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A full-stack compensation model for virtual power plants: Uniting the top-down and local-level approaches

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Introduction

Virtual power plants (VPPs) have the potential to be a core part of the electricity system. They could provide a low-cost way to meet the growth in electricity demand, reduce CO_2 emissions, improve local air quality, enhance local and system reliability and resilience, and reduce the need for new backup coal generation.[1] In short, VPPs could provide a range of valuable services, including at the transmission and local distribution system levels.

Since 2020, VPPs have received wide attention in China from central government agencies, provincial governments and, in some cases, municipal governments. A 2021 directive by the National Development and Reform Commission underscored the importance of "unlocking the flexibility potential of the demand-side resources through VPPs to aggregate demand-side resources." [2] The role of VPPs in the energy transition was further elevated in a joint statement by the Central Committee and the State Council on accelerating the green transition of economic development. One key strategy of the energy transition outlined in the document is to accelerate the development of microgrids and VPPs to enhance demand-side flexibility.[3] However, despite calls for broader adoption of VPPs in central and provincial policy directives, and successful pilot programmes in some localities, VPPs still generally lack sustainable revenue for achieving scale.

Policies established so far mostly incentivize VPPs from a top-down perspective by establishing mechanisms to plan, invest, dispatch and compensate VPPs at the provincial and regional levels in a centralized manner. Recent developments in Guangdong, Shanxi and Shandong exemplify this approach by allowing VPPs to participate in provincial electricity spot markets.[4] In addition, VPPs in the northwest provinces can participate in their regional ancillary service market to provide peaking services.[5] These developing markets provide valuable channels for valuating and compensating VPPs at an aggregated, bulk-grid level.

However, there is still a large set of local services whose values remain uncaptured and can provide another important source of revenue for VPPs. These local services are characterized by operating VPPs according to disaggregated signals and needs at the level of the city, district and

[1] The author would like to thank Max Dupuy, Shawn Enterline and Jinglin Duan for their detailed comments, Steena Williams and Evan Jeffries for their editing support, and David Moskovitz for providing inspiration.

[2] NDRC, NEA. (2021). 关于推进电力源网荷储一体化和多能互补发展的指导意见 [Guiding Opinions on Promoting the Integration of Power Generation, Grid, Load, and Storage and the Development of Multi-Energy Complementarity]. https://www.ndrc.gov.cn/xxgk/zcfb/ghxwj/202103/t20210305_1269046.html.

[3] CPC Central Committee and State Council. (2024). 关于加快经济社会发展全面绿色转型的意见 [Guiding Opinions on Accelerating the Comprehensive Green Transition of the Economic and Social Development]. https://www.gov.cn/zhengce/202408/content_6967663.htm.

[4] For example, see 广东省能源局, 国家能源局南方监管局. (2024). 广东省虚拟电厂参与电力市场交易实施方案 [Implementation plan for virtual power plants participating in electricity market trading in Guangdong province]. https://drc.gd.gov.cn/gdsnyj/gkmlpt/content/4/4526/post_4526578.html#3869; 山西省能源局, 国家能源局山西监管办公室. (2024). 电力市场规则体系V14.0 [Electricity market rules system V14.0]. http://www.sx.sgcc.com.cn/lf/docs/202403/171050128043150347.pdf; and 山东省能源局. (2024). 山东电力市场规则（试行）[Shandong electricity market rules (Trial implementation)]. https://sdb.nea.gov.cn/dtyw/tzgg/202404/P020240419659603804969.pdf.

[5] 国家能源局西北监管局. (2020). 西北区域省间调峰辅助服务市场运营规则 [Operating rules for the inter-provincial peaking regulation ancillary service market in the northwest region]. https://xbj.nea.gov.cn/upload/2022/05/11/1652255578938000.pdf.

even street. This includes all services provided at the distribution level, as well as responding to fine-grained locational signals in various electricity markets.

The key to establishing sustainable revenue sources for VPPs is to develop a full-stack compensation mechanism for them, rewarding all segments of value that a VPP can provide. Much work has been done from a top-down perspective, so this paper will make some references to this while complementing existing work by going into more detail on the mechanisms to compensate local services and how they might be incorporated into revenue streams for three core VPP compensation models: retail rates, wholesale markets, and demand-side management programmes. The paper also describes progress and challenges in efforts to create revenue streams for the local grid services of VPPs in the United States, focusing on New York State.

