Virtual Power Plants and Energy Justice

Brittany Speetles, Eric Lockhart, and Adam Warren

National Renewable Energy Laboratory

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List of Acronyms

ALA	American Lung Association
BIPOC	Black, Indigenous, and People of Color
CEJST	Climate and Economic Justice Screening Tool
DERs	distributed energy resources
DERMS	DER management system
DOE	US Department of Energy
EJ	energy justice
EJScreen	EPA Environmental Justice Screening Tool
EV	electric vehicle
FERC	Federal Energy Regulatory Commission
FFR	fast frequency response
IBEW	International Brotherhood of Electrical Workers
IRA	Inflation Reduction Act
ISO	Independent System Operator
IT	Information technology
JISEA	Joint Institute for Strategic Energy Analysis
kW	kilowatts
kWh	kilowatt-hours
LPO	Loan Programs Office
MW	megawatts
MWh	megawatt-hours
NECA	National Electrical Contractors Association
NREL	National Renewable Energy Laboratory
PHEV	plug-in hybrid electric vehicle
PV	photovoltaics
REV	Reforming the Energy Vision
SCE	Southern California Edison
V2G	vehicle-to-grid
VPP	virtual power plant

Executive Summary

The Federal Energy Regulatory Commission's (FERC) Order 2222, issued in September 2020, allows aggregated distributed energy resources (DERs) to participate in wholesale energy markets as a single entity, often referred to as a virtual power plant (VPP). VPPs control dispatchable, aggregated DERs (including flexible, responsive loads), contribute to multiple electricity market types, and provide various grid services [1]. VPPs are not limited to any specific DER technologies; the scope of VPP projects can vary based on geography, specific program drivers, and other program eligibility requirements. Common technologies in VPP projects include household devices, electric vehicles, solar generation, storage, and hot water heaters.

The ability to flexibly control and aggregate DERs through scaling VPP deployment could avoid significant grid infrastructure investments, earn revenue by delivering grid services, lower peak demand, accelerate the adoption of renewable energy, reduce electricity bills, and provide local resilience at a lower cost to customers. If developed and operated with environmental and energy justice in mind, VPPs also have the potential to reduce greenhouse gas emissions, improve indoor and outdoor air quality, support workforce and economic development, and address challenges faced by underserved communities[1], such as energy burden [2], [3], [4].

The topic of VPPs has become more relevant because DER adoption is experiencing rapid growth in the US, and peak electricity demand is also on the rise [2]. This paper explores the potential for VPPs to provide energy system and societal benefits through an energy justice (EJ) lens. Energy justice refers to the goal of achieving equitable outcomes both socially and economically in the energy system transition, while also remediating social, economic, and health burdens on those historically harmed by the energy system [5]. VPPs have the potential to support underserved communities in achieving just transition goals and outcomes, but cost-related, socioeconomic, and historical barriers can make VPP adoption challenging in underserved community contexts. These challenges are addressed throughout the paper, and we include a representation of their hierarchal relevance to the four tenets of energy justice in Table 2.

The key questions guiding our research include: What are VPP use cases, value streams, and business models? How is energy justice related to VPPs, and how can VPPs be designed for underserved community participation and benefit? What program incentives and other strategies can improve opportunities for underserved communities to access and benefit from VPPs?

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[1] Throughout the paper, we use the term "underserved communities" to refer to communities that have limited access to resources and opportunities. This disproportionately refers to communities with high Black, Indigenous, and People of Color (BIPOC) populations, low-income populations, populations that face persistent levels of poverty, and other vulnerable, historically disenfranchised, or persistently marginalized groups. In our literature review, we use the terms "low-income" and "disadvantaged" where they are appropriate to describe a particular study's methods.

The discussions in this paper focus on four tenets of energy justice: procedural justice, distributive justice, recognitional justice, and restorative justice.

- *Procedural justice* refers to participation in fair, transparent decision-making processes.
- *Distributive justice* refers to equitable allocation of outcomes related to energy investments.
- *Recognitional justice* refers to taking a community's needs into consideration and including vulnerable, remote, or underserved communities in energy transition programs.
- *Restorative justice* refers to remediation and community development efforts.

These four tenets overlap and their relevance or importance to VPPs varies with which use cases are prioritized, which DERs are included, and other business decisions, such as how a VPP is financed. Table 1 in this paper offers a mapping of energy justice tenets to various VPP use cases [6]. Using the four tenets of energy justice to frame our discussions, we:

- Provide background information on the current VPP landscape, and historical context of its evolution within a transactive energy system,
- Provide a review of the current VPP marketplace, value chain, and relationships with the broader renewable energy economy and energy justice (see Figure 1),
- Evaluate VPP use cases in terms of energy system and social benefits such as grid services provision, economic development, and public health,
- Discuss barriers to adoption in terms of costs, socioeconomic barriers, and historical barriers, and discuss how these barriers might be overcome in underserved communities,
- Analyze and catalog the potential for VPPs to advance and align EJ and economic goals, and
- Provide background information on how proposed and existing VPP programs and projects relate to use cases and VPP adoption in underserved communities, context on how programs that prioritize EJ goals have been designed, and opportunities on how future program design could be improved to be more supportive of EJ goals.

In the Introduction section of this paper, we briefly discuss the scope, methodology, and limitations of the paper, and differentiate VPPs from six closely related concepts: (1) distributed energy resource management systems, (2) distributed energy resources, (3) non-wires alternatives, (4) demand response, (5) microgrids, and (6) local electricity exchange.

In the Background section, we provide an overview of various VPP operator structures/models and discuss policy incentives and impacts from the Inflation Reduction Act of 2022 (IRA) that have laid the foundation for VPP market growth, including electrification rebates and others. We mention impacts of the 2020 Justice40 Executive Order which requires that 40% of federal climate investments go towards underserved communities. And we briefly cover two FERC regulations passed in 2018 and 2020 that allow VPPs to compete with conventional resources in wholesale electricity markets, which has concentrated the creation of VPP programs and incentives in states with wholesale electricity markets.

Sections 3 and 4 analyze VPP use cases through an EJ lens and adoption in underserved communities. To formulate these analyses, we conducted a literature review on the relationship between emerging technologies and engagement in underserved communities, discussed in Section 2.3. We then listed and described common challenges in underserved communities and noted underlying causes for each challenge. To clearly illustrate how introduction of a VPP could impact a community contending with these challenges, we predicted and described impacts and cited examples. We note that this approach could be used to apply an EJ lens in analyzing other emerging technologies within and beyond the literature review.

To understand how VPPs create value, we reviewed industry reports and analyzed over 40 current and past VPP projects and pilot programs, focusing on examples in the US. Several industry reports were particularly relevant in guiding our understanding of the current VPP space as captured in Section 2 of this paper [1], [2], [3], [4], [6], [7]. Additional literature and examples inform the discussion of use cases and barriers to VPP adoption in Sections 3 and 4. Our paper concludes with a discussion of potential avenues to continue exploration of this topic.

The key findings of this paper include:

- **Benefits of VPPs:** VPPs can provide grid services (reducing capital requirements, supporting resource adequacy, frequency response, peak shaving, voltage regulation and increasing system resiliency), support economic development (providing local resiliency, reducing electricity bills and supporting workforce and economic development), and improve public health (reducing greenhouse gas emissions and reducing indoor/outdoor air and noise pollution). For most of these use cases, there are examples of instances where people have quantified this benefit and markets in turn have monetized that benefit. For those use cases that are not monetizable, externalities such public health costs and the social cost of carbon create cost savings that could be monetized in the future.

- **Barriers to VPP Adoption in Underserved Communities:** Underserved communities face common barriers to VPP adoption. We discuss cost-based barriers (lack of capital, loan challenges, lack of affordable home ownership, need for additional upgrades), socioeconomic barriers (energy limiting behavior, lack of flexibility capital), and historical barriers (community mistrust, knowledge barriers, exposure to the fossil fuel economy and poor indoor/outdoor air quality, natural disaster vulnerability, and disproportionate power outage impacts). Cost-based barriers can be addressed through alternative financing methods. Socioeconomic and historical barriers have fewer examples of being overcome in practice so far.

- **Energy Justice and Clean Energy Goals:** Programs that seek to advance clean energy and EJ goals must have a program design based in EJ goals [8], [9], [10], [11]. There are limited examples of VPPs that were designed with an intentional focus on underserved community participation and benefits. We predict that VPPs that are specifically geared toward underserved communities can differ from general-purpose VPP projects because of at least two factors: funding avenues and project drivers. Funding avenues for projects targeting underserved communities could include additional subsidy programs such as loans, grants, bonds, leasing of devices, and on-bill financing. Additionally, while the primary driver of VPP projects overall is to provide grid services, the drivers for VPP project development in underserved communities may also include factors that mitigate historical harms, such as reducing indoor and outdoor air pollution.

This paper provides background information on how proposed and existing VPP programs and projects relate to use cases and VPP adoption in underserved communities, provides context on how programs that prioritize EJ goals have been designed, and suggests how future program design could be improved to be more supportive of EJ goals (by, for example, including community engagement early on in the project development process) [12]. VPPs can achieve grid services, economic benefits, and public health benefits. Ensuring that the tenets of justice are considered early on during VPP development is important for realizing benefits for underserved communities.

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1 Introduction

Factors such as the sustained drop in the price of renewables and energy storage, changes in energy demand patterns, aging infrastructure, the rapid increase in commercial and residential DER uptake, and the desire to reduce greenhouse gas emissions are driving a transformation of the power system [2], [13]. This transformation is creating the opportunity to consider factors such as energy justice in design and planning processes alongside system stability and costs.

The US bulk-scale electricity grid largely operates by sending electricity from large generators to substations, through transmission lines, and eventually through a transformer to step-down voltage so that electricity can be delivered when and where it is needed.[2] However, interest in the grid edge is growing through applications such as smart inverters, smart meters, demand response methods, and other technologies that are able to actively manage load and/or sell electricity generated behind the meter back to the grid (such as at times of high peak demand).

In recent years, interest in a transactive energy system, which refers to "a system of economic and control mechanisms that allows the dynamic balance of supply and demand across the entire electrical infrastructure, using value as a key operational parameter," has increased [14]. Such a system allows for the conversion from electricity end-use consumers to "prosumers", those both producing and consuming electricity, through bidirectional electricity flow that supports the electricity grid [15].

One way a transactive energy system is coming to fruition is through virtual power plants (VPPs). Definitions of VPPs have changed over time, and the absence of a standardized definition for VPPs has historically limited categorization that enables the analysis of VPPs [16]. Before 2010, definitions of VPPs were associated with terms such as transmission system operators, distribution system operators, microgrids, combined heat and power plants, and power markets; after 2015, they were more commonly associated with terms such as cloud computing, smart cities, water-energy management, internet of energy, smart make decisions, artificial intelligence, and vehicle-to-grid charging [16]. We define VPPs as ***aggregated, dispatchable groups of DERs (including flexible, responsive loads) that are overseen by a centralized controller to participate in multiple electricity market types and provide various grid services*** [1].

We do not limit this discussion of VPPs to any specific DER technologies or economic sectors. The technologies in VPP projects can vary based on geography, specific program drivers, and other program eligibility requirements. Common technologies in VPP projects include household devices, electric vehicles, solar generation, storage, and hot water heaters. More than 150 existing VPPs in North America use battery storage technologies, and almost 200 VPPs employ low-entry cost smart thermostats [7]. Although smart vehicle charging is a part of many current

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[2] "Electricity explained: How electricity is delivered to consumers," US EIA, 2022, https://www.eia.gov/energyexplained/electricity/delivery-to-consumers.php

VPP projects, vehicle-to-grid integration could present a nascent and high-potential market that has not yet participated in the VPP industry outside of pilot programs [7].

