LCOS) analyses along with US EIA and national lab reports (Gannon et al., 2015; Lazard, 2018, 2017; Sandia National Labs, 2015; US Energy Information Administration, 2018). These approaches have

extensively identified potential markets that BESS could access and have developed robust empirical assessments of BESS economics in addition to general Li-ion technological trends. As reiterated in the latest LCOS Version 4.0 (Lazard, 2018), key trends include cost declines that have exceeded expectations in addition to improving project economics for most use cases. LCOS 4.0 reports capital costs of Li-ion BESS between 1,140 – 1,814 \$/kW operating in the Wholesale market, with a 5-year capital cost reduction of 28% and CAGR of 8% over the same time period from 2018-2022. This cost range is also in line with US EIA estimations of \$ 1,857 \$/kW for new entrant battery storage in 2018 (US Energy Information Administration, 2019c).

BESS is cost competitive and indeed already cheaper than other traditional sources of ancillary services such as Combined Cycle Gas Turbine (CCGT) and Coal in select markets (Lazard, 2015). This analysis paired with recent experiences in Australia’s FCAS market, California’s wholesale market (CAISO), and PJM’s frequency regulation service, imply that Li-ion battery storage will continue to capture market share based on price competitiveness alone (AEMO, 2018; Lee, 2017; Parkinson, 2018). Therefore the second key assumption is that V2X will primarily compete in the market with lithium-ion BESS and we do not consider other technologies further. Finally, as shown later in the 4 V2X Regulatory Issues section, many market rules that benefit V2X will also benefit BESS in addition to other capacity-restrained Distributed Energy Resources (DERs). We postulate that V2X and BESS will exhibit coopetition behavior; competition in the energy market yet cooperation in lobbying energy market regulatory change.

3.2 V2X Value Streams

Table 1 is a summary of the core contributions of this paper, the V2X Value Stream Framework with explanations of the underlying energy services translated into how they are provided by V2X along with where value is generated⁹. Each Value Stream description expands upon both uni-directional (V1X) and bi-directional (V2X) operation, where X refers to multiple topologies or is replaced by the specific topology referenced (i.e. V2G, V1B). Where no distinction is made indicates that both V1X and V2X operate in the same manner. Additionally Table 1 highlights which Value Stream is accessible by each V2X topology, whether the service is provided by an individual or aggregated resource, if the service is Power or Energy based, and designates where each physically operates in the electric grid either In-front-of or Behind-the-Meter.

Table 1: V2X Energy Service Value Streams

(Table 1 here)

⁹ Note here we adopt US-centric definitions but attempt to make definitions general enough to be readily identified across world wholesale markets (i.e. frequency regulation as a 4 second signal, spinning reserves as a response to contingency, etc)

3.2.1 Power vs Energy Based Services

We introduce a key distinction between Energy and Power (or Capacity) Based Value Streams as these have significant implications for battery degradation costs and greatly impact viability for any energy-constrained resource. As explored in (Thompson, 2018) and (Uddin et al., 2018), unintelligent prolonged energy throughput (charge and discharge) has pronounced negative effects on Li-ion battery lifetime. These lifetime effects are significant to the point that nearly any large energy throughput V2X service will be cost prohibitive if not managed with a thorough understanding of the intricacies of battery degradation.

Conversely, intelligent degradation-cognizant V2X provision has been shown to improve battery lifetime even for large energy throughput, a valuable secondary benefit (Uddin et al., 2017). In general, V2X Services which result in smaller changes in battery State-of-Charge (SOC) will have smaller degradation costs than large energy throughput services which induce greater SOC swings. Similarly, V2X services which are able to maintain temperature-dependent optimal SOC set points will also induce less battery degradation. Therefore Power Based Value Streams which either do not contain an energy component or require less energy throughput will be crucial for V2X development.

The first Power Based service is Frequency Regulation (FR) which fundamentally is derived from charge/discharge power flexibility i.e. the ability to vary charge power quickly to follow a grid signal from the system operator. As the regulation signal is typically designed to result in zero net-energy exchange over the contract period, FR can be provided around an optimal SOC point without inducing large SOC swings. Resource Adequacy (RA) or Capacity Payments are compensatory mechanisms to develop new capacity to maintain safety margins above projected future peak demand. In the case of V2X the ability to alleviate future system peak loads is provided by either interrupting charge (V1G/V2G) thus reducing demand, or by discharging to the grid thus increasing supply (V2G) during peak hours. RA or Capacity payments can be stable, high revenue Value Streams and are remunerated in terms of power (\$/kW per month or per year) as opposed to energy. Similarly, Network Deferral mechanisms develop capacity (or ability to alleviate load at peak hours) in specific capacity-constrained locations in Distribution and Transmission grids to avoid infrastructure investments and build-out.

The remaining Energy Based V2X services must be balanced with their respective degradation costs within the confines of the energy capacity of the aggregated or individual resource. Large energy throughput services such as Non-spinning or Tertiary Reserves are therefore not considered in the V2X Value Stream Framework due to likely cost prohibitive battery degradation. A preference to capture Power Based Value Streams is important not only for degradation considerations but also since they allow more for stacking of Value Streams.

3.2.2 Stacked Value Streams

Currently BESS assets are capable of providing a variety of simultaneous energy services thus accessing multiple revenue streams however most V2X economic analyses to date have assessed viability based on only one energy service. An important point we make is that V2X Value Streams will need to be stacked much like current BESS operation. In practical terms this means that a V2X resource can be used to provide simultaneous services throughout the course of the year (i.e. X number of hours/yr for FR

while providing Resource Adequacy and Demand Response (DR). This is an area where recent regulation from CAISO on Multiple Use Applications is illustrative of market development and is explored in the following [4 V2X Regulatory Issues](#) section.

3.3 Annual Value Stream Estimation

Figure 2 and Figure 3 are data visualizations of a meta-analysis of selected V2X Value Stream annual revenue potential across various wholesale energy markets using data from (Lazard, 2018, 2017; Rocky Mountain Institute, 2015) which also incorporate several additional sources (see Data Collection Log in the supplementary materials). While Figure 2 provides a general overview of the Value Streams ranked in descending order of valuation and includes international markets in Australia, the UK, and Canada, Figure 3 only focuses on US wholesale markets as these have been given more investigation in the literature.