Virtual power plants and local grid services

A working definition of ‘virtual power plant’

In this paper, VPP refers to distribution-level resources that are controlled and aggregated to provide services to the grid. This definition covers a range of distributed energy resources (DERs): demand response (DR), distributed generation and distributed storage.

VPP aggregations of DERs can be simple or more complex. An example of a simpler VPP might be an aggregator that manages charging at one or more EV charging stations. An example of a more complex VPP might be an aggregator that manages net loads for a combination of industrial customers, residential buildings and charging depots, each with different combinations and amounts of DERs.

Several factors distinguish VPPs from most existing DR-only aggregations:

1. New communications and control technologies have lowered the cost of aggregation and enable remote control of resources with relatively high precision.
2. Lower-cost storage enables load and generation to be more flexibly shifted across time periods.
3. New kinds of loads, such as electric vehicles (EVs), may have more inherent flexibility in when and where they consume power

Background on local grid services

VPPs can provide an array of grid services, such as generation capacity, energy, ancillary services (AS) and transmission and distribution capacity deferral. Many of these services have two approaches to fulfill their obligations:

1. Demand reduction approach, where the VPP reduces or shifts loading (net withdrawals) on the distribution and transmission system to avoid capacity constraints or high energy and AS costs.
2. Supply approach, where the VPP injects power onto the grid to provide resource adequacy capacity, energy or AS.

For grid services, each service has a local component, described in Table 1. Distribution capacity deferral, also described in the table, is inherently a local service. Distribution capacity deferral refers to when investments in distribution facilities (substations, wires, protection equipment etc.) can be delayed or avoided due to reductions in net load. From a utility perspective, the value of capacity deferral is the value of paying less now or paying later rather than paying now.[6]

Table 1. Virtual power plant grid service types and local component

	Description		
Grid service	**Demand reduction service**	**Supply service**	**Local component**
Generation capacity	VPP reduces loading on the transmission system during peak demand and other periods with high loss-of-load probabilities, reducing the need for new generation capacity to meet resource adequacy (RA) requirements.	VPP injects power onto the transmission system during peak demand and other periods with high loss-of-load probabilities, displacing more expensive RA supply options.	VPP reduces loading or injects power in transmission-constrained zones; transmission-constrained zones have higher costs to supply capacity, which means that VPPs have higher value in these zones.

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[6] In real terms, this value is the present value cost of the deferred investment versus the cost of the investment made today. For instance, a USD 10 million investment made today (2024) would have a deferral value of USD 3.8 million if deferred five complete years (to 2030) with a weighted-average cost of capital of 10%, because the present value cost of a USD 10 million investment five years into the future at a 10% discount rate is USD 6.2 million.

Grid service	Description: Demand reduction service	Description: Supply service	Local component
Energy	VPP reduces net loading on the transmission system during periods of high energy prices (demand reduction, demand shifting), and increases it during periods of low energy prices (demand shifting), reducing average energy costs. Periods of low energy prices include periods in which wind and solar generation is on the margin, when prices will be very low or negative.	VPP injects power onto the transmission system during periods of high energy prices, displacing more expensive generation.	VPP reduces loading or injects power in transmission-constrained areas with higher nodal or zonal energy prices; by doing so, the VPP can support local renewable integration.
Ancillary services	VPP reduces net loading on the transmission system during periods when reserve margins are tight, reducing AS costs.	VPP directly provides operating reserves to the system operator, displacing more expensive reserve supply options.	VPP reduces loading or provides AS in transmission-constrained areas that have higher AS prices.
Transmission capacity deferral	VPP reduces net loading on the transmission system during periods that trigger reliability violations, reducing the need for new transmission upgrades to meet reliability standards.	No supply service.	VPP reduces net loading in areas that are transmission-constrained and may have higher marginal transmission costs.
Distribution capacity deferral	VPP reduces net loading on the distribution system during periods that trigger reliability violations, reducing the need for new distribution upgrades to meet reliability standards.	No supply service.	Distribution capacity deferral is a local grid service, but even within a distribution company's territory some parts of its distribution system may be more constrained than others.