A VPP is distinct from six closely related concepts, which are:

- **Distributed Energy Resource Management System (DERMS):** A DERMS refers to hardware and software that can aggregate, monitor, control and forecast/predict DER sources [1]. A core component of a VPP is a DERMS, but a VPP involves more capabilities, such as market participation, that are not included in the DERMS definition [1]. Use cases and stakeholder involvement also differ slightly between the two concepts; while VPPs are used by aggregators, utilities, and other stakeholders to satisfy multiple grid services, DERMS are often managed by distribution network system operators, and are usually used to support and expand DER integration.

- **Distributed Energy Resource (DERs):** DERs refer to small responsive load, generation or storage assets that are often connected to the lower-voltage distribution grid or behind-the-meter [17]. Responsive load (or demand flexibility) DERs include flexible, controllable resources such as smart thermostats and smart water heaters [2]. Generation DERs include rooftop solar PV systems or residential or commercial diesel backup power generators. Storage DERs include home storage systems and EV batteries. Even though VPPs are made up of a group of DERs, the two are distinct from one another from an operational perspective. First, a VPP uses a DERMS to control DERs collectively. FERC Order 2222 allows VPPs to participate in wholesale markets, whereas DERs are usually not able to do so, which limits the grid services that they can provide to retail only. The ability to be compensated for grid services, which provide distributional justice benefits by improving electricity grid stability, reducing costs, and avoiding traditional infrastructure upgrades, is a key area that separates VPPs and DERMS from individual DERs from a grid operator's perspective (grid services are discussed in more detail in Section 3.1) [18].

- **Non-Wires Alternatives:** Non-wires alternatives refer to investments in the electric system that are specifically meant to avoid the need for additional transmission or distribution investments or upgrades.[3] Thus, although a VPP can act as a *type* of non-wires alternative, the two terms are not interchangeable because non-wires alternatives can also refer to energy efficiency standards, microgrids, combined heat and power, or demand response, among other things. Moreover, ensuring that VPPs can operate successfully and provide increased stability to the grid might also require significant grid investment to allow backflow into the grid. This is discussed in more detail in Section 3.1.1.

- **Demand Response:** Demand response refers to a form of increased customer interaction with the electric system through a shift in electricity use during peak demand periods. Often, these behavioral changes are incentivized through time-of-use rates or other financial

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[3] "What is an NWA?" National Grid, https://www.nationalgridus.com/Business-Partners/Non-Wires-Alternatives/What-is-an-NWA.

returns.[4] VPPs are related to demand response because many existing programs are specifically meant to defer power during peak demand. VPPs can act as a form of demand response and leverage demand response program designs. For example, VPP projects that include solar and energy storage will often have customers sign a contract with a third party or utility allowing them to dispatch their battery to the grid during certain hours of certain days of the year (the days when peak demand events are most likely to occur), and customers are compensated for this. This is slightly different than what is traditionally thought of as demand response, which incentivizes customers to manually change their behaviors and move demand around through strategies such as time-of-use pricing or critical peak pricing but does not usually require dispatchable devices that can be called on by a utility or market interface in real time. From a software perspective, a demand response program does not require customer-side devices to be aggregated via a DERMS, whereas this is a key characteristic of a VPP. VPPs can also interact with market interfaces and generally provide a broad scope of grid stability benefits beyond peak shaving that may not be encompassed in the definition of demand response.

- **Microgrids:** A microgrid refers to an interconnected group of DERs and loads that can act as a single entity and interact with the electricity grid or form a separate grid in "islanded mode".[5] Microgrids are self-contained systems, often include a storage component, and are commonly deployed in settings where resilience is a priority (such as at a facility that requires reliable power in the event of a grid outage). They are interconnected in one central place and are predominantly focused on satisfying the supply needs of end-users, as opposed to being dispersed geographically selling electricity in a wholesale market (as is often the case with VPPs). VPPs are not typically designed to be islandable and do not prioritize providing resilience benefits to participating end users.

- **Local Electricity Exchange:** The term "local electricity exchange" is commonly used to describe a microgrid and refers to a scenario wherein people both generate and consume their own electricity and can sell excess energy to the grid or to other local individuals [19]. Unlike a VPP, which focuses on centralized control and optimization of DERs, a local electricity exchange refers to a decentralized, community-based system of bidirectional electricity exchange. One example of local electricity exchange is a blockchain peer to peer network for electricity trading [19].

Emerging research focuses on how underserved communities are impacted by the introduction of new technologies such as VPPs. At the federal level in the United States, there is increased

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[4] "Demand Response," DOE, https://www.energy.gov/oe/demand-response.
[5] "Microgrids," National Renewable Energy Laboratory, https://www.nrel.gov/grid/microgrids.html.

support for EJ initiatives, with the federal Justice40 Initiative requiring 40% of energy transition investments to directly benefit “marginalized, underserved, and overburdened” communities.[6,7]

In this paper, we use a literature review of industry reports, energy justice, and examples of over 40 current and past VPP projects (focused on the US) to provide background information on VPPs, discuss the VPP business model space, evaluate use cases of VPPs, and evaluate adoption in underserved communities. This paper is limited in that it does not look at the accessibility of VPPs for specific income groups, nor does it analyze the accessibility of adopting specific DER technologies in underserved communities. We investigate the following key questions:

- What are VPP use cases, value streams, and business models?
- How is energy justice related to VPPs, and how can VPPs be designed for underserved community participation and benefit?
- What program incentives and other strategies can improve opportunities for underserved communities to access and benefit from VPPs?

The remainder of the paper is organized as follows. Section 2 of the paper outlines background related to policy, the interconnectedness of EJ and clean energy, and the stages of VPP project development. Section 3 outlines proven use cases of VPPs and discusses how they are related to energy justice, and Section 4 discusses VPP adoption in underserved communities. Finally, Section 5 concludes this paper and outlines future research avenues.

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[6] Energy justice is defined as “the goal of achieving equity in both the social and economic participation in the energy system, while also remediating social, economic, and health burdens on those disproportionately harmed by the energy system.” This definition comes from the Initiative for Energy Justice, and the US Department of Energy has also adopted this language in its Justice40 initiative. (“What Is Energy Justice?” Initiative for Energy Justice, accessed 2019, https://iejusa.org/).

[7] “Justice40: A Whole-of-Government Initiative,” The White House, https://www.whitehouse.gov/environmentaljustice/justice40/.

2 Background

2.1 Current VPP Landscape

VPP operators can interact (1) directly with utilities or retailers, (2) by bidding directly into a wholesale market through a market interface, or (3) by participating in a utility program that could also include bidding into a wholesale market [7]. Currently, VPP operators that interact with utilities in some fashion make up the most common VPP project types in the US. In fact, according to a Wood Mackenzie report which analyzes the VPP market in North America, 74% of current North American VPPs operate through utility programs [7].

Additionally, in the US, VPPs are concentrated in states with wholesale electricity markets, a trend facilitated by two FERC orders:

- FERC Order 841, issued in 2018, requires independent system operators and regional transmission organizations to allow storage participation in their wholesale markets, including capacity, energy, and ancillary service markets [20].
- FERC Order 2222, issued in 2020, allows aggregated DERs to participate in wholesale regional markets [20].

These orders allow behind-the-meter resources and VPPs (including those with storage) to compete with conventional resources in wholesale markets, and they motivate the creation of more programs/incentives that encourage VPP project development [20]. In areas served by vertically integrated utilities without trading options, there is less incentive to support VPP project development. In other words, allowing participation in wholesale markets motivates more VPP programs because it allows them to interact with the grid in more ways and to earn revenue by doing so.

The majority of US VPP projects are currently located in California and New York, followed by Massachusetts, North Carolina, Texas, and Indiana [7]. In these states, strong climate policies and state incentives for storage, DERs, and demand response are creating an environment that is favorable for VPP expansion.[8] There is room to strengthen state incentives' relationship to EJ and support for low-income communities for states that also intend to incentivize underserved community participation; for example, while over half of the US states had multiple types of storage incentives—inclusive of policies, studies, financial incentives, and deployment—only eight of the battery financial incentive programs included a low-income-specific measure as of 2021 [21], [22].

At the federal legislative level, the Inflation Reduction Act of 2022 (IRA) greatly increased federal climate and energy investments and allocated $370 billion to a variety of energy and climate initiatives, a portion of which could help to support VPP growth.

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[8] Battery storage increases the grid service value of VPPs by expanding the applications that VPPs can help achieve, but batteries are not usually installed absent state incentives (rebates, mandates or both) [7].

The Inflation Reduction Act also increased funding coverage for the Justice40 Initiative, which emerged from an executive order signed in January 2021 and requires 40% of federal climate investments to benefit underserved communities.[9,10] Separately, the IRA includes a measure for solar and wind projects sited in low-income communities. Specifically, projects can receive a 10% bonus credit if they are less than 5 MW and located in either a qualified low-income area or on tribal land. And a bonus credit of up to 20% can be received for projects that are less than 5 MW which are either part of qualified low-income residential buildings or are qualified as low-income economic benefit projects.[11] Additionally, the electrification rebates built into the IRA pay for 100% (up to $14,000) of residential electrification costs for low-income households on eligible devices, such as heat pumps, hot water heaters, and electric wiring.[12] Some of these qualifying devices could potentially be enrolled into a VPP project, and upgrades such as electric wiring and weatherization could provide easier access to VPP compatibility.

The Loan Programs Office (LPO) closed a commitment in September 2023 to give Sunnova a $3.3 billion loan guarantee on an effort to expand VPP infrastructure with a focus on low-income and underserved areas.[13]

2.2 The VPP Project Value Chain

There are several embedded roles that make up what we call a VPP [3]. The components of a VPP project include (1) participant enrollment, (2) hardware attainment, (3) effective aggregation software, and (4) creating ample opportunities for operation and trading [1].

Participant enrollment is a crucial step for a VPP project, because a VPP can achieve higher grid benefits if it has more MW/GW generation capacity that can be used by the grid at key times. The most straightforward example of participant enrollment is of the individual customers who own, lease, or install a DER device to participate in the VPP. However, engaging participants in

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[9] Disadvantaged communities are defined by the Climate and Economic Justice Screening Tool as census tracts or tribes that experience burdens related to health, climate change, the environment, and other factors ("Climate and Economic Justice Screening Tool: Explore the Map," https://screeningtool.geoplatform.gov/en/).

[10] Programs are covered under the Justice40 mandate if they can provide benefits to disadvantaged communities in one or more of seven relevant initiative areas: climate change, clean energy and energy efficiency, clean transit, affordable and sustainable housing, training and workforce development, pollution remediation, and clean water and wastewater infrastructure. This coverage includes programs from a variety of federal agencies, such as the US Departments of Transportation, Agriculture, Housing and Urban Development, Energy, and others.

[11] "Low-Income Communities Bonus Credit Program," US DOE, https://www.energy.gov/diversity/low-income-communities-bonus-credit-program

[12] "The Inflation Reduction Act: Electrification Rebates (The High-Efficiency Electric Home Rebate Program)," Rewiring America, n.d., https://assets.ctfassets.net/v4qx5q5o44nj/7LiHS6hhVKaIdph8bdVV8b/aec9fc3a35985027af3f97111304db7a/factsheet_Electrification_Rebates.pdf

[13] "LPO Offers First Conditional Commitment for a Virtual Power Plant to Sunnova's Project Hestia to Support Grid Reliability and Expand Clean Energy Access," US DOE, https://www.energy.gov/lpo/articles/lpo-offers-first-conditional-commitment-virtual-power-plant-sunnovas-project-hestia

all stakeholder groups (customers, utilities, governmental entities, distribution system stakeholders, software-as-a-service companies, retailers, etc.) is necessary for a VPP's success.[14]

Next, *hardware attainment* encompasses the manufacture, financing, siting, and installation of energy equipment, including not only individual DER devices but the systems and controls equipment that integrates the DER aggregation platform.[15] In this stage, customers spend money to install devices at their homes or a centralized location to participate in the VPP, and utilities spend money to procure (or build) DERMS that aggregate and control the devices that make up the VPP. Hardware distributers and installers (i.e., Sunrun, Sunnova, Swell), make money when they sell their devices and products to other program participants. Some customers who opt into a VPP will already have the necessary DER devices installed, and their cost of entry to participate in the VPP will then be lower. On the other end of the spectrum, additional grid connectivity hardware upgrades and building upgrades for device compatibility could be required for some customers *before* they are able to install or purchase a participating DER device, which raises the cost of entry for these customers compared to those who just must install devices without upgrades.