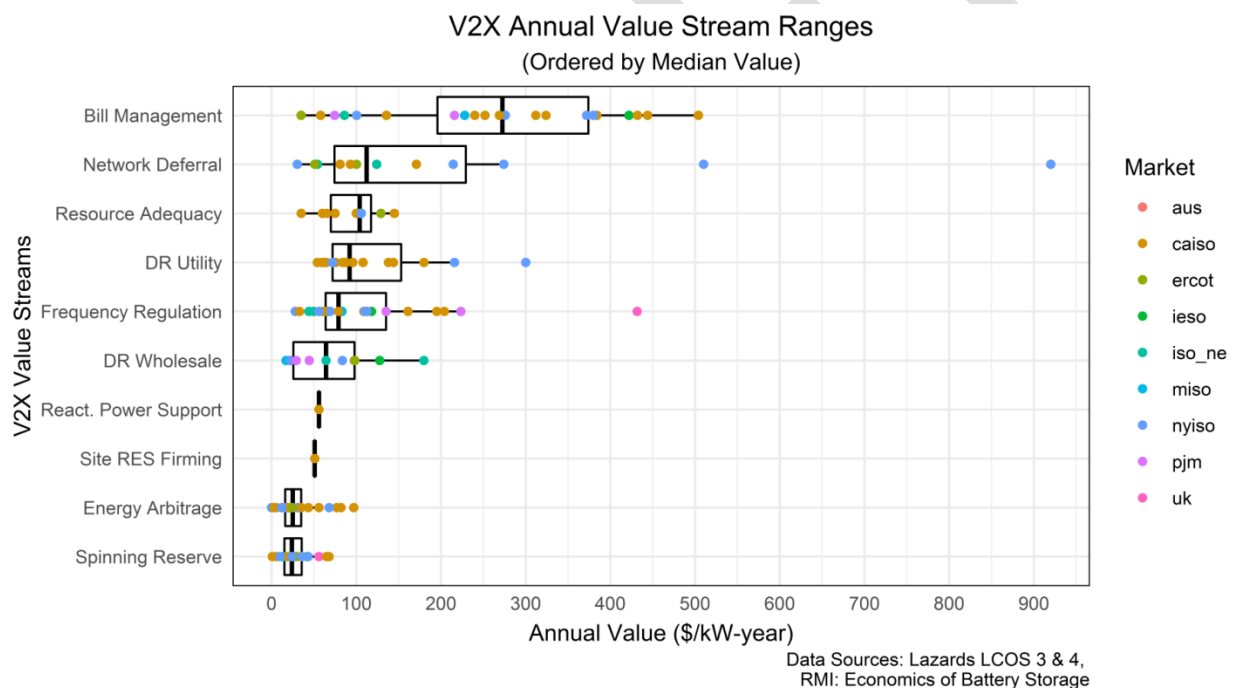


Figure 2: V2X Annual Value Stream Meta-Analysis

This data visualization shows overall economic potential of key V2X Value Streams in terms of annual revenue (\$/kW-year) which are ordered by median value via boxplots where the individual data points are color-coded by wholesale market to show clustering and outliers.

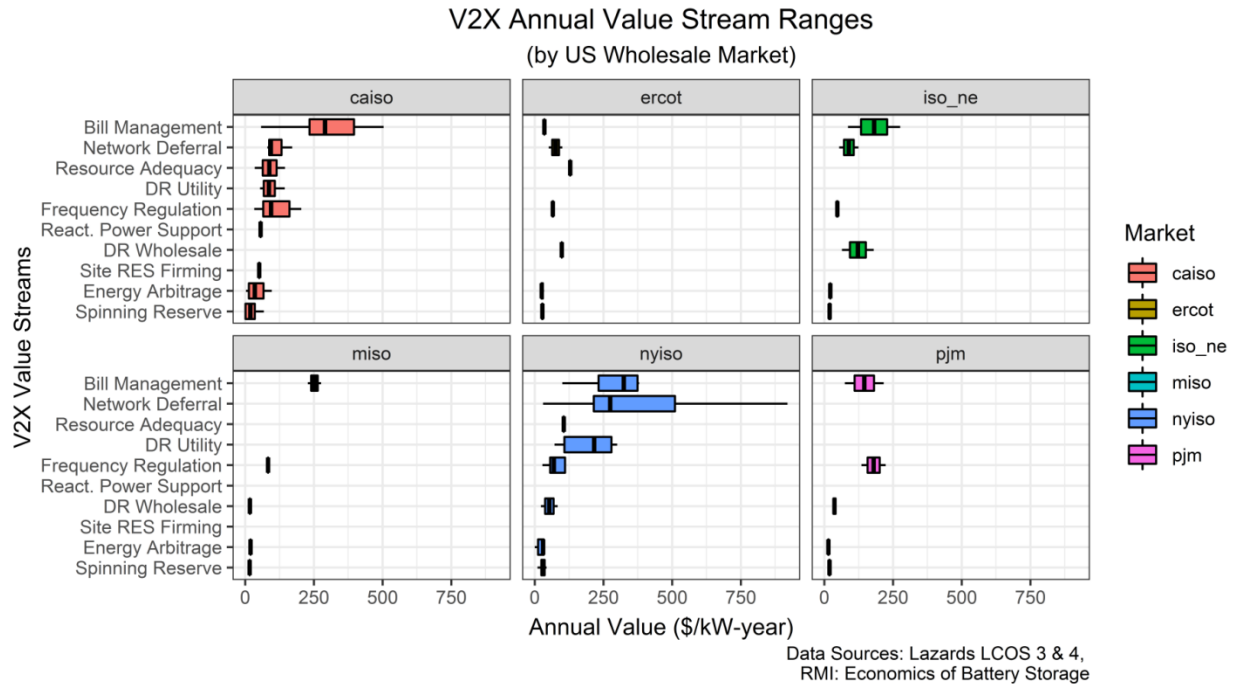


Figure 3: V2X Value Stream Meta-Analysis by US Wholesale Market

This data visualization shows economic potential of key V2X Value Streams in terms of annual revenue (\$/kW-year) faceted by US Wholesale market to show similarities in valuation across markets. Here the boxplots are color-coded by market and only show descriptive statistics without individual outliers. It is interesting to note the surprising consistency of median ordered Value Streams with notable exceptions in ERCOT and PJM.