The value of these services could be compensated through wholesale prices, retail rates, or DR and other programmes. In China, most provinces have time-of-use (TOU) retail prices and demand charges that reflect some generation capacity, energy and transmission and distribution capacity deferral value, including possibly local value.

Provincial wholesale markets reflect system energy and, in some cases, AS value and capacity values. However, current wholesale market designs do not reflect local values and, to our knowledge, do not compensate for transmission and distribution deferral value. That said, some existing DR programmes may reflect system and local RA value and transmission capacity deferral value.

We discuss how retail rates, wholesale prices and programmes in China could be reformed to reflect a broader range of system and local values in the next section.

NYISO primer

In the United States, the state of New York provides a helpful illustration of the value of local services and how they can differ substantially from wholesale value at the system level. The New York Independent System Operator (NYISO) control area is organized into 11 load zones. Each zone has different capacity market prices, locational marginal energy prices (LMPs), and, in some cases, locational AS prices. Many of the zones in southeast New York are transmission-constrained, with two zones in particular subject to significant transmission constraints: New York City and Long Island. As a result, these two zones generally have higher capacity market prices, LMPs and AS prices than the rest of the NYISO system. This means that a VPP in New York City or Long Island will have higher value and opportunity for higher compensation than a VPP in upstate New York.

To account for the higher value of VPPs in transmission-constrained areas like New York City and Long Island, revenue streams (incentives) for VPPs in these areas should also be higher than in other areas of the electricity system — and indeed this is the logic of the locational price design in NYISO. The next section will expand on how retail rates, wholesale rates and programmes can be designed to reflect the full stack of values and incentivize VPPs in higher-value zones, with examples from New York State.

Virtual power plant compensation models

In general, there are three compensation models to support VPPs: (1) retail, (2) wholesale and (3) programmatic. These models differ in their incentives and time horizons (i.e., how far in advance of an operating window incentives are set).

At a high level, time horizons can be categorized into (a) planning horizons and (b) operating horizons. For instance, retail rates are typically set on a planning horizon (months to years in advance), whereas wholesale energy prices are determined on an operating horizon (minutes to days in advance). There is a trade-off in accuracy and outcomes between these two horizons: setting incentives closer to the operating horizon will more accurately reflect system conditions (such as changing weather conditions), but some customers will not be able to respond on shorter time horizons.

Because of these kinds of trade-offs, the three models described below may be complementary — using a combination of models to support VPPs may help to balance VPP scale and effectiveness and reduce risks to grid companies, consumers and VPPs themselves. Moreover, doing so would compensate VPPs for the full range of values they could potentially provide to the grid, thus fostering the long-term financial sustainability of this sector.

Retail model

In the retail compensation model, VPPs earn revenues by reducing demand in, or shifting demand away from, time periods with higher retail energy prices and higher retail demand charges. In provinces with TOU prices and demand charges, VPPs are already able to participate in this model.

Box 1 shows the example of TOU rates for industrial, commercial and residential customers in Shanghai Municipality. Smaller industrial and commercial customers can choose between a single-part TOU rate or a two-part rate with TOU prices and a demand charge;[7] larger industrial customers only have a two-part rate.[8,9]

[7] A two-part rate is a pricing structure that separates a customer's bill into fixed charges and variable charges. The fixed charge is designed to recover fixed costs, such as infrastructure costs, whereas the variable charge is a per-unit charge based on the amount of electricity consumed.

[8] Shanghai is also one of the leading cities that compensate VPPs through programmatic payment. For instance, see 上海市经济和信息化委员会. (2020). 关于同意进一步开展上海市电力需求响应和虚拟电厂工作的批复. https://www.shanghai.gov.cn/nw49248/20200920/15f042adfcdc48e29124235a8e6f7dc2_65719.html

[9] 上海市人民政府, n.d.,上海市销售电价表, https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fwww.shanghai.gov.cn%2Fcmsres%2Fbd%2Fbdef6cb5da0745ac901a1a3a89194719%2Fd3975ef3b153d6c151802eb2066dc1b8.xlsx&wdOrigin=BROWSELINK

Box 1. Virtual power plant retail model case study: Shanghai

The table below shows summer and winter peak/off-peak TOU prices and demand charges for a small (< 1kV) industrial customer in Shanghai.