The *software aggregation* step includes on-site optimization, operation of the DER aggregation platform, valuing DER capacity, forecasting DER availability based on real-time or day-ahead conditions, and operating the market-utility interface. The main player in this part of the value chain is the software provider, which is usually a software-as-a-service company that provides their DER aggregation software to the VPP controller (utility, independent system operator, third-party company, etc.).

Finally, *operation and trading* refer to a VPP's participation in various value pools to create revenue. This step of the value chain translates to lower energy bills and/or on-bill compensation for customers, which can have benefits related to reducing the financial burdens that are disproportionately felt by underserved populations.

These four stages of a VPP project define what we term the "VPP project value chain" [1]. Different VPP companies have different strengths and areas of growth with respect to this value chain, some of which are overlapping. Throughout this paper, we refer to the value chain as we discuss its relationship with VPP use cases and the four tenets of energy justice, and we conclude by visualizing how links between the value chain and energy justice can be strengthened.

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[14] The key players and scale of investments in the VPP space have changed significantly as the VPP space has evolved [1]. Between 2010 and 2017, over 100 separate investments in VPP companies took place. Though the number of investments stagnated after 2017, the amount of money invested in VPP companies continued to climb [1]. Also since 2017, the key stakeholders involved in VPPs have changed as at least 25 VPP companies have been acquired by larger energy incumbents, including those in the oil and gas (Shell, BP), utility (CPower, Engie), and industrial (GM, Siemens) spaces [1]. The procurement of small and specialized VPP companies by larger conglomerates has created new challenges for industry growth, and in fact, no VPP-specific company has turned a profit yet [1].

[15] Participation eligibility of DER devices in VPP projects vary, but as a reminder, we include generation-based (rooftop solar), storage-based (EV charger and battery storage), and responsive load DERs (smart thermostats, HVAC systems, hot water heaters) in our overall DER definition [2].

2.3 Clean Energy Technologies and Energy Justice

The energy justice concept of distributive justice asserts that the costs and benefits of investments in the energy transition should be equitably shared throughout society. While VPPs have the potential to improve distributive justice through community benefits such as local resiliency, improved indoor and outdoor air quality, reduced emissions, and increased feelings of energy autonomy, there are challenges to adoption in underserved communities that have impacted how DER adoption has been distributed in the US so far [23]. Lower adoption in underserved communities creates recognitional justice concerns related to the equitable inclusion of vulnerable and underserved populations, and procedural justice concerns related to the fairness of processes associated with VPP participation and bearing upgrade costs that may be needed to accommodate a DER. Barriers to DER adoption can also be rooted in historical challenges, which can be overcome by restorative energy justice measures such as targeted community development. Challenges to DER and VPP access in underserved communities are outlined in Section 4. The four tenets of energy justice are used to analyze cost-based, socioeconomic, and historical barriers and ways that these barriers can be overcome.

One example of DER distribution in the US involves rooftop PV adoption, which is skewed towards mid- to high-income households, with entry barriers such as lack of capital, lower likelihood of home ownership, and lower grid connectivity making it more difficult for low-income customers to install DERs such as solar panels.[16] The median annual household income of solar adopters in 2021 in the U.S. was $110,000 as compared to the overall U.S. median household income of $63,000 and the owner-occupied median household income of $79,000 [24]. Solar adopters in the United States are more likely to be non-Hispanic white, middle-aged, primarily English-speaking, have business or finance-related jobs, live in higher-value homes, have higher-than-average credit scores, and have higher education levels than the general US population overall [24]. The average cost of adopting rooftop solar in California is also higher for low-income customers, who may need to undergo more compliance upgrades or face additional barriers to compatibility. For example, in 2022, GRID Alternatives identified the cost of solar as $3.30/kW-DC on average but $4.28/kW-DC for low-income households.[17] This additional need for upgrades to install DERs is discussed further in Section 4.1.4.

Several studies directly explore the intersection of EJ and more advanced power systems such as VPPs via literature reviews, data analyses, and community surveys [8], [9], [10]. Other research

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[16] "Grid connectivity" refers to the connection between generation capacity and the transmission or distribution system that allows reliable access to grid-connected electricity. Low grid connectivity can occur for a variety of reasons and make the electricity grid less reliable in certain locations. One example is in rural and remote areas, where costs of infrastructure upgrades and distance from electricity lines can delay or prevent grid connectivity. In areas where grid connectivity is lower, upgrades to the grid may be required to accommodate VPPs that provide grid services. (Sources: "Grid Connection definition," Law Insider, n.d., https://www.lawinsider.com/search?q=grid+connection; "Sector Assessment (Summary) Energy," Energy Supply Improvement Investment Program, 2014, https://www.adb.org/sites/default/files/linked-documents/47282-001-ssa.pdf)

[17] "Reply Comments of Grid Alternatives, Vote Solar, and Sierra Club on the Proposed Decision Revising Net Energy Metering Tariff and Subtariffs," Rulemaking 20-08-020, California Public Utility Commission, Filed December 5, 2022, https://docs.cpuc.ca.gov/PublishedDocs/Efile/G000/M499/K625/499625409.PDF.

employs case studies to analyze impacts of individual VPPs or other smart technologies, asking what their impacts on EJ are and which levers can increase or negate these impacts [11], [22], [25], [25].

Several researchers note that solving many of the barriers to advanced energy system adoption faced by underserved communities is related to recognition of communities and benefits throughout VPP design [8], [11]. Sovacool et al. (2019) recommends tactics such as local labor requirements, public feedback avenues, and increased transparency about raw materials and waste management in projects to decrease injustices during project implementation [26]. Results from research by McGee and Greiner (2019), who questioned whether renewable energy deployment in general helps reduce inequality and found that this is not automatically the case based on an analysis of clean energy initiatives in 175 countries between 1990 and 2014, suggest that renewable growth should be considered alongside EJ initiatives that promote inequality reduction to prevent inequitable outcomes [10]. A top-down analysis of procedural and distributive justice to analyze two “successful” low-carbon community energy transitions in Germany (Feldheim) and Denmark (Samsø) by Mundaca et al. (2018) finds that social acceptance of local energy transitions is more prevalent when distributive and procedural justice factors are recognized throughout project development [11]. Research from Hanke et al. (2021) found that targeted engagement, lower membership fees for underserved groups, and collaboration between project partners can improve renewable energy community membership, and that a lack of these three indicators in project planning can create membership barriers in VPPs [9]. Research from NREL also suggests that early-stage engagement and considerations across the four tenets of justice are necessary to incorporate stakeholder needs and ensure that injustices are not “locked in” to the project development processes [12].

While emerging technologies such as VPPs have the capability to promote energy justice initiatives, they do not do so automatically; rather, potential barriers to achievement of justice goals must be actively anticipated and prevented throughout project design [8], [10], [26]. Thus, the rest of this paper focuses on (1) the use cases of VPPs and how energy justice can be realized through each benefit (Section 3), and (2) the common challenges faced in underserved communities, which create unique considerations for VPP adoption (Section 4).

3 VPP Use Cases

VPPs can result in a variety of system-wide and customer benefits, many of which can be monetized. By monetizable, we mean that there are examples of instances where the benefit has been quantified and markets in turn have monetized that benefit. Monetizable benefits of VPPs include reducing capital requirements, supporting resource adequacy, enabling frequency response, peak shaving, enabling voltage regulation, reducing electricity bills, supporting economic and workforce development, and reducing greenhouse gas emissions.

There are also some use cases that have economic benefits which are often neglected from traditional revenue streams. Use cases that are not currently monetizable include increasing system resiliency, providing local resiliency and reducing noise and indoor/outdoor air pollution. However, these use cases do have the potential to be valued through inclusive financing methods that consider factors such as reduced public health costs, costs avoided from outages and high carbon costs. Valuing these externalities can help to acknowledge the challenges faced by underserved communities, which advances recognitional justice. Many of the challenges faced in underserved communities are visualized by GIS tools such as the US Environmental Protection Agency's Environmental Justice Screening Tool (EJScreen), the California Office of Environmental Health Hazard Assessment's CalEnviroScreen, and the US White House Council for Environmental Quality's Climate and Economic Justice Screening Tool (CEJST).[18,19,20] These tools typically combine metrics such as demographics, income level, pollution burden, health, housing costs, etc., into a single "EJ" index, that can be compared between census tracts or counties in the US to measure the unique challenges faced by underserved communities, and they could be used to value location-based externalities monetarily.

Through an analysis of existing and past VPP projects, pilots, and incentive programs, we determine several use cases of VPPs and describe their relevance to EJ tenets. We introduce our discussion in Table 1 and organize use cases into those that predominately focus on (1) grid services, (2) economic benefits, and (3) public health benefits.

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[18] "EJScreen: Environmental Justice Screening and Mapping Tool," US EPA, 2023, https://www.epa.gov/ejscreen

[19] "CalEnviroScreen 4.0," OEHHA, 2023, https://oehha.ca.gov/calenviroscreen/report/calenviroscreen-40

[20] "Explore the Map," Council on Environmental Quality, 2022, https://screeningtool.geoplatform.gov/en/#3/33.47/-97.5

Table 1. Use Cases of VPPs

Use Cases	Category	Relevant Tenet of Energy Justice				Monetizable
		Recognitional	Distributive	Procedural	Restorative	
Reduce Capital Requirements	Grid service		✓			✓
Support Resource Adequacy	Grid service		✓			✓
Frequency Response	Grid service		✓			✓
Peak shaving	Grid service		✓			✓
Voltage regulation	Grid service		✓			✓
Increase system resiliency	Grid service	✓	✓		✓	
Provide local resiliency	Economic development	✓	✓			
Reduce electricity bills	Economic development		✓	✓		✓
Support workforce and economic development	Economic development	✓	✓	✓	✓	✓
Reduce Greenhouse Gas Emissions	Public health	✓	✓	✓		✓
Reduce Noise and Indoor/ Outdoor Air Pollution	Public health	✓	✓		✓	

3.1 Grid Services

A VPP can provide multiple grid services, which create monetary savings by using dynamic load control techniques to reduce electricity costs.[21] Interest in load control techniques has risen as the grid has become increasingly strained from higher demand, extreme climate events, and increasing rates of intermittent renewable energy generation.

A VPP's ability to provide grid services can create distributional justice benefits in the project's operating area by lowering system costs, increasing overall system efficiency, avoiding the need for additional fossil fuel investments, and lowering the likelihood of grid disruptions that could lead to power outages. These distributional justice benefits are realized in the "operation and

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[21] "Grid Services," Connected Communities at the US DOE, n.d., https://connectedcommunities.lbl.gov/resources/general-information/grid-services

trading" stage of the VPP project value chain and can be achieved through six use cases: reducing capital requirements, supporting resource adequacy, frequency response, peak shaving, voltage regulation, and increasing system resiliency.

3.1.1 Reduce Capital Requirements

By circumventing traditional infrastructure investments in the local grid while still ensuring that there is enough available generation, transmission, and distribution capacity to meet load requirements, VPPs can reduce capital expenditures that are necessary to maintain the electricity grid and act as non-wires alternatives. According to a 2023 Rocky Mountain Institute study, VPPs could "reduce annual power sector expenditures by $17 billion in 2030" in the United States due to avoided generation and infrastructure upgrades [3]. Further, the US Department of Energy's VPP Liftoff report estimates that implementing between 80 and 160 GW of VPP capacity by 2030 could defer $10 billion in grid costs annually [2]. These savings would result in benefits for a variety of stakeholders, potentially including electricity consumers in underserved and/or remote communities.