The meta-analysis is intended as an indication of Value Stream potential but not of overall economic viability due to complexities arising from locational characteristics, differing market conditions and regulation. One particular difficulty arises in aligning Value Stream definitions as often different studies consider different product definitions e.g. Capacity products as including Demand Response or Bill Management as encompassing both TOU management and demand charge reduction in some studies but only TOU management in others. We endeavor to maintain the Value Streams as defined in Table 1 to the extent possible and have adapted data from each study as outlined in the Data Collection Log in the supplementary materials. Although this study was intended to find general valuation trends we can draw several interesting conclusions.

The first is there are very wide-ranging estimations of market value across Value Streams as evidenced by the spreads in Figure 2. For example Network Deferral show estimations ranging from 30 – 920 \$/kW-year while Bill Management ranges from 35 – 504 \$/kW-year. Hence any condemnation of V2X viability based on one Value Stream in one market alone is myopic as the same service or collection of services can be profitable in different markets with more favorable characteristics. Conversely claims of universal economic viability are also unfounded due to market intricacies such as tariff structure, local and regional energy technology mix and demand growth, which make drawing conclusions applicable to all

markets nearly impossible. Therefore analyses of V2X economic viability must be taken in the context they are performed and may not be transferrable to other markets.

That being said, previously under-investigated Value Streams such as Bill Management, Network Deferral, and Resource Adequacy have higher valuations with surprising consistency across markets as seen in Figure 3, whereas Energy Arbitrage and Spinning Reserves which have dominated the V2X literature are much less lucrative overall. Interesting deviations from the ordered ranking are seen in ERCOT with Demand Response via both Utility and Wholesale and in PJM with Frequency Regulation. The latter is unsurprising due to the introduction of the Reg-D FR signal which has attracted a record amount of battery storage investment in the PJM market. Therefore, we present this meta-analysis as a clear contradiction of most previous work and as an indication of where the potential future of V2X lies.

NYISO remains a highly lucrative market for Network Deferral with the highest valuation of all the investigated sources. While Network Deferral likely presents a large opportunity for V2X as the second highest ranked Value Stream, we issue a large caveat that it cannot be heavily relied upon for long periods of time. Network Deferral will only generate between 2 - 3 years of cash flows and not 10+ year project life projections which contradicts Lazard's and most other valuation methods. This is due to trade-offs between near future and far future demand projections. Since large increases in demand will eventually necessitate network capacity increase, build-out will result as the most cost-effective solution. Therefore Transmission/Distribution Deferral alternatives are evaluated annually and will only provide sufficient demand reduction for 2-3 years maximum before build-out would become necessary.

4 V2X Regulatory Issues

4.1 Modular Framework for Aggregator Participation in Energy Markets

In electricity markets, there is no perfect market design for the architecture nor for definition of energy services and ex-post governance solutions are needed to correct for unforeseen issues or innovations like V2X (Glachant and Perez, 2009). Current rules need to be modified to better accommodate Aggregators offering Distributed Energy Resources (DERs) such as V2X and BESS (Codani et al., 2016; Eid et al., 2016). Therefore to analyze three forms of entry barriers, we adapt the analytical framework of (Borne et al., 2018a) on market readiness for Aggregator participation in energy markets for the V2X context. This modular framework is summarized in Table 2 and is expressed by a decision tree in Figure 4. We explain this modular framework as it relates to V2X in the following sections however note that all policy suggestions will additionally benefit BESS and other small-scale DERs.

Table 2: Summary of Modular Framework for Aggregator Participation in Energy Markets adapted for V2X

Module A: Definition of Aggregation	A1	Technical Discrimination
	A2	Interoperability among DSOs
	A3	Aggregation Methodology
Module B: Definition of Energy Products	B1	Bid Structure
	B2	Power vs Energy Balance
	B3	Distance to Real-time Reservation
	B4	Value Stream Stacking
	B5	Product Symmetry
Module C: Definition of Remuneration	C1	Nature of Payment
	C2	Performance Bonus

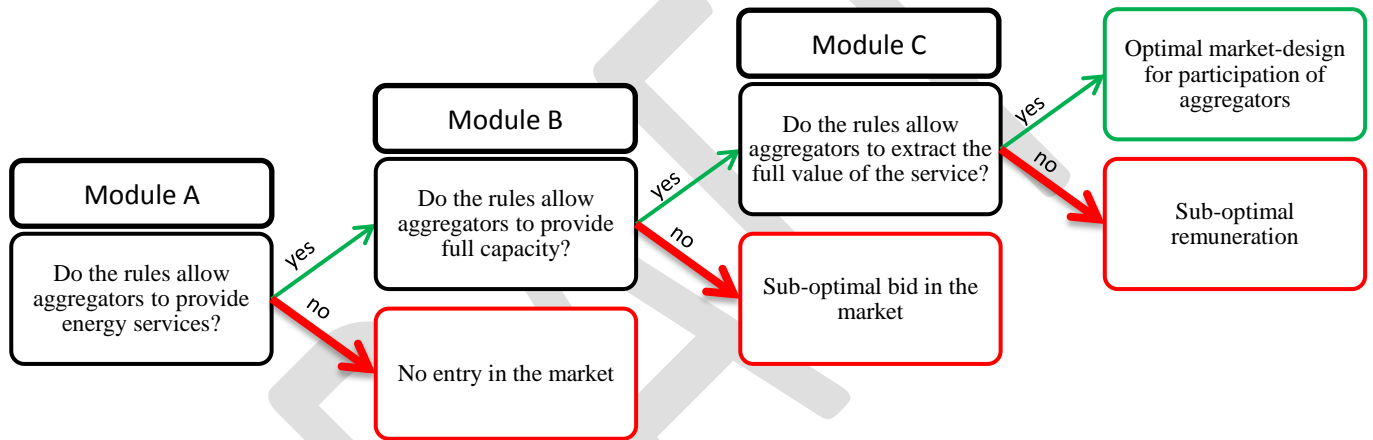


Figure 4: Decision Tree for Aggregator Participation in Energy Markets. Adapted from (Borne et al., 2018a)

4.2 Module A: Rules Regarding Aggregation

4.2.1 Technical Discrimination

Some market rules discriminate against V2X resources through outright bans on aggregation of energy sources, which precludes smaller capacity resources (V2X, DER, and BESS) from participating in wholesale markets *ipso facto*. Rule discrimination can be based on technology type or when the Generation sector in electric grids is envisioned as supply-only resources (e.g. no concept of consumption units). This discrimination can also be based on the voltage level connection to the Transmission grid, by limiting the amount of capacity that can be provided by aggregated resources, or by giving priority to specific non-aggregated market units. Action can be taken regulators in this module by removing administrative barriers to entry to allow for aggregation of energy resources.

4.2.2 Interoperability among Distribution System Operators (DSO)

As there are a growing number of DSOs in developed energy markets, to ensure that aggregation is possible new entrants must be able to aggregate units across multiple DSOs. This is especially important for V2G aggregating individual vehicles which can move from one DSO to another daily but is less important for V2G fleets which are typically geographically constrained to sites or microgrids which would be serviced by one DSO.

4.2.3 Aggregation Methodology

Two methods of aggregation are identified in (Codani, et al., 2015a): telemetry and financial aggregation. Telemetric aggregation allows the Aggregator to combine bids and power flows and to dispatch energy utilizing optimized algorithms which take characteristics of the combined resource into account (capacity limitation and need to maintain optimal SOC set points as examples for V2X). Conversely, financial aggregation only allows for the aggregation of economic bids. Here energy dispatch is controlled solely by the TSO which can lead to over-use and violation of SOC constraints in a V2G or V2B resource. Thus to allow greater participation of V2X, aggregation methodology should be telemetric where economic bids and energy dispatch are controlled by the Aggregator.

4.3 Module B: Rules Defining Energy Products

4.3.1 Bid Structure (Size, Increment, Temporal Granularity, Type)

4.3.1.1 Bid Size

Current wholesale markets vary widely in minimum bid size from 100 kW in PJM to 10 MW and greater in several European markets (Andersen et al., 2010). This minimum bid size will dictate the number of vehicles necessary to provide an aggregated V2X resource. If the minimum bid is set too high, a V2X resource will be prohibitively complex due to coordination of too many entities and would result in lower revenues per vehicle overall. 100 vehicles with an effective charge rate of between 10-15 kW per vehicle can provide a 1 MW V2G resource, however any minimum bid size higher than this would render a V2X resource unable to access the market due to threshold effects.

4.3.1.2 Bid Increment and Temporal Granularity

Additionally the minimum bid size increment and the temporal granularity can potentially constitute barriers to market entry as shown in (Borne et al., 2018b) where the authors show impact of different bid increments and temporal granularity on fleet size assuming a 1 MW minimum bid. Table 3 below shows bid structure impact on fleet size to achieve an annual revenue of € 50 /per vehicle which only have access to 3kW charging at home.

Table 3: Bid Structure Impact on V2G Fleet Size with 3kW Charging only at Home, adapted from (Borne et al., 2018b)

Bid Increment	Temporal Granularity	Number of Vehicles
1 MW	Week	NA
0.1 MW	Week	NA
1 MW	Peak/Offpeak	1400
0.1 MW	Peak/Offpeak	903
1 MW	4 Hour	400
0.1 MW	4 Hour	50
1 MW	1 Hour	350
0.1 MW	1 Hour	40

As seen in Table 3, a temporal granularity of one week renders a V2G resource unable to participate in the Ancillary Service market whereas a change from a Peak/Off Peak to a 4 hour granularity reduces the necessary number of aggregated vehicles by 1,000. Similarly, continuing from a 1MW to a 0.1 MW minimum increment further reduces the fleet size by an additional 350 vehicles such that a fleet of 50 can offer Ancillary Services despite having access at the lowest charge rate (3kW). Additionally it was shown that fleets with access to higher charge rates (22 kW) could meet 1 MW minimum bids with as little as 17 vehicles if there is a temporal granularity of 4h regardless of the bid increment size.

4.3.1.3 Bid Type: Simple vs Complex

Finally whether bids are simple or complex can impact the optimality of an aggregated V2X resource. Simple bids are effective when system supply and demand are easily aligned and constitute of a price-quantity pair given in either hourly or multi-hour blocks for a 24h day. Complex bids are increasingly important in systems with high penetration of Renewable Energy Resources (RES) and flexible demand to allow market players to specify intertemporal dependencies with their bids (Neuhoff et al., 2015). An example is taken from Spain which allows for an indication of up to four complex conditions along with bids (OMIE, 2018):

- 1.) Indivisibility: all bids with this condition must be matched in their entirety (to eliminate fractional power dispatch due to inframarginal market clearing).
- 2.) Minimum Income: bids with this condition are only accepted for market clearing if the supplier is guaranteed to recover their designated minimum income.
- 3.) Scheduled Stop Condition: this condition allows bids which are not matched due to the minimum income condition to be treated as simple bids.
- 4.) Production Capacity or Load Gradient: bids can designate a maximum upward or downward difference in energy variation between two consecutive hourly scheduling periods.

In particular the minimum income and load gradient complex conditions are very relevant to V2X to allow Aggregators to better plan fleet scheduling when costs are guaranteed to be met without undue

stresses to the V2X resource from energy dispatch required from the system operator. Regulators can design market rules to better incorporate V2X, BESS, and DERs by creating minimum bid sizes as low as possible (100 kW) with minimum bid increments as low as possible (100 kW) and temporal granularity of at least 4h (hourly or 15 minute intervals are better) along with complex bids to allow for more optimal aggregated bids.

4.3.2 Power vs Energy Balance

V2X and BESS would greatly benefit from having energy services better defined by how much energy throughput or power intensity they require. The development of better metrics of service utilization rates and ranking of energy services by energy throughput would allow V2X resources to better manage risk and battery degradation cost tradeoffs imposed by Power and Energy Based Value Streams (see Table 1). To that end proposals for new energy statistics to be maintained by the System Operator have been made but have remained largely absent in practice.

The first is the Dispatch-to-Contract ratio (R_{d-c}) originally identified by (Kempton and Tomić, 2005) which would measure the quantity of dispatched energy (how much energy was actually called upon) vs the contracted energy amount. In a similar vein we designate the Call Rate (C_r) which tracks the frequency of dispatch calls of an energy service over time which is useful for Demand Response and Spinning/other Contingency Reserves. We also designate an FR-Energy-Imbalance statistic (FR_i) for Frequency Regulation which measures energy imbalances throughout the year or, stated differently, tracks when net-energy is non-zero over contract periods.