A nuance of this use case is that there may be instances where upgrades to outdated grid infrastructure are needed to support a VPP project. For example, VPPs could require additional investment to support VPP-related aggregation software and DER control tools, or to integrate DERMS with standardized DER aggregation platforms [27]. A 2018 National Renewable Energy Laboratory (NREL) technical report that identified lessons learned from US-based utility DER aggregation projects identified equipment-related challenges (such as DER communication gaps, inverter design, and software compatibility), in all five of its detailed case studies, and noted that the standardization of communication platforms is a key need for DER aggregation [27].

Assuming that proper communication protocols are in place to support a VPP, VPPs can act as an alternative to traditional infrastructure investments by deferring the need to build additional grid-scale capacity. One example of a VPP acting as a non-wires alternative in practice is Southern California Edison (SCE) and software provider Stem Inc.'s Distribution Energy Storage Virtual Power Plant. California, although not part of a capacity market, has resource adequacy requirements for load-serving entities such as SCE. This 85 MW project, located in Western Los Angeles, was motivated by the need to meet long-term capacity requirements in an area with limited availability.[22] The VPP supported Southern California's grid operations after the San Onofre Nuclear Power Plant closed and is expected to continue doing so as the area retires its natural gas plants. It predominately dispatches 4-hour distributed storage during peak times to provide increased flexibility.

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[22] "Non-Wires Alternatives: Case Studies from Leading US Projects," E4 The Future, November, 2018, https://e4thefuture.org/wp-content/uploads/2018/11/2018-Non-Wires-Alternatives-Report_FINAL.pdf

3.1.2 Support Resource Adequacy

Resource adequacy refers to making sure that peak demand can be reliably met by electricity system supplies.[23] VPPs can do this by acting as a form of demand-side management that supports the electricity grid during key times. One 2023 study from Brattle finds that VPPs can contribute to resource adequacy requirements at the scale of conventional resources, and they also perform at similar reliability levels [4]. Moreover, they find that a cumulative 60 GW of VPPs could satisfy resource adequacy requirements at a much lower cost, on the scale of $15-35 billion (2022$) in savings over ten years from a utility's perspective [4].

An example of a project that is expected to support resource adequacy is Swell Energy and Hawaii Electric's large solar plus storage VPP. At full capacity, the project will allocate 25 MW of solar power and 80 MW of battery capacity. The VPP is expected to support Hawaii's electric grid by providing grid services such as peak shaving, frequency response, and reducing capital requirements. The VPP will also likely defer the need for new fossil fuel infrastructure while ensuring that Hawaii's grid continues to perform reliably.[24]

The capability of VPPs to support resource adequacy has distributional justice benefits across stakeholder groups. Utilities can save money by meeting resource adequacy requirements at a lower cost, and customers can save money by using their devices to support the electricity grid at key times. The demand-side management of DER devices that helps to support resource adequacy can also translate to other benefits, such as reduced peaker plant use, improved air quality, and reduced electricity bills. In each case the distributional justice benefits depend on including those VPP program attributes in design and operation (e.g., including underserved community members in device incentives to increase adoption).

3.1.3 Frequency Response

Frequency response is a form of demand response that provides grid flexibility by managing electricity system frequency changes in a matter of seconds.[25] Maintaining a constant electrical frequency is important for balancing supply with demand and avoiding equipment damage. Fast-acting devices, such as hot water heaters or battery storage, can be collectively controlled and dispatched in seconds to help stabilize the grid as part of a VPP project. The short-timescale energy and cost savings that can be achieved through VPP-enabled frequency response can benefit underserved communities by reducing their electricity bills.

For example, a 2.5 GW VPP in the United Kingdom that is managed by flexibility operator Centrica began adding "smart" residential hot water tanks to its VPP in 2019 as a form of

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[23] "Resource Adequacy: The need for sufficient energy supplies," California ISO, 2023, https://www.caiso.com/Documents/Resource-Adequacy-Fact-Sheet.pdf

[24] OpenADR Utility Case Study: Virtual Power Plant (Swell Energy/Hawaii Electric)," OpenADR, 2021, https://www.openadr.org/assets/SWELL%20Case%20Study%201-2022.pdf

[25] "Fast Frequency Response Concepts and Bulk Power System Reliability Needs," North American Electric Reliability Cooperative, 2020, https://www.nerc.com/comm/PC/InverterBased%20Resource%20Performance%20Task%20Force%20IRPT/Fast_Frequency_Response_Concepts_and_BPS_Reliability_Needs_White_Paper.pdf

frequency response.[26] The tanks can store energy from the grid and quickly respond to grid conditions to balance frequency. Compared to traditional hot water tanks, the "smart" tanks can also learn and adapt to usage patterns, reducing heat losses, water, and energy usage by an estimated 40% per year. Over 1 MW of hot water tanks (which translates to tanks in over 1,000 homes) were added to the VPP as of 2021.[27] Hot water tanks' inclusion in this VPP also has the benefit of providing a lower capital cost option for VPP access than solar and storage DER programs.

Sunrun and PG&E's VPP in California, announced in 2023, is another example of a project that will participate with the grid by quickly smoothing daily power fluctuations and compensating customers for device use.[28] Participants, which will include up to 7,500 residential solar and battery owners, will be compensated through a flat, up-front payment of $750, as well as a smart thermostat, in exchange for agreeing to discharge their battery daily between 7:00 p.m. and 9:00 p.m. in the summer. When fully built out, this VPP will be able to dispatch 30 MW of capacity back to the grid.

3.1.4 Peak Shaving

During peak electricity demand periods, such as summer heat waves, VPPs can be programmed to dispatch devices to reduce grid strain, avoid outages, and save money. Utility peak shaving is a common project driver in North American VPPs, according to a 2023 market analysis [7]. Brehm et al. (2023) estimate that demand response measures from VPPs could help decrease US peak demand by at least 60 GW by 2030 [3]. Additionally, depending on whether an area uses time-of-use rates, electricity bill reductions from demand side management that reduces peak demand could be significant, as peak demand electricity rates under time-of-use agreements are higher than other times of the day.[29] According to the Massachusetts *State of Charge* Report, the highest 10% of annual demand hours explain roughly 40% of total system costs in Massachusetts [28].

Peak shaving can also reduce the use of "peaker power plants", which are usually powered by coal or natural gas and are disproportionately placed in low-income areas in the US, leading to poor local outdoor air quality [29].

Specific peak demand reduction examples in VPP projects include:

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[26] "Centrica to Use Hot Water Tanks for Frequency Response in VPP," Agile Energy, October 2019, https://agileenergy.net/centrica-to-use-hot-water-tanks-for-frequency-response-in-vpp/

[27] "Centrica and Mixergy hit 1 MW Milestone in Hot Water Tank VPP Rollout," Current News, October 2021, https://www.current-news.co.uk/centrica-and-mixergy-hit-1mw-milestone-in-hot-water-tank-vpp-rollout/

[28] "PG&E is testing different flavors of virtual power plant," Canary Media, February 20, 2023, https://www.canarymedia.com/articles/grid-edge/pg-e-is-testing-different-flavors-of-virtual-power-plant.

[29] "Demand Response and Time-Variable Pricing Programs," Federal Energy Management Program, n.d., https://www.energy.gov/femp/demand-response-and-time-variable-pricing-programs#:~:text=These%20often%20include%20simple%20time,in%20the%20hours%20in%20between.

- Tesla's VPP pilot in California, which provided ≈31 MW of peak power contributions in summer 2022.[30]

- Active demand response programs including ConnectedSolutions, which reduced Massachusetts' summer peak load by 0.9% in 2020. Modeling that was cited in the ConnectedSolutions report suggests that battery VPPs could reduce Massachusetts' peak by up to 5% in 2030 [21].

- Sunrun's 20 MW VPP in Independent System Operator (ISO) New England's territory, which it secured in a forward capacity auction.[31] ISO-New England's territory encompasses six states. The project, which is made up of thousands of residential solar and storage devices, confirmed its value in wholesale markets and for customers in the summer months of 2022, when it delivered over 1.8 GWh to the grid during diurnal peak hours and helped to reduce peak demand.[32]

3.1.5 Voltage Regulation

Voltage regulation refers to "maintaining reliable and constant voltage within a transmission or distribution line to ensure electrical equipment is not damaged due to over- or under- voltage" [27]. A 2018 NREL report which analyzed five case studies of DER aggregation (including responsive load aggregation) in Vermont, Hawaii and California found that each of the five cases promoted voltage regulation as a grid service [27]. The cumulative capacity of the five projects ranged from less than 1 MW to over 100 MW in size, and included batteries, solar PV, EVs, and home appliances, suggesting that voltage regulation is a relevant use case for many project types. The improved real-time response made possible by controlling DER power output with VPPs reduces the likelihood of grid disruptions, which would have distributional justice benefits [27].

3.1.6 Increase System Resiliency

Resilience refers to the ability to prepare for, respond to, and recover from an emergency event. VPPs increase system flexibility and can decrease strain on the grid during peak hours, thereby increasing system resiliency.

Two examples of system resiliency in practice come from Sunrun's projects in Hawaii and Puerto Rico. Sunrun's VPP in Hawaii is set to install 1,000 residential solar-battery systems in Oahu by 2024. This VPP will provide 4.3 MW of capacity to Oahu over the next 5 years and is expected help provide stability and resilience after the island's coal power plant—which

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[30] "PG&E is testing different flavors of virtual power plant," Canary Media, February 20, 2023, https://www.canarymedia.com/articles/grid-edge/pg-e-is-testing-different-flavors-of-virtual-power-plant.

[31] "Sunrun Wins Big In New England Capacity Auction With Home Solar and Batteries," Green Tech Media, 2019, https://www.greentechmedia.com/articles/read/sunrun-wins-new-england-capacity-auction-with-home-solar-and-batteries#gs.0r9glo

[32] "Sunrun Activates Nation's First Residential Virtual Power Plant in Wholesale Market," Sunrun, 2022, https://investors.sunrun.com/news-events/press-releases/detail/273/sunrun-activates-nations-first-residential-virtual-power

provided a sixth of peak demand on the island—was retired in 2022.[33] Similarly, Sunrun's VPP in Puerto Rico aims to increase reliability and reduce outages on Puerto Rico's power grid by aggregating more than 7,000 solar-powered battery systems.[34]

3.2 Economic Development

By making the electricity grid operate more smoothly and supporting enterprise development and growth along the VPP value chain, VPPs can support economic growth and the local economy through many of the use cases described. In this section we describe economic development potential for VPPs as it relates to local resiliency, reduced electricity bills and support for workforce and enterprise development, which each have benefits across the four tenets of energy justice.

3.2.1 Provide Local Resiliency

From a building owner's perspective, VPPs have the potential to provide backup power that a PV and battery system typically provide for a lower cost if the building owner receives ongoing payments for allowing the VPP operator to use their devices at certain key times and the system is designed to operate during an outage. This is a key benefit that could make a VPP project financially attractive from a customer perspective compared to placing the battery and solar PV systems on the grid [30].

The tax incentives offered by the Inflation Reduction Act (see Section 2.1), and the opportunity to enroll in a VPP and receive additional payments, make it more affordable to adopt DERs (including electric vehicles) and access the local resiliency benefit. However, some populations may need additional financial assistance in addition to the policy incentives outlined to access DERs and VPPs, such as up-front cost reduction [31]. A non-profit called GRID Alternatives is attempting to mitigate the cost burden faced by low-income rooftop solar customers by covering the up-front cost to install solar PV on rooftops in low-income communities, and has served thousands of homes so far.[35] The cost barriers associated with VPP access are discussed further in Section 4.1.

3.2.2 Reduce Electricity Bills

Reduced electricity bills can be achieved by load shifting and using electricity more efficiently through demand response programs, which can decrease energy use overall and shift usage to less expensive times. Customers are often incentivized to make their devices available during peak hours, which makes them eligible for on-bill compensation, further reducing bills. The

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[33] "Sunrun Lands Another Big Virtual Power Plant Deal, This Time in Hawaii," GreenTech Media, September 20, 2019, https://www.greentechmedia.com/articles/read/sunrun-lands-1000-home-solar-and-battery-grid-services-contract-in-hawaii

[34] "Sunrun to Build and Operate Puerto Rico's First Virtual Power Plant, A Customer-Driven Energy Solution," Sunrun, November 1, 2022, https://investors.sunrun.com/news-events/press-releases/detail/275/sunrun-to-build-and-operate-puerto-ricos-first-virtual

[35] "The solar power revolution can benefit working-class people and communities of color," Canary Media, 2021, https://www.canarymedia.com/articles/climate-justice/the-solar-power-revolution-can-benefit-working-class-people-and-communities-of-color

savings achieved by individuals who can access VPP projects vary depending on factors such as size, type of incentive program, technology types, and location.

One example of how a project could be structured to achieve this use case is the 2500R Midtown project in Sacramento, which describes 34 affordable “smart” homes built by a non-profit affordable housing company Pacific Housing Inc. Each smart home includes a 2.25 kW solar PV system, an 11.7 kWh lithium-ion battery, a smart thermostat, and a smart energy outlet or “modlet” [27].

The active demand-response battery incentive program in Massachusetts known as ConnectedSolutions has also created on-bill savings for customers. In 2020, the benefits of this VPP “totaled $2.14 for residential customers and $4.18 for commercial and industrial customers, for every dollar spent” [21]. Battery owners can receive up to $1,500 per year for participating in dispatch events [30].

Demand response and the desire to meet climate goals are key drivers for VPPs in New York [7]. The New York Reforming the Energy Vision (REV) Initiative, launched in 2014, increased funding for state-wide sustainability measures and spurred a suite of energy policies. These include the Value of Distributed Energy Resources program, wherein customers are compensated for DER capacity beyond a 1:1 rate of use. The program considers environmental and external factors such as location and demand reduction, and these reductions are credited on customer electricity bills. Programs like this could improve access to VPPs by increasing the monetization of VPP value streams.[36]

3.2.3 Support Workforce & Economic Development

Economic development benefits can occur throughout the VPP value chain, including during participation enrollment, hardware attainment and operation and trading. Participatory budgeting[37] or alternative ownership mechanisms like energy co-op formation can help to attain hardware and gain more participants [31]. The tax incentives included in the IRA can also help communities to adopt DERs and access VPPs.

Workforce development could also be an outcome of VPPs throughout the VPP project value chain. Clean energy jobs grew by 3.9% in the US between 2021 and 2022, according to the 2023 United States Energy and Employment Report [32]. Jobs related to battery electric vehicles increased by 26.8% between 2021 and 2022, and electric power generation jobs rose by 6.1% [32]. EV charging and battery storage specific jobs grew by 6.1% and 5.5% respectively between 2021 and 2022 [32]. These trends can be expected to continue, as solar and wind job growth has been on the rise since 2020 and clean energy jobs in general accounted for over 84% of new jobs in the electric power generation sector in 2022 [32].

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[36] “The Value Stack,” New York State Energy Research and Development Authority, https://www.nyserda.ny.gov/All-Programs/NY-Sun/Contractors/Value-of-Distributed-Energy-Resources.

[37] Participatory budgeting refers to allowing voters to democratically decide how to use a public budget (NYC Council definition). In New York City, citizens were allowed to decide how about $30 million in capital funding should be allocated in 2023 to public spaces such as schools, libraries and parks (“Participatory Budgeting,” New York City Council, 2023, https://council.nyc.gov/pb/).

If VPPs at scale result in increased development of DERs such as rooftop solar and distributed battery storage, VPPs would likely spur jobs in multiple sectors, including installation, manufacturing, operation and maintenance of systems, and wholesale interactions.[38,39] About a third of jobs in the electricity sector are related to installation, maintenance and repair of infrastructure [32].

Workforce development for VPP-related jobs will require capacity building for full-time jobs related to installing and maintaining DERs [2]. Workforce development and DER installation can likely be expedited through utility cooperation with union organizations such as the International Brotherhood of Electrical Workers (IBEW) and the National Electrical Contractors Association (NECA), which have years of experience conducting training programs that are responsive to market and technology changes [2].

However, ensuring that local communities benefit from these new jobs will require outreach to target people who are not currently in the workforce or people who are transitioning to a new career. Developing training to prepare people for the types of jobs that VPPs will spur will also be necessary [2]. In other words, even if the jobs are available, the local workforce might not be ready; this is a recognitional and procedural justice issue that must be anticipated. Additionally, some minority groups such as women and Black workers are still underrepresented in the energy sector compared to the US workforce in general, and targeted outreach and training will likely be necessary to grow this representation [2], [32].

The Sunnova Project Hestia, announced in April 2023, is one example of how VPPs can promote economic and workforce development in underserved communities. The project received a $3 billion partial loan guarantee from the DOE's Loan Programs Office and directly targets disadvantaged communities in the United States and Puerto Rico through the Justice40 Initiative. The predominately solar-powered battery project, which is projected to include over 500 MW of capacity over 25 years, is anticipated to create benefits such as avoiding pollution (deferring an expected 7.1 million tons of CO_2) and creating more than 3,000 jobs.[40] Because the project is covered by the Justice40 Initiative, many of these potential benefits are expected to flow to underserved communities.

3.3 Public Health Benefits

Successful VPPs can advance recognitional and distributive justice, reduce fossil fuel dependence, and ultimately result in public health benefits. These benefits are demonstrated by public health-related use cases—reducing greenhouse gas emissions, reducing noise pollution, and reducing indoor/outdoor air pollution—described in the subsections below.

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[38] "National Solar Jobs Census 2022", IREC, 2022, https://irecusa.org/census-executive-summary/

[39] "U.S. Energy and Employment Report Fact Sheet," US DOE, 2022, https://www.energy.gov/sites/default/files/2022-06/USEER%202022%20Fact%20Sheet.pdf

[40] "LPO Offers First Conditional Commitment for a Virtual Power Plant to Sunnova's Project Hestia to Support Grid Reliability and Expand Clean Energy Access," DOE, April 20, 2023, https://www.energy.gov/lpo/articles/lpo-offers-first-conditional-commitment-virtual-power-plant-sunnovas-project-hestia

3.3.1 Reduce Greenhouse Gas Emissions

In states with ambitious clean energy policies such as California, New York and Massachusetts, reaching clean energy goals is a common motivation for DER and VPP incentives [7]. Reducing emissions in the electricity sector can have monetary benefits that could support economic growth when there are markets or trading mechanisms for emissions reductions [33].

One way that VPPs can reduce greenhouse gas emissions is by supporting electrification. The ability to opt into a VPP can provide supplementary value streams that incentivize electrification of residential and commercial appliances, fleet and personal vehicles, commercial processes, and industrial processes [3]. In other words, getting a regular credit from a utility or other entity in exchange for the use of devices to support the electricity grid at key times could make it more cost-effective to go electric.

An example of how reducing greenhouse gas emissions could play out in practice is through electric vehicles, which have a readily available battery that could be used to support the grid. For instance, Autogrid and Zum's plan to deploy a 1-GW VPP made up of more than 10,000 school buses across the United States by 2025 is expected to be one of the largest VPPs in the world and will help to displace some of the 500,000 diesel school buses currently on the road.[41] Another example of VPPs' potential to support public health is a V2G project for Mitsubishi Outlander Plug-in Hybrid Electric Vehicles (PHEVs) in Thailand, which is part of the Electricity Generating Authority of Thailand's broader VPP feasibility study. Mitsubishi Outlander PHEVs are equipped with bidirectional charging technology and can act as a form of backup power supply along with providing power back to the grid. Along with promoting the electrification of vehicles, which reduces air and noise pollution, the project is expected to contribute to Thailand's carbon neutrality targets and reduce greenhouse gas emissions over time.[42]

With additional subsidies available, underserved communities may be more incentivized to purchase an EV or other electric device if they can access a VPP that provides them with periodic on-bill payments, which could improve recognitional and distributive justice. However, there may still be cost-based barriers related to DER adoption and VPP access, and accessibility will likely depend on the assistance that is offered by specific VPP programs. This paper does not study the accessibility of EVs or other DERs for specific underserved communities or income groups, but this is a topic that should be explored further to understand the additional economic benefits that VPPs can provide to individuals through electrification.

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[41] "Autogrid and Zum Partner to Create 1 Gigawatt of Flexible Capacity Using Electric School Buses As Virtual Power Plants," July 15, 2021, Autogrid and Zum, https://www.auto-grid.com/news/autogrid-and-zum-partner-to-create-1-gigawatt-of-flexible-capacity-using-electric-school-buses-as-virtual-power-plants/

[42] "Mitsubishi Motors Thailand Joins Hands with EGAT to Pioneer Virtual Power Plant Project in Preparation for Public Participation," October 2022, Mitsubishi, https://www.mitsubishi-motors.co.th/en/news-activity/news/mmth-joins-hands-with-egat-to-pioneer-virtual-power-plant-project#:~:text=The%20Virtual%20Power%20Plant%20project,with%20Mitsubishi%20Motors%20Thailand's%20policy

3.3.2 Reduce Noise & Indoor/Outdoor Air Pollution

VPP projects can reduce outdoor air pollution and noise pollution by, for example, encouraging the use of electric vehicles over internal combustion engine vehicles. Software provider Autogrid and Zum's 1-GW VPP US-wide electric school bus VPP (mentioned in Section 3.3.1) and other similar electric school bus VPP projects can provide both air quality and noise reduction benefits. Diesel school buses produce noise pollution, particulate matter, nitrogen oxides, and poor internal air quality that adversely impact children's health, and a VPP can create an additional monetary incentive to electrify school bus fleets. VPP projects can also support outdoor air quality improvements by reducing the need to run fossil fueled power plants that typically serve peak load (see Section 3.1.4).

Reduced indoor air pollution can also result from VPP incentives that motivate electrification of the built environment, such as through responsive load DERs like heat pumps or hot water heaters.[43] In some programs, devices such as smart thermostats are provided free of charge in exchange for VPP participation, as is the case in Sunrun and PG&E's VPP in California.[44] Also, as mentioned in Section 2.1, the electrification rebates that are built into the IRA pay for 100% of residential electrification costs for low-income households on select devices, including heat pumps, hot water heaters, and electric wiring.[45] Some of these qualifying devices could potentially be enrolled into a VPP project, and upgrades such as electric wiring and weatherization could provide easier access to VPP compatibility. For example, VPP developers could promote VPP access by coordinating with programs such as the Weatherization Assistance Program (WAP), which provides weatherization to low-income households as a complementary investment [46]. An area of future work is to identify a specific range of economic benefits that could result from VPP access after weatherization takes place or eligible household devices are installed.

In the built environment, retrofits related to energy conservation and weatherization can improve indoor air quality and public health as well as increasing VPP compatibility. One paper, which modeled a case study of kids' exposure to indoor air pollution in an affordable multifamily housing complex in Boston, found that energy-saving and ventilation retrofits could result in annual healthcare cost savings of over US $200/year [34]. Another study identified a range of health and climate co-benefits associated with electricity savings in US buildings, which could be increasingly enabled by VPP access [35].

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[43] "Centrica and Mixergy hit 1 MW Milestone in Hot Water Tank VPP Rollout," Current News, October 2021, https://www.current-news.co.uk/centrica-and-mixergy-hit-1mw-milestone-in-hot-water-tank-vpp-rollout/

[44] "PG&E is testing different flavors of virtual power plant," Canary Media, February 20, 2023, https://www.canarymedia.com/articles/grid-edge/pg-e-is-testing-different-flavors-of-virtual-power-plant.