4.3.3 Distance to Real-time Reservation

This parameter defines how long in advance of delivery the procurement of energy services is made which can be days, weeks, months, or even multi-month periods in advance. Naturally the farther in advance a service is required to be reserved the more conservative V2X Aggregators must be with the amount of capacity they can provide due to the need to predict behavior of a mobile resource. Long procurement times also negatively impact bidding ability of other intermittent RES (Wind and Solar) which have imperfect long-term forecasting ability. Therefore markets with shorter procurement times (hour ahead or real-time) will allow for more accurate estimation of aggregated capacity and more participation from V2X, DERs, and RES alike.

4.3.4 Value Stream Stacking (Multiple-Use Applications)

As with BESS, V2X can operationally offer several simultaneous energy services due to the inherent flexibility of these resources. However nearly all markets, tariffs, and bi-lateral contract provisions have been designed assuming that resources will only provide one service at a time and therefore do not have adequate language or rules to allow for the paradigm-changing concept of Multiple-Use

Applications (MUA). This is an area where recent developments in California (CAISO) may serve as a guide for other Wholesale markets (CPUC, 2017).

Recently adopted rules designate energy services (Value Streams) as either Reliability Services or Non-reliability Services as listed in Table 4. Furthermore CAISO has designated three categories of Multiple-Use Applications: 1) Time Differentiated MUAs, 2) Capacity Differentiated MUAs, and 3) Simultaneous MUAs in efforts to introduce necessary regulatory vocabulary along with 11 rules for governing MUAs to allow for revenue from multiple services so long as they are “*specific and measurable*” (CPUC, 2017). Naturally, having Time-Differentiated MUAs are only feasible in markets with sufficiently fine temporal granularity to allow for multi-use throughout the day.

Table 4: CAISO Multiple-Use Applications: Reliability Services vs Non-Reliability Services (CPUC, 2017)

Domain	Reliability Services	Non-Reliability Services
Customer	None	TOU Bill-Management; Demand charge management; On-site RES firming; Back-up Power; DR program participation
Distribution	Distribution deferral; Reliability (back-tie) services; Voltage support; Resiliency/microgrid/islanding	None
Transmission	Transmission deferral; Inertia*; Primary frequency response*; Voltage support*; Black start	None
Wholesale Market	Frequency regulation; Spinning reserves; Non-spinning reserves; Flexible ramping product	Imbalance Energy
Resource Adequacy	Local capacity; Flexible capacity; System capacity	None
*Voltage support, inertia, and primary frequency response have traditionally been obtained as inherent characteristics of conventional generators, and are not today procured as distinct services. We include them here as placeholders for services that could be defined and procured in the future by the CAISO		

The fundamentals of the 11 rules regard connection and direction of energy service provision, the principle of reliability priority/exclusivity, and service transparency which we summarize below:

- Connection
 - Energy services can be provided to domain in which they are interconnected or a higher level grid domain but not in reverse (Customer connection → All, Distribution connection → Transmission, Transmission connection → Transmission only).
 - However resources at all connections points may access the Wholesale market or provide Resource Adequacy provided they are they not limited by their physical location.
- Reliability Priority/Exclusivity
 - For any bid capacity, priority must be given to reliability services over non-reliability services.

- The same capacity cannot be committed at the same time for multiple reliability services and provision of one reliability service cannot interfere with technical requirements of providing another. The exclusivity principle therefore assumes provision of multiple reliability services are both time and capacity differentiated by definition.
- Transparency
 - Penalties for non-compliance of service provision are clearly communicated in the service definition.
 - Resources must declare any other services they are providing apart from the current solicitation.
 - Any MUA must be able to be clearly distinguished and measured

These guidelines have significant implications for V2X and BESS economics and constitute positive advancement toward realizing their full potential while upholding the Principle of Network Access which is a fundamental tenet in most liberalized markets.

4.3.5 Product Symmetry

Product Symmetry relates to Ancillary Service markets and the procurement of frequency regulation/reserves and reserve margins. Two types of regulation/reserve products exist: upward products – increase of generation or reduction of consumption (i.e. provision of positive reserve) – or downward products – reduction of generation or augmentation of consumption (i.e. provision of negative reserve).

Upward and downward regulation/reserves constitute distinct operations and there is more inherent value in resources which can provide upward regulation/reserves however not all markets differentiate these products. Most markets that do differentiate allow for separate bids for upward and downward provision; while markets that do not only allow for symmetrical bids, meaning the provider must deliver the same amount of downward and upward reserve.

Product symmetry limits new market entrants as explored in (Thompson, 2016) which showed that wind energy can economically provide downward reserves through curtailment but not upward reserves due to imperfect forecasting and efficiency losses of sub-maximal production. Similarly, V1G can provide downward reserves with faster reaction times than most other traditional sources; however an obligatory symmetrical offer of upward reserves would preclude it from the market. V2G would likely be limited as well and would have to offer the minimum of available upward reserve or downward reserve throughout the day.

4.4 Module C: Rules Defining Remuneration

4.4.1 Nature of Payment (Regulated vs Market Solution and Mandatory vs Voluntary Service Offer)

Different remuneration schemes exist such as regulated tariffs or market solutions (pay-as-bid and uniform pricing) which are applied to energy service provision that can be on a mandatory or voluntary offer basis. The use of a regulated tariff is typically associated with mandatory service provision and is applied to specific market participants (often large producers). Even if rules allow service provision from new-entrant Aggregators, selection is made by an administrative rule and does not allow Aggregators to compete effectively with incumbent actors. This ultimately leads to market inefficiencies and exercise of market power as energy services are not procured based on their costs.

For market solutions, uniform pricing incentivizes actors to bid at the marginal cost of service which gives efficient pricing signals for the short and long term. Whereas pay-as-bid schemes incentivize actors to bid as high as possible below the expected clearing bid price, which can lead to clearing price elevation and erosion of customer benefits (The Brattle Group, 2017). Voluntary service offers allow Aggregators to bid based on temporal efficiency depending on fleet size and behavior. Therefore, market solutions with uniform pricing bid schemes and voluntary service offers result in more fair and competitive remuneration.

4.4.2 Performance Bonus

If a resource offers additional flexibility, a faster response time, or is available a higher percentage of the year, this constitutes added value and should be remunerated as such. However as market rules and service definitions have been based on the technical limits of large-scale thermal generation, many wholesale markets have not defined performance bonuses to reflect the value of faster-acting resources. Clearly defined performance metrics and methods for remuneration of resources which meet or exceed them are a fundamental component of Performance Based Regulation (PBR) which has proven to result in greater market efficiencies while unlocking the full potential of new energy technologies.

5 Conclusions and Policy Implications

5.1 V2X Topology

All V2X topologies are developing in tandem with and in spite of the others at varying speeds. Technological maturity and lack of competition remain problems predominately in the enabling hardware and V2X as a whole is still regarded as a nascent technology recently making steps from research labs and demonstration projects into the commercial realm. However V2X exhibits significantly reduced capital costs compared to BESS and bi-directional enabling costs have decreased by 90% since 2014 and will likely continue to decline as V2X develops. The lines between each topology can be

blurred and confused yet can be easily identified by focusing on the aggregation, connection, or control point and by defining where the operational benefit is derived (see [*Figure 1: V2X Topology Explained*](#)).

We present the example of a fleet of 100 EVs providing active and reactive power while dynamically responding to grid characteristics but doing so through a building's central energy control hub with the goals of minimizing site inductive loads (Power Factor Correction) and flattening the electricity demand profile. This case would represent a V2B topology despite interaction with the grid as the control/connection point is through the building with operation intended to benefit the building or site. This same fleet can alter active and reactive power output in response to grid conditions which are translated into control signals from an Aggregator. The Aggregator dispatches this fleet with the operational goals of providing Voltage Regulation (VR) to maintain node voltage levels on the distribution grid and to reduce peak loading in specific areas. This second situation constitutes a V2G topology as the fleet operation is for the benefit the grid.

5.2 V2X Value Stream Framework

We present the V2X Value Stream Framework as a means to categorize the full range of energy services that V2X can provide, designate which topology can provide each service, and identify where value is derived within the Energy Industry (see [*Table 1: V2X Energy Service Value Streams*](#)). The meta-analysis of V2X Value Stream potential in Figure 2 and Figure 3 shows results that are contradictory to most previous work in that the under-investigated value streams of Bill Management, Resource Adequacy, and Network Deferral have more economic potential compared to the frequently studied Energy Arbitrage and Spinning Reserves. V2G provision of DSO services are underrepresented globally which seems to stem from lack of DSO service maturity (regulatory policy) rather than limitations of V2G technical ability (EVConsult, 2018).

Economic viability of V2X must be analyzed and applied only to the market context in which analysis is conducted as results are non-transferrable due to geographic particularities. The differentiation between Energy and Power Based services is important and V2X economic valuations should be based on stacked Value Streams. Hence any universal condemnation or confirmation of V2X viability based on one Value Stream in one market alone is myopic as the same service or collection of services can be profitable in different markets with more favorable characteristics. With the addition of Frequency Regulation, overall the Power Based Value Streams tend to exhibit the highest economic potential across markets which highlights a clear opportunity for V2X deployment. We present this meta-analysis as an indication of where the potential future of V2X lies.

Another key insight is that most use cases for BESS in the Residential Sector, Microgrids, and additionally some Commercial Sectors, have been deemed to be economically unviable due to prohibitively high capital costs. This may indicate another large opportunity for V2X in these niche markets providing Bill Management, Demand Response, and Reactive Power Support services. Other benefits that V2X affords such as increased Renewable Energy Resource (RES) integration and firming, reduced greenhouse gas

emissions, and decreased RES curtailment due to better energy management have significant demonstrable societal value however monetization is largely an artifact of energy policy and regulation.

5.3 V2X Regulatory Issues

While we agree with (Kester et al., 2018) in that V2X technology is a product largely of and by the market, we modify this stance to emphasize that V2X is a product of the market which will develop within the constraints of the environment set by regulators. If regulators do not take positive actions in changing rules we predict that industry development of V2X will only be directed toward use-cases where minimum investment and complication is needed. Indications of this limited development which reflects the current market environment are seen in (EVConsult, 2018) which affirms that Smart Charging (V1G) is sufficient for many energy services and that V2G offers value in specific scenarios where location matters, in areas with surplus solar capacity, in markets with high peak pricing or demand charges, and allows for longer duration of service provision over V1G.

Insufficient regulatory action however will limit the full range of environmental and economic benefits from an electrified Transportation Sector. Transport electrification and integration with the Energy Sector must therefore be implicit goals which can be realized through regulatory policy. We presented a discussion of how regulatory policy can better incorporate V2X which results in three overarching objectives: First, to remove administrative barriers to aggregation of energy resources; Second, to design rules which allow for A.) greater and more efficient Aggregator access to energy markets and B.) through developing technology-agnostic energy service definitions; and Third, to design equitable remuneration schemes which give incentives to actors to reveal their costs while ensuring they are compensated for the full value of service they provide. These policy proposals not only benefit V2X but also Battery Energy Stationary Storage (BESS) and other Distributed Energy Resources (DERs). In conclusion V2X is an innovative development within the energy industry and its effectiveness as one of the suite of solutions to our most pressing energy problems in the 21st Century is not only market driven but driven by regulatory policy.