[45] "The Inflation Reduction Act: Electrification Rebates (The High-Efficiency Electric Home Rebate Program)," Rewiring America, n.d., https://assets.ctfassets.net/v4qx5q5o44nj/7LiHS6hhVKaIdph8bdVV8b/aec9fc3a35985027af3f97111304db7a/factsheet_Electrification_Rebates.pdf

[46] "Weatherization Assistance Program," US DOE Office of State and Community Energy Programs, n.d., https://www.energy.gov/scep/wap/weatherization-assistance-program

3.4 Summary

Our analysis of existing VPP programs and projects suggests that use cases for VPPs overlap and complement each other throughout the VPP value chain and across EJ tenets. For example, electrification can support economic growth and reduce greenhouse gas emissions and indoor/outdoor air pollution. Support for economic development is tied to grid services and reduced electricity bills. Many of the grid services and economic development benefits that VPPs can provide are also intertwined, broadly distributing benefits to the local grid and its customers and demonstrating the benefits of DER control systems from a variety of stakeholder perspectives.

From a utility or retailer's perspective, effective VPP software platforms can provide increased visibility about the amount of DERs that are forecasted versus available, which has the potential to help with short-duration grid operations and stability [15]. Additionally, as VPPs scale, utilities or retailers can save money by deferring carbon intensive upgrades while achieving similar reliability as before [4]. From the customer perspective, access to VPPs can promote energy justice across the four tenets by making local resiliency more accessible, reducing electricity bills, and promoting economic growth.

The use cases analyzed also suggest that VPPs could help to support greenhouse gas emissions reductions in the electricity sector through peak shaving, reducing capital requirements, improving air quality, and reducing greenhouse gas emissions. Since low-income communities and communities of color are impacted by poor air quality and gas peaker plants at higher rates than average in the US, bringing VPPs to these communities could have substantial benefits for underserved populations [29].

Ensuring that the benefits from VPP use cases can be realized by underserved communities directly may require paying special attention to these populations' needs, providing alternative financing options, and targeting VPP enrollment with recognitional justice in mind [9]. In Section 4, we discuss the barriers to VPP access faced by underserved communities and present examples of how barriers have been overcome in practice.

4 VPP Adoption in Underserved Communities

VPPs can create opportunities for underserved communities to benefit from the use cases outlined in Section 3. However, underserved communities face important barriers that make participation in a VPP more challenging. In this section, we analyze how the introduction of a VPP could impact certain challenges faced by underserved communities. The challenges that we discuss have to do with cost-based, socioeconomic, and historical barriers, and these are summarized in Table 2.

Table 2: Challenges faced by underserved communities

Challenge	Relevant Tenet of Energy Justice				
	Category	Recognitional	Distributive	Procedural	Restorative
Lack of capital	Cost-based		✓	✓	✓
Loan challenges	Cost-based	✓	✓	✓	✓
Lack of affordable home ownership	Cost-based	✓	✓		✓
Need for additional upgrades	Cost-based	✓	✓	✓	✓
Energy-limiting behavior	Socioeconomic	✓	✓		
Lack of flexibility capital	Socioeconomic	✓	✓		
Community mistrust	Historical	✓	✓	✓	✓
Knowledge barriers	Historical	✓		✓	✓
Exposure to fossil fuel economy & poor indoor/outdoor air quality	Historical	✓	✓	✓	✓
Natural disaster vulnerability & disproportionate power outage impacts	Historical	✓	✓		✓

4.1 Cost-Based Barriers

Cost-based barriers, including lack of capital, loan challenges, energy burden, lack of affordable home ownership, and additional upgrade limitations, often prevent the inclusion of underserved communities in VPP projects as early as the participant enrollment phase of the VPP project value chain. Mitigating these barriers results in ramifications across the four EJ tenets.

4.1.1 Lack of Capital

The devices that make up VPPs, such as residential solar and battery systems, often have high up-front costs that make them inaccessible to underserved populations.

In practice, alternative financing approaches, such as grants, guarantees, or concessional rates from governments, non-profits, and commercial banks or green banks, have helped to mitigate this barrier and increase recognitional and distributive justice [31]. One example of an alternative financing method in practice is in Tesla's large VPP in Australia, which includes participants from many low-income homes. Installation of solar PV and Tesla Powerwalls for this project is supported by a $2 million grant from the Australian government and a $30 million loan from the South Australian Government's Renewable Technology Fund. Such loans can lower entry barriers for underserved communities to participate in VPPs.[47]

Another way to mitigate the lack of capital challenge is to allow low-cost devices to participate in VPPs. One example is flexibility operator Shifted Energy's 2.5 MW VPP in Hawaii, which installs smart, programmable water heaters for VPP participation. Water heaters are a technology option with a low up-front cost entry and allowing them to participate in VPPs lowers the up-front cost barrier and makes existing clean energy VPPs more accessible to underserved populations.[48]

Energy burden is one example of lack of capital, and is defined as the disproportionate amount of income spent on electricity [36]. Low-income communities in the U.S. spend ~8.6% of income on energy bills on average, which is about three times more than mid- and high-income households spend.[49] The successful adoption of VPPs has been shown to lower system costs and reduce electricity bills (see Section 3.2.2), which could advance distributive justice and lower energy burden. An analysis from RMI suggests that lower electric bills for non-participants could be an additional benefit [3].

The National Grid Fruit Belt Pilot Program, which installed 74 residential solar PV systems that are aggregated for market participation, was driven by the goal of reducing electricity bills for low-income residents through the installation of utility-owned and maintained distributed solar PV systems. As of 2018, the participants received an on-bill credit of $15 per month. Third-party ownership of DERs is one way to reduce the costs associated with VPP entry.[50]

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[47] "Tesla expands its virtual power plant to new regions in Australia," Electrek, 2022, https://electrek.co/2022/04/27/tesla-expands-virtual-power-plant-new-regions-australia/

[48] "This startup turns electric water heaters into grid batteries," Canary Media, 2023, https://www.canarymedia.com/articles/grid-edge/this-startup-turns-electric-water-heaters-into-grid-batteries#:~:text=Shifted%20Energy%20is%20tapping%20water,the%20grid%2C%20starting%20in%20Hawaii.

[49] "Low-Income Community Energy Solutions," Accessed 2023, The US Department of Energy Office of State and Community Energy Programs, https://www.energy.gov/scep/slsc/low-income-community-energy-solutions

[50] "Fruit Belt Demonstration Project Achieves Milestone," National Grid, 2018, https://www.nationalgridus.com/news/2018/10/fruit-belt-demonstration-project-achieves-milestone/

4.1.2 Loan Challenges

DER technologies that make up VPPs are often associated with long return-on-investment periods. The cost of VPP adoption is more inaccessible for underserved communities on average due to lower credit and reduced likelihood of receiving a loan at competitive rates for technologies with a high up-front cost [31]. This represents a barrier across all tenets of energy justice, as there are ways that communities could be more involved in loan related processes and policies that are supportive of fair lending practices.

Because of this, some VPPs include special incentives to attract DER adoption in underserved communities. For example, the Massachusetts ConnectedSolutions VPP includes incentives specifically for low-income households to adopt battery storage. These include third-party ownership of batteries, up-front rebates to help with capital costs, low- or no-cost financing, on-bill payment, virtual or community storage, and stackable rate adders including one specifically for low-income participants [30]. By reducing up-front cost and loan barriers, the ConnectedSolutions VPP can increase recognitional and distributive justice, and provide benefits such as energy resilience improvements, greater access to renewable energy, and support for economic development.

4.1.3 Lack of Affordable Home Ownership

Another common barrier to VPP adoption for underserved populations is that many underserved community members cannot afford to buy a home, which greatly reduces access to DERs. Renters have less control over whether to opt into a VPP and fewer direct pathways to access benefits of DER installations [37]. Renting a house is correlated with reduced potential for rooftop PV adoption as landlords would pay the up-front cost of the technology without seeing immediate monetary benefits from improved energy consumption; in 75% of renter-occupied households, renters are responsible for paying all energy costs [38]. In addition, Black and Hispanic households are more likely to rent than white households in the United States, meaning the potential for DER adoption is lower for Black and Hispanic populations [38].

Affordable housing policies, subsidized housing down payments, and social housing projects that make it easier for low-income people to become homeowners would improve the distributional justice of residential DER adoption and thus would create opportunities to improve distributional justice through participation in VPPs. Additionally, there is increasing interest in expanding access to DERs to residents of multifamily housing through both on-site and off-site shared solar, which could increase recognitional justice by acknowledging the roughly 60% of renters in the US who live in multifamily housing [39].

Affordable smart-home programs, though usually small in size, can help to increase recognitional justice for the inclusion of first-time homeowners in VPPs. Examples include:

- Community choice aggregator MCE’s VPP in Richmond, California is a smart-home program that equips low-income home buyers with smart energy devices. In exchange for a low-interest or zero-interest home ownership loans, new homeowners opt into a program that helps MCE use their smart home devices to achieve system-wide benefits such as lower peak demand.[51]

- In the 2500R Midtown project described in Section 3.2.2, wherein 34 low-income customers were sold smart device-equipped homes, the costs of devices were bundled into the overall housing cost, which reduced barriers related to payment periods and loan challenges as well as promoting more accessible smart home and DER ownership.[52]

4.1.4 Need for Additional Upgrades

Many of the cost-based barriers are relevant because homeowners or renters in underserved communities are less likely to have DER devices installed at the time of participation enrollment [38]. Further, as noted in Section 2.3, additional compatibility upgrades may be necessary to install DERs in rural or older homes, which can raise the cost of hardware attainment.

One type of additional upgrade relates to limitations with building compatibility for devices. Low-income communities often live in older houses that are less energy efficient than average [30]. Older houses may not be able to participate in VPP projects due to incompatibility with DER device installation, presenting a missed opportunity for participation. The additional upgrades that might be needed to install DERs on older homes raise the average cost of installation, further making it less likely that low-income communities can benefit from VPPs.

Another additional upgrade challenge can be a lack of grid hosting capacity for DERs. There is some evidence of hosting capacity disparities that track with demographic and socioeconomic factors, particularly race [40].[53] Underserved communities may have lower levels of hosting capacity and limits to grid infrastructure that require further upgrades for DER installation. This raises the average cost of VPP participation compared to a customer who is in an area that does not need grid connectivity upgrades and could discourage VPP developers from intentionally including underserved communities because of overall cost or profitability concerns.

Programs such as up-front cost assistance (through companies like GRID alternatives, mentioned in Section 3.2.1, and other forms of alternative financing), can assist in reducing the overall cost of VPP access (from the DER attainment phase). For example, Green Mountain Power's

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[51] "These California programs steer solar+batteries to low-income households," Canary Media, 2022, https://www.canarymedia.com/articles/solar/these-california-programs-steer-solar-batteries-to-low-income-households

[52] "If Affordable Housing Can Draw Zero Net Energy, Then Anything Can," Sunverge, 2015, https://www.sunverge.com/if-affordable-housing-can-draw-zero-net-energy-then-anything-can

[53] NREL defines hosting capacity as: "the amount of distributed photovoltaic systems (DPV) [or other DERs] that can be added to distribution system before control changes or system upgrades are required to safely and reliably integrate additional [DERs]." Also note that "as upgrades are implemented, the hosting capacity of the system increases." Although this source focuses on hosting capacity analyses of DPVs, the hosting capacity definition can be expanded to include all DERs, not just DPV. (Source: "Advanced Hosting Capacity Analysis," National Renewable Energy Laboratory – Solar Market Research & Analysis, n.d., https://www.nrel.gov/solar/market-research-analysis/advanced-hosting-capacity-analysis.html#:~:text=Hosting%20capacity%20is%20the%20amount,added%20to%20the%20distribution%20system.)

McKnight Lane Redevelopment Project aimed to revitalize a struggling community by allowing low- and middle-income residents to rent smart homes and connecting them with a DERMS.