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Bibliography

- AEMO, 2018. Quarterly Energy Dynamics - Q4 2018, Australian Energy Market Operator.
- Andersen, A.N., Erge, T., Sauer, C., Siewierski, T., Romanovsky, G., Mutale, J., Watts, M., 2010. Market Access for Smaller Size Intelligent Electricity Generation (MASSIG) - Critical survey of requirements for market participation of small scale intelligent generators.
- Bishop, J.D.K., Axon, C.J., Bonilla, D., Tran, M., Banister, D., McCulloch, M.D., 2013. Evaluating the impact of V2G services on the degradation of batteries in PHEV and EV. *Appl. Energy* 111, 206–218. doi:10.1016/j.apenergy.2013.04.094
- Black, D., 2014. U . S . Department of Defense Vehicle-to-Grid Demonstrations in California.
- Borne, O., Korte, K., Perez, Y., Petit, M., Purkus, A., 2018a. Barriers to entry in frequency-regulation services markets: Review of the status quo and options for improvements. *Renew. Sustain. Energy Rev.* 81, 605–614. doi:10.1016/j.rser.2017.08.052
- Borne, O., Perez, Y., Petit, M., 2018b. Market integration or bids granularity to enhance flexibility provision by batteries of electric vehicles. *Energy Policy* 119, 140–148. doi:10.1016/j.enpol.2018.04.019
- Campbell, A.M., 2014. Assessing the economic viability of electric vehicle-to-grid services through infrastructure and market participation investments. Humboldt State University.
- Cano, Z.P., Banham, D., Ye, S., Hintennach, A., Lu, J., Fowler, M., Chen, Z., 2018. Batteries and fuel cells for emerging electric vehicle markets. *Nat. Energy* 3, 279–289. doi:10.1038/s41560-018-0108-1
- Codani, P., Perez, Y., Petit, M., 2016. Financial shortfall for electric vehicles: Economic impacts of Transmission System Operators market designs. *Energy* 113, 422–431. doi:10.1016/j.energy.2016.07.070
- CPUC, 2017. Decision on Multiple-Use Application Issues.
- Ding, Y., Cano, Z.P., Yu, A., Lu, J., Chen, Z., 2019. Automotive Li-Ion Batteries: Current Status and Future Perspectives. *Electrochem. Energy Rev.* 2, 1–28. doi:10.1007/s41918-018-0022-z
- Eid, C., Codani, P., Perez, Y., Reneses, J., Hakvoort, R., 2016. Managing electric flexibility from Distributed Energy Resources: A review of incentives for market design. *Renew. Sustain. Energy Rev.* 64, 237–247. doi:10.1016/j.rser.2016.06.008
- Electric Vehicles Initiative, 2019. EV30@30 Campaign. Vancouver, Canada.
- Electricity North West, 2018. Value of Lost Load to Customers Customer Survey (Phase 3) Key Findings Report.
- Enerdata, 2016. World Energy Council - Energy Efficiency Indicators [WWW Document]. *Aver. Electr. Consum. per electrified Househ.* URL <https://wec-indicators.enerdata.net/household-electricity-use.html> (accessed 6.18.19).
- European Commission, 2017. Proposal for a Regulation of the European Parliament and of the Council on the Internal Market for Electricity. Brussels.

- Eurostat, 2019. Electricity Price Statistics [WWW Document]. URL https://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_price_statistics (accessed 6.19.19).
- EVConsult, 2018. V2G Global Roadtrip: around the world in 50 projects.
- Falvo, M.C., Sbordonè, D., Bayram, I.S., Devetsikiotis, M., 2014. EV charging stations and modes: International standards. 2014 Int. Symp. Power Electron. Electr. Drives, Autom. Motion, SPEEDAM 2014 1134–1139. doi:10.1109/SPEEDAM.2014.6872107
- Gannon, J., Chow, L., Brant, S., Brooks, D., 2015. CPUC: The 2013 – 2014 Resource Adequacy Report.
- Ghaderi, A., Nassiraei, A.A.F., 2015. The Economics of Using Electric Vehicles for Vehicle to Building Applications Considering the Effect of Battery Degradation, in: IECON 2015 - 41st Annual Conference of the IEEE Industrial Electronics Society. IEEE, pp. 3567–3572. doi:10.1109/IECON.2015.7392654
- Glachant, J.-M., Perez, Y., 2009. The Achievement of Electricity Competitive Reforms: A Governance Structure Problem?, in: Regulation, Deregulation, Reregulation: Institutional Perspectives. p. 20. doi:<https://doi.org/10.4337/9781848449282.00019>
- International Energy Agency, 2018. Global EV Outlook 2018.
- IRENA, 2015. Case studies: Battery storage. Int. Renew. Energy Agency.
- Kempton, W., Tomić, J., 2005. Vehicle-to-grid power fundamentals: Calculating capacity and net revenue. J. Power Sources 144, 268–279. doi:10.1016/j.jpowsour.2004.12.025
- Kempton, W., Udo, V., Huber, K., Komara, K., Letendre, S., Baker, S., Brunner, D., Pearre, N., 2009. A Test of Vehicle-to-Grid (V2G) for Energy Storage and Frequency Regulation in the PJM System, University of Delaware. Newark, Delaware.
- Kester, J., Noel, L., Zarazua de Rubens, G., Sovacool, B.K., 2018. Promoting Vehicle to Grid (V2G) in the Nordic region: Expert advice on policy mechanisms for accelerated diffusion. Energy Policy 116, 422–432. doi:10.1016/j.enpol.2018.02.024
- King, C., Datta, B., 2018. EV charging tariffs that work for EV owners, utilities and society. Electr. J. 31, 24–27. doi:10.1016/j.tej.2018.10.010
- Knezovic, K., Marinelli, M., Moller, R.J., Andersen, P.B., Traholt, C., Sossan, F., 2014. Analysis of voltage support by electric vehicles and photovoltaic in a real Danish low voltage network. Proc. Univ. Power Eng. Conf. doi:10.1109/UPEC.2014.6934759
- Koh, S.L., Lim, Y.S., 2016. Methodology for assessing viability of energy storage system for buildings. Energy 101, 519–531. doi:10.1016/J.ENERGY.2016.02.047
- Lazard, 2018. Lazard’s Levelized Cost of Storage Analysis — Version 4.0.
- Lazard, 2017. Lazard’s Levelized Cost of Storage Analysis — Version 3.0. doi:10.1017/CBO9781107415324.004
- Lazard, 2015. Lazard’s Levelized Cost of Storage Analysis - Version 1.0.

doi:10.1017/CBO9781107415324.004

Lee, T., 2017. Energy Storage in PJM: Exploring Frequency Regulation Market Transformation.

Mullan, J., Harries, D., Br, T., Whitely, S., 2012. The technical , economic and commercial viability of the vehicle-to-grid concept 48, 394–406. doi:10.1016/j.enpol.2012.05.042

Nelder, C., Newcomb, J., Fitzgerald, G., 2016. Electric Vehicles As Distributed Energy Resources.

Neuhoff, K., Ritter, N., Schwenen, S., 2015. Bidding Structures and Trading Arrangements for Flexibility across EU Power Markets.

Nissan Motor Corporation, 2018. Nissan to create electric vehicle ‘ecosystem’ [WWW Document]. Press Release. URL <https://newsroom.nissan-global.com/releases/nissan-to-create-electric-vehicle-ecosystem?lang=en-US> (accessed 6.20.19).

Noel, L., Zarazua de Rubens, G., Kester, J., Sovacool, B.K., 2019. Vehicle-to-Grid: A Sociotechnical Transition Beyond Electric Mobility. Springer.

NREL, 2013. Renewable Energy in Alaska. doi:10.2172/1072803

OMIE, 2018. Day-Ahead and Intraday Electricity Market Operating Rules: Non-binding Translation of Market Operating Rules.

Parkinson, G., 2018. Renew Economy [WWW Document]. URL <https://reneweconomy.com.au/tesla-big-battery-turns-one-celebrates-50-million-in-grid-savings-95920/> (accessed 6.28.19).

Pearre, N.S., 2019. Review of research on V2X technologies , strategies , and operations. Renew. Sustain. Energy Rev. 105, 61–70. doi:10.1016/j.rser.2019.01.047

Robledo, C.B., Oldenbroek, V., Abbruzzese, F., Wijk, A.J.M. Van, 2018. Integrating a hydrogen fuel cell electric vehicle with vehicle-to-grid technology , photovoltaic power and a residential building. Appl. Energy 215, 615–629. doi:10.1016/j.apenergy.2018.02.038

Rocky Mountain Institute, 2015. The Economics of Battery Energy Storage: Technical Appendix A : Detailed Overview of Services.

Sandia National Labs, 2015. DOE/EPRI Electricity Storage Handbook in Collaboration with NRECA.

Schittekatte, T., Momber, I., Meeus, L., 2018. Future-proof tariff design: Recovering sunk grid costs in a world where consumers are pushing back. Energy Econ. 70, 484–498. doi:10.1016/j.eneco.2018.01.028

Schröder, T., Kuckshinrichs, W., Schröder, T., 2015. Value of Lost Load: An Efficient Economic Indicator for Power Supply Security? A Literature Review. Front. Energy Res. 3, 1–12. doi:10.3389/fenrg.2015.00055

Tan, K.M., Padmanaban, S., Yong, J.Y., Ramachandaramurthy, V.K., 2019. A multi-control vehicle-to-grid charger with bi-directional active and reactive power capabilities for power grid support. Energy 171, 1150–1163. doi:10.1016/j.energy.2019.01.053

Tesla Inc., 2019. Tesla Powerwall [WWW Document]. URL

<https://www.tesla.com/powerwall?redirect=no> (accessed 6.20.19).

- The Brattle Group, 2017. Uniform Price vs Differentiated Payment Auctions: A Discussion of Advantages and Disadvantages.
- Thingvad, A., Martinenas, S., Andersen, P.B., Marinelli, M., Olesen, O.J., Christensen, B.E., 2017. Economic comparison of electric vehicles performing unidirectional and bidirectional frequency control in Denmark with practical validation. Proc. - 2016 51st Int. Univ. Power Eng. Conf. UPEC 2016 2017-Janua, 1–6. doi:10.1109/UPEC.2016.8113988
- Thompson, A.W., 2018. Economic implications of lithium ion battery degradation for Vehicle-to- Grid (V2X) services. J. Power Sources 396, 691–709. doi:10.1016/j.jpowsour.2018.06.053
- Thompson, A.W., 2016. Economic Feasibility of Wind Energy Participation in Secondary Reserves Markets, in: Proceedings of the 1st Italian Association of Energy Economics (AIEE) Energy Symposium. Milan. doi:<http://www.aieeconference2016milano.eu/pages/programme.html>
- Uddin, K., Dubarry, M., Glick, M.B., 2018. The viability of vehicle-to-grid operations from a battery technology and policy perspective. Energy Policy 113, 342–347. doi:10.1016/j.enpol.2017.11.015
- Uddin, K., Jackson, T., Widanage, W.D., Chouchelamane, G., Jennings, P.A., Marco, J., 2017. On the possibility of extending the lifetime of lithium-ion batteries through optimal V2G facilitated by an integrated vehicle and smart-grid system. Energy 133, 710–722. doi:10.1016/j.energy.2017.04.116
- US Energy Information Administration, 2019a. Average Price of Electricity to Ultimate Customers by End-Use Sector [WWW Document]. Electr. Power Mon. URL https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a (accessed 6.19.19).
- US Energy Information Administration, 2019b. Electric Sales, Revenue, and Average Price [WWW Document]. URL https://www.eia.gov/electricity/sales_revenue_price/ (accessed 6.25.19).
- US Energy Information Administration, 2019c. Cost and Performance Characteristics of New Generating Technologies , Annual Energy Outlook 2019.
- US Energy Information Administration, 2018. U.S. Battery Storage Market Trends.
- Wang, D., Coignard, J., Zeng, T., Zhang, C., Saxena, S., 2016. Quantifying electric vehicle battery degradation from driving vs. vehicle-to-grid services. J. Power Sources 332, 193–203. doi:10.1016/j.jpowsour.2016.09.116
- Wang, X., Liu, Y., Qian, W., Wang, B., Lu, X., Zou, K., González-Santini, N., Karki, U., Peng, F.Z., Chen, C., 2018. A 25kW SiC Universal Power Converter Building Block for G2V, V2G, and V2L Applications, in: 2018 IEEE International Power Electronics and Application Conference and Exposition (PEAC). pp. 1–6. doi:10.1109/PEAC.2018.8590435
- Wu, Q., Nielsen, A.H., Ostergaard, J., Cha, S.T., Marra, F., Chen, Y., Tröholt, C., 2010. Driving Pattern Analysis for Electric Vehicle (EV) Grid Integration Study. 2010 IEEE PES Innov. Smart Grid Technol. Conf. Eur. (ISGT Eur. 1–6. doi:10.1109/ISGTEUROPE.2010.5751581

European commission needs to read (Article 2(2)(h) of the Proposal for a Regulation of the European Parliament and of the Council on the internal market for electricity (recast), 30.11.2016, COM(2016) 861 final 2016/0379 (COD)).

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