One lesson learned during the McKnight Lane Redevelopment Project had to do with connectivity issues, such as issues with internet connection (modems) and communication when dispatching batteries to respond to peak demand. These setbacks were sometimes present even after upgrades were made [27]. Increasingly, DER aggregation and control uses app-based software such as Google Nest, OhmConnect, or other information technology (IT) connections [2]. Areas with unreliable Wi-Fi, limited cellular coverage, or limited Bluetooth capability may have issues with remote DER aggregation, and upgrades may be required to accommodate a VPP [2]. Because underserved communities may require upgrades at a higher rate to achieve DER device installation compliance, understanding and anticipating these potential setbacks in advance can contribute to program success.

4.2 Socioeconomic Barriers

Barriers to DER adoption in underserved communities can also be socioeconomic in nature, and these barriers also largely occur during participant enrollment (discouraging participation). These barriers are typically associated with recognitional injustices, and sometimes also relate to procedural and restorative injustices. Socioeconomic barriers include energy limiting behavior and lack of flexibility capital.

4.2.1 Energy Limiting Behavior

Energy limiting behavior describes how underserved communities use energy differently to save on electric bills [36]. This is distinct from energy efficiency measures, and instead describes a type of energy poverty wherein households are unable to maintain comfortable household temperatures because of significant budgetary constraints [36]. While many low-income energy incentive programs use percent of income spent on energy to describe the energy burden of a household, there is evidence of low overlap between energy burden and energy-limiting households [36]. Thus, energy limiting behavior is a recognitional justice issue that is not captured by income-based metrics alone [36].

Although energy limiting behavior is distinct from energy burden, the impacts of introducing VPPs could be similar in mitigating both barriers. VPPs could create more affordable energy and include devices or upgrades that enable increases in demand locally, and programs have been shown to decrease electricity bills (Section 3.2.2). Understanding whether VPP introduction mitigates energy limiting behavior in practice will require studies that look beyond electricity bills and into the customer's household energy usage and comfort metrics [36].

4.2.2 Lack of Flexibility Capital

The concept of flexibility capital represents an additional recognitional justice challenge for underserved communities. Powells and Fell (2019) define flexibility capital as "the capacity to responsively change patterns of interaction with a system to support the operation of that system" [41]. The concept is used to describe the differences in time, convenience, comfort, and flexibility that separate income groups, allowing higher-income populations to benefit from time-of-use rates more fully and device response to price signals. This is one factor that causes some people to save money when it comes to smart energy systems, whereas others can miss chances to do so, or sacrifice some level of convenience for comfort [41]. The lack of flexibility capital that a person in an underserved community might have could affect their desire to access a VPP in which they are required to cede control of their device at times that may be inconvenient. This represents a recognitional barrier that occurs during the participant enrollment stage of the VPP value chain.

4.3 Potential to Overcome Historical Challenges

Underserved communities also face historical challenges that create additional barriers in many of the categories described above. Addressing these challenges will likely require transformative changes that are beyond the scope of this paper, but they are important dimensions of advancing energy justice. The benefits that would occur when reducing these barriers would likely take place in the operation and trading part of the VPP value chain. Historical barriers, which relate to the restorative injustices that are associated with challenges faced by underserved communities, include community mistrust and data security concerns, knowledge barriers, exposure to the fossil fuel economy and poor indoor/outdoor air quality, natural disaster vulnerability, and disproportionate power outage impacts.

4.3.1 Community Mistrust

Customers may have feelings of less trust when entities that historically have not been trustworthy or have left communities out, such as corporate third parties or utilities, want to gain insight into how customers use their energy [23]. There are a variety of ways to ensure that communities and customers feel heard throughout project development, and studies suggest that emerging technologies such as VPPs will be met with more public acceptance if community concerns are taken into account early on in development [42], [11]. For instance, even as it is necessary for bidirectional systems to have more energy data visibility to maintain electric system balances in real time as VPPs scale, proper protocol can be used to ensure data governance and privacy [23], [42], [43]. Research regarding specific regulations that could improve procedural justice by strengthening community trust and security is identified as an area of future work.

The concept of procedural justice describes establishing fair decision-making processes, and collaborating with or deferring to communities during VPP development can help to ensure that this tenet of EJ is recognized [42]. NREL’s Joint Institute for Strategic Energy Analysis (JISEA) outlines five recommendations for community engagement, which are based on NREL’s experience and lessons learned regarding community interactions. These are:

1. **Do your homework:** Before entering a community, perform research on community culture, community structures, and appropriate stakeholders to involve as conveners or third parties. Maintaining cultural sensitivity can promote restorative and recognitional justice for communities that have been historically neglected or harmed [42].

2. **Be humble, authentic, and honest:** In your interactions with communities, maintaining honesty, recognizing and being sensitive to the fact that you are not a community member, and avoiding making commitments that are unsustainable can all help to build trust [42].

3. **Respect and support community agency:** Prioritizing the community's goals related to project outcomes can help to build trust and promote restorative, recognitional and procedural justice. Recognizing power dynamics can also be helpful; one suggestion involves having an initial meeting to define key terms that may be used throughout project development [42].

4. **Meet communities where they are:** When meeting with a community, tactics such as building knowledge of the technology at hand, ensuring that the messaging matches the audience, and providing compensation for their time (through an honorarium, subcontract, or gift cards) can help to build trust [42].

5. **Democratize participation:** Finally, building inclusive practices in both virtual and in-person environments can provide opportunities for all voices to be heard, building distributive justice within the community, and procedural justice of practices. Democratization practices for meetings include scheduling multiple meetings at different times, offering opportunities for low bandwidth customers to participate virtually, recording meetings, and scheduling follow-ups with community members who need extra guidance. Outside of meetings, polls and other opportunities for feedback can be used to gage progress [42].

Even if every best practice is followed, community mistrust could still be a barrier to VPP adoption in underserved communities. Building trust with underserved communities does not happen overnight and will likely involve ongoing engagement, even after project deployment has occurred. Sources of mistrust also extend beyond the power system and the design of a given VPP, so a VPP can only build trust in a narrower way.

4.3.2 Knowledge Barriers

In general, in the power system, there is a lack of targeted knowledge sharing, technicality of concepts and lack of translation of material benefits which can make technology transitions seem like a "black box" to some customers. These knowledge gaps are fueled by communication and language barriers, limited communication channels, and lack of customer engagement [9].

A VPP has traditionally meant different things to different people, and across stakeholder boundaries there are still barriers to understanding what a VPP is and what benefits it can provide. For VPPs specifically, knowledge gaps can emerge in a variety of ways:

1. **Customers:** First, customers with DERs or participating devices may not understand VPP technology and how it benefits them, or they might not be aware of VPPs as an option. The US DOE's VPP Liftoff Report recommends tactics such as consumer education on the concept of VPPs, or facilitating participation enrollment through strategies such as automatic enrollment (with the ability for opt-out) for DER owners if access to a VPP is available [2].

2. **Workforce development:** Next, gaps of understanding may also occur during workforce development, and capacity building and training programs will likely be needed to ensure that employees can be contracted locally and that underserved communities benefit from employment opportunities. Promoting agency and self-reliance in project training

programs, as well as meeting parties where they are during project development and messaging, can sustain stakeholder or customer knowledge of an emerging technology such as a VPP [42].

3. **Other stakeholders:** Utilities, ISOs, or other stakeholders may not understand the benefits of VPPs or think that the learning curve to implement such a project in their operating areas or homes is more trouble than it is worth, which could limit equitable distribution during participation enrollment. Help from interveners, researchers, lawyers, community leaders, and stakeholders to navigate technical and procedural concepts during program design is one way to mitigate the knowledge barriers about VPPs that exist across stakeholder groups [31]. Additionally, incorporating VPPs into the utility planning process, incentivizing VPP development, and ensuring wholesale market participation through FERC Order 2222 will likely help to increase the knowledge and awareness of VPPs in practice [2].

4.3.3 Exposure to the Fossil Fuel Economy & Poor Indoor/Outdoor Air Quality

This challenge refers to the disproportionate impact that the location of fossil fuel infrastructure (e.g., peaker plants) has in underserved communities [29], [44]. The American Lung Association (ALA) has studied the poorer air quality of underserved communities, especially nonwhite populations in the United States.[54] According to the ALA and other leading studies, nonwhite and especially Black communities have higher risks of particulate air pollution, and due to decades of segregation and discriminatory policies like redlining, disadvantaged communities of color are more likely to live closer to highways and other overburdened areas where more polluting infrastructure is installed [44].[55] One study found that redlining resulted in double the amount of oil and gas wells in minority neighborhoods in the US compared to White neighborhoods, which contributes to pollution [45]. VPP use cases such as peak shaving, reducing noise and indoor/outdoor air pollution and reducing greenhouse gas emissions could thus be supportive of recognitional, distributive, and restorative tenets of energy justice.

4.3.4 Natural Disaster Vulnerability & Disproportionate Power Outage Impacts

Although natural disasters and power outages are distinct barriers that can occur separately from one another, they are combined in this section because their impacts on underserved communities often overlap. The term "social vulnerability" is commonly used to describe an individual or community's risk of adverse effects during an emergency event (such as a natural disaster or outage).[56] The Center for Disease Control and the Agency for Toxic Substances and Disease define sixteen census indicators for social vulnerability, which are grouped under four

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[54] "Disparities in the Impact of Air Pollution," April 17, 2023, American Lung Association, https://www.lung.org/clean-air/outdoors/who-is-at-risk/disparities

[55] "Disparities in the Impact of Air Pollution," American Lung Association, last updated April 17, 2023, https://www.lung.org/clean-air/outdoors/who-is-at-risk/disparities.

[56] "CDC/ATSDR Social Vulnerability Index," ATSDR, 2022, https://www.atsdr.cdc.gov/placeandhealth/svi/index.html

themes: socioeconomic status, household characteristics, racial and ethnic minority status, and housing type/transportation.[57]

Data from the US News and World Report suggests that racial minorities have a higher social vulnerability to natural disasters in the US, based on a “National Risk Index” published on the Federal Emergency Management Agency’s site.[58] The map considers 18 natural hazards including flooding, hurricanes, and wildfires and finds that Alaska Native, American Indian, and Native Hawaiian populations are at the most risk overall, and that Black populations are at the most risk of heat waves, flooding, hurricanes, and tornadoes.[59] The US News and World Report study also suggests that there are historical reasons for such discrepancies, such as redlining for home loans that has forced minority populations to live in more vulnerable and polluted areas [44].[60] Social vulnerability metrics such as health risks, lack of preparedness, and lack of an evacuation plan can also put individuals at increased risk during long-duration power outages, which often occur after or during natural disasters [46].

Several examples demonstrate how natural disasters and power outages have impacted socially vulnerable populations:

- **Winter Storm Uri in Texas:** Several studies have demonstrated that low-income and minority populations, as well as those with infrastructure inequities, experienced more and longer power outages as part of the rolling blackouts that took place during the storm [47], [48].

- **Hurricane Maria in Puerto Rico:** In the aftermath of Hurricane Maria, it took nearly 11 months to restore power to all Puerto Rican residents. Geospatial analyses have indicated that areas that experienced the longest outages tended to be in low-income and rural communities.[61]

- **Hurricane Harvey in Texas:** An overlayed map that shows both Harvey’s flood data from the Dartmouth Flood Observatory, and the Center for Disease Control’s social vulnerability index map, indicates that more vulnerable census tracts were hit harder after Hurricane Harvey.[62]

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[57] “CDC/ATSDR SVI Fact Sheet,” ATSDR, 2023, https://www.atsdr.cdc.gov/placeandhealth/svi/fact_sheet/fact_sheet.html

[58] “National Risk Index – Explore the Map,” FEMA, n.d., https://hazards.fema.gov/nri/map

[59] “The Demographics of Disaster,” US News and World Report, 2022, https://www.usnews.com/news/health-news/articles/2022-06-22/disaster-disparities-natural-hazards-climate-change-threaten-underserved-communities

[60] “Redlined, Now Flooding,” Bloomberg, 2021, https://www.bloomberg.com/graphics/2021-flood-risk-redlining/

[61] “When power utilities’ monitoring services are disrupted during a hurricane, novel satellite technology comes to the rescue,” Earth from Space Institute, 2022, https://www.usra.edu/efsi-case-study-hurricane-maria#:~:text=The%20data%20also%20identified%20large,losses%2C%20suffered%20the%20longest%20outages.

[62] “Hurricane Harvey hit low-income communities hardest,” ThinkProgress, 2017, https://thinkprogress.org/hurricane-harvey-hit-low-income-communities-hardest-6d13506b7e60/

- **The Camp Fire in California:** Expensive real estate in California and gentrification has forced lower-income residents into areas with higher fire risk, meaning that low-income neighborhoods have higher levels of wildfire vulnerability.[63]

Although VPPs do not prevent natural disasters, a VPP could help to bolster disaster response by providing energy system resiliency and local resiliency if designed to so (see Sections 3.1.6 and 3.2.1).

4.4 Summary

Section 4 provides a framework and basic taxonomy to think about the challenges faced by underserved communities. This taxonomy was included to help think about VPPs through an energy justice lens but could also be used to consider how other emerging technologies interact with underserved communities. Although we grouped challenges in terms of cost-based, socioeconomic, and historical barriers for ease of discussion, these categories are heavily interconnected.

To overcome cost-based barriers, inclusive financing methods have been used in VPP projects to boost underserved community participation. Inclusive financing methods include, but are not limited to, the use of public bonds or grants, green banks, and other up-front payment assistance for homes and DERs, compensating program participants at retail rates, using value stacking to efficiently value DERs in VPPs, and capping electricity bills at a certain percentage of income level [31]. There are several examples of non-profits, government grants, and other forms of alternative funding that have helped to increase access to VPPs through lowering cost-based barriers. Socioeconomic and historical barriers have less examples of mitigation in practice but are tied to VPP use cases such as increased energy resiliency, supporting workforce and economic development, reducing greenhouse gas emissions, supporting climate goals, reducing noise and indoor/outdoor air pollution, voltage regulation, optimization of DER dispatch, and frequency response. As noted in Section 2.3, these barriers will likely need to be anticipated throughout VPP program design to advance energy justice.

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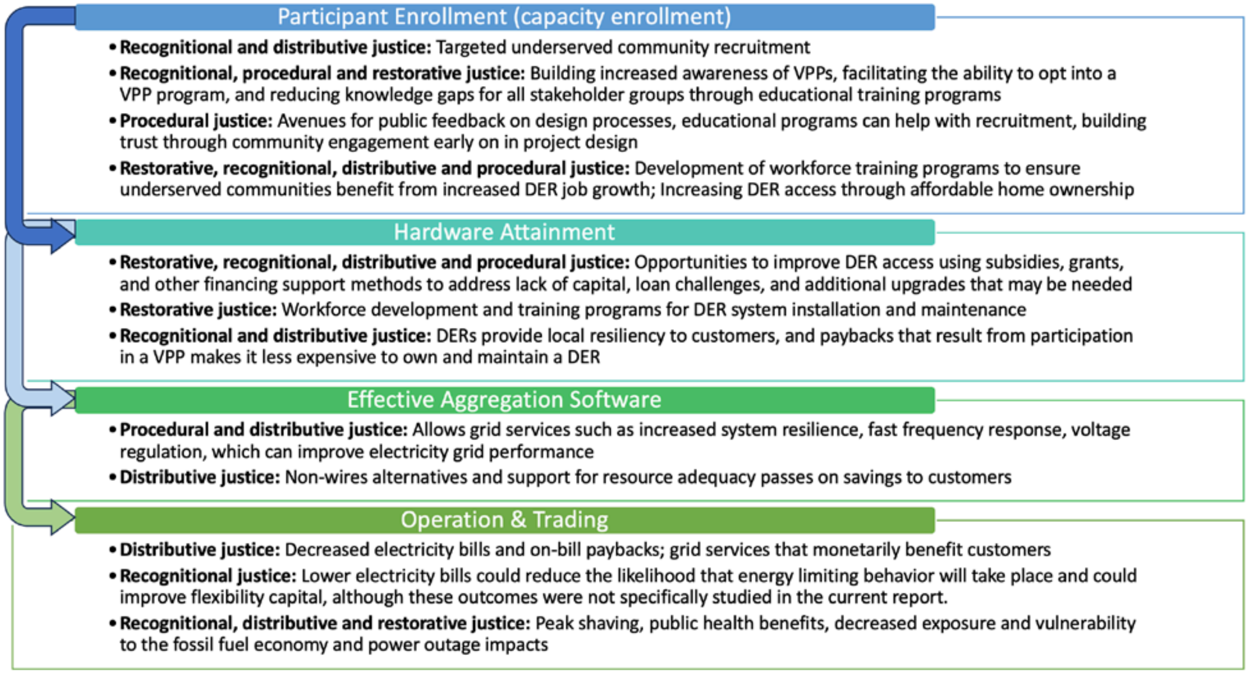
[63] "What the Camp Fire Revealed," Annie Lowrey, the Atlantic, 2019, https://www.theatlantic.com/ideas/archive/2019/01/why-natural-disasters-are-worse-poor/580846/

5 Future Work & Conclusion

In each step of the VPP project value chain, there are opportunities to strengthen a VPP project's relationship to the tenets of EJ. A representative summary of these opportunities drawing on VPP use cases and considerations for adoption in underserved communities is shown in Figure 1 below.



Participant Enrollment (capacity enrollment)

- **Recognitional and distributive justice:** Targeted underserved community recruitment
- **Recognitional, procedural and restorative justice:** Building increased awareness of VPPs, facilitating the ability to opt into a VPP program, and reducing knowledge gaps for all stakeholder groups through educational training programs
- **Procedural justice:** Avenues for public feedback on design processes, educational programs can help with recruitment, building trust through community engagement early on in project design
- **Restorative, recognitional, distributive and procedural justice:** Development of workforce training programs to ensure underserved communities benefit from increased DER job growth; Increasing DER access through affordable home ownership

Hardware Attainment

- **Restorative, recognitional, distributive and procedural justice:** Opportunities to improve DER access using subsidies, grants, and other financing support methods to address lack of capital, loan challenges, and additional upgrades that may be needed
- **Restorative justice:** Workforce development and training programs for DER system installation and maintenance
- **Recognitional and distributive justice:** DERs provide local resiliency to customers, and paybacks that result from participation in a VPP makes it less expensive to own and maintain a DER

Effective Aggregation Software

- **Procedural and distributive justice:** Allows grid services such as increased system resilience, fast frequency response, voltage regulation, which can improve electricity grid performance
- **Distributive justice:** Non-wires alternatives and support for resource adequacy passes on savings to customers

Operation & Trading

- **Distributive justice:** Decreased electricity bills and on-bill paybacks; grid services that monetarily benefit customers
- **Recognitional justice:** Lower electricity bills could reduce the likelihood that energy limiting behavior will take place and could improve flexibility capital, although these outcomes were not specifically studied in the current report.
- **Recognitional, distributive and restorative justice:** Peak shaving, public health benefits, decreased exposure and vulnerability to the fossil fuel economy and power outage impacts

Figure 1. Opportunities for Strengthening Energy Justice Relationship Along the VPP Value Chain

As discussed in Section 2.3, energy justice opportunities—and potential barriers to equitable access—can be identified and anticipated throughout a project's design [8], [10], [26]. For example, in the participant enrollment stage, targeted engagement and knowledge sharing is one strategy that can help to engage communities, and providing opportunities for feedback could improve future programs [9]. In the hardware attainment stage, the on-bill payments associated with VPPs make the local resiliency provided by VPPs more affordable, and additional programs such as grants, bonds, or leasing agreements can also be used to help with VPP access. In the software aggregation and operations and trading stage, VPP grid services could provide increased stability, flexibility and reliability that have procedural and distributive justice benefits. Finally, also in the operation and trading stage, on-bill payments and demand-side management can help to reduce electricity bills. As mentioned in Section 3.2.3, VPP-driven economic growth and workforce development can also support underserved communities.

Beyond the project value chain and before project design, incentive programs that motivate VPP development can also include recognition of low-income and underserved populations (an example of this is the low-income bonus tax incentive program included in the Inflation Reduction Act, mentioned in Section 2.1).

Along with the use cases discussed in Section 3, we also identify several unproven use cases for VPPs which have not yet been demonstrated in practice. Unproven use cases include accelerating retirement of fossil fueled generation capacity, replacing peaker power plants, accelerating DER adoption, and accelerating the achievement of clean energy goals. It remains to be seen whether and how these applications will play out as VPPs scale, but the long-term drivers of VPP projects suggest potential for these use cases as VPPs continue to evolve.

Future research avenues could consider blending business model and EJ analyses to investigate pathways to monetizing social and environmental benefits of strategic VPP deployment while optimizing for EJ in program design. Future research questions include:

- When, where, and at what scale do VPPs make sense when optimizing for their ability to meet underserved community needs?
- How much investment could be deferred by widespread adoption of VPPs, and do VPPs make it cheaper to realize highly electrified futures?
- Can aggregated DERs improve value, lower costs, and improve equity outcomes more than a DER connected directly to a DERMS or time-of-use rates?
- Is there a business model or program that best serves underserved communities?
- What is the role of policy in (1) enabling VPP business models and (2) incentivizing participation by underserved populations?

Additionally, we are interested in the extent to which VPPs could reduce peaker plant use, which would be beneficial for underserved populations due to the higher risks of particulate air pollution and exposure to fossil fuel infrastructure that underserved communities disproportionately face [29], [44], [45].

VPPs are a complex technology that require the cooperation of various entities and parties, and one of the challenges of VPPs is that the existing body of research focuses more on benefits and technology capabilities than on issues such as:

- The parties (grid operators, regulators, utilities, building owners, residents) required to engage in the development of VPP policies, regulations, business processes and technologies,
- The determination of how the benefits of VPPs are distributed to affects parties,
- The ability to scale these business models once the processes, policies, regulations, and technologies are implemented, and
- The need for a strategy to increase awareness or knowledge for underserved communities to engage in developing VPPs.

To this end, another important area of future work could be to identify frameworks for cooperative approaches to VPP development, including the potential hurdles and benefits to VPP scaling from a variety of stakeholder viewpoints. This would likely include an analysis of how VPPs can act as a grid solution—and what challenges may arise—from the perspective of key players such as IOUs, municipal utilities, electric cooperatives, CCAs, distribution companies, VPP customers, regulators, states and others.

Inclusive financing methods for home ownership, electric compatibility upgrades, installation of DERs, adoption of EVs, etc. can make VPP participation more affordable. Additionally, the extra on-bill payments that are received through opting a DER or EV into a VPP can increase the economic motivation to adopt these technologies. However, there still may be VPP access barriers related to the energy justice concepts of recognitional, procedural, distributive, and restorative justice. This paper does not look at the accessibility of VPPs for specific income groups, nor does it analyze the accessibility of adopting DER technologies in underserved communities. This should be explored in future work to better quantify the additional impacts that can be achieved through specific VPP program types.

One other limitation of this paper is that it does not consider the life cycle of VPPs beyond country boundaries and related to the manufacture and sourcing of DER equipment such as solar panels. This is related to an additional form of energy justice, called “cosmopolitan justice,” which is not discussed and involves a human-centered approach beyond borders [42]. Although a life-cycle analysis of VPPs is beyond the scope of this work, it is identified as an area of future exploration.

This paper analyzes how use cases of VPPs and barriers to adoption in underserved communities relate to the four tenets of energy justice and the VPP value chain. VPPs can achieve grid services, economic benefits, and public health benefits. Ensuring that the tenets of justice are achieved during VPP development is important for helping these benefits to be realized by underserved communities, who often face non-trivial barriers to VPP entry and DER adoption. If VPP design can enable broader VPP access in underserved communities, then transformative changes across the four tenets of energy justice can take place as VPPs continue to evolve and scale.

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