Table 2. Comparison of seasonal TOU prices in Shanghai

TOU period	Summer		Winter		Demand charge (yuan/kW-mo)
	Price (yuan/kWh)	Time intervals	Price (yuan/kWh)	Time intervals	
Peak (高峰)	0.940	8-11, 13-15, 18-21	0.912	8-11, 18-20	34.02
Shoulder (平时)	0.591	6-8, 11-13, 15-18, 21-22	0.562	6-7, 11-17, 21	
Valley (谷时)	0.218	1-6, 22-24	0.270	1-5, 22-24	

Based on these rates, a VPP that can shift 4 hours of load from peak to off-peak periods on 260 days per year (130 summer and 130 winter days) could save 709 yuan per kW per year (= [0.940 yuan/kWh – 0.218 yuan/kWh] × 4 hrs/day × 130 days/yr + [0.912 yuan/kWh – 0.270 yuan/kWh] × 4 hrs/day × 130 days/yr).

If the VPP can reduce its peak demand uniformly in each month, for each kW of demand reduced the VPP can lower costs by 408 yuan/kW/yr (= 34.02 yuan/kW/mo × 12 mo/yr).

These 1,118 yuan/kW/yr in total savings (revenues) can be compared against VPP costs (including charging losses and customer payments) to determine whether revenues would be greater than costs. Shanghai's TOU price differentials are reasonably high but may not be high enough, at least not yet, to attract significant investments in VPPs.

One strategy for increasing retail incentives for VPPs would be to refine TOU rates by including more seasonal and temporal granularity in TOU periods and higher price differentials in some periods that better reflect long-term and short-term marginal system costs. For example, this might include a summer and winter peak month with a much larger (e.g., 2-3 yuan/kWh) differential in peak and off-peak rates that reflects the cost of adding new generation, transmission and distribution capacity (marginal capacity costs).

Although demand charges are not the most optimal tool to provide timely and accurate signals to consumers, there is still some room to refine existing rate structures to align incentives with compensation. If demand charges are primarily intended to provide marginal cost-based incentives, they could be based on transmission or distribution system coincident peak rather than customer peak, whereas if they are mainly intended to collect embedded costs they could be based on customer peak.

In addition, retail rates to support VPPs can (and should) be designed to reflect local costs. For instance, a well-designed cost-reflective VPP retail rate in Guangzhou may be much higher than a retail rate in other parts of Guangdong, reflecting Guangzhou's higher long-term marginal costs for supplying electricity. At a more granular level, ideal retail rates in some parts of Guangzhou may also be set higher than in other parts, in order to reflect distribution system constraints.

VPP rates should be compared against embedded and marginal costs to ensure that they balance cost recovery and incentives and are still lower-cost than new supply or new network infrastructure. In designing rates for VPPs, care is needed to balance incentives for avoiding high marginal cost periods and the potential for shifting fixed costs onto other customers.

International example

One example is New York State's proposed Full Value Tariff (FVT), which includes a small customer charge ($/customer) for administrative costs, demand charges ($/kW-month) for embedded costs and dynamic (time-varying) volumetric charges ($/kWh) for marginal costs. The proposed FVT includes local costs, with dynamic prices that could vary both across and within zones.

Across the United States, policymakers and stakeholders have expressed concern about rate designs like the FVT, saying that they are too complex and customers will not be able to respond to them. However, VPPs have professional management that should be able to handle complexity. As VPPs gain experience in customer acquisition, load optimization and compensation model development, policymakers may accept that these kinds of rates could become more widespread in the United States.

Wholesale model

In the wholesale model, VPPs earn revenues through wholesale prices for RA capacity, energy, AS, transmission and distribution. These prices could be transmitted through a wholesale tariff, in which case the VPP would not participate directly in the wholesale market but its compensation would be settled at wholesale market prices. (We discuss these kinds of wholesale tariffs in the *Programmatic model* section.) The main focus for this section is VPPs that directly participate in the wholesale market, submitting supply offers and demand bids in capacity, energy and AS markets.

In China, a growing number of provinces allow VPP participation in wholesale markets. For instance, Shanxi's market rules allow VPPs to participate in both the medium and long-term (MLT) contract market and the day-ahead spot energy market.[10] In real time, VPP loads are settled based on actual metered consumption.

[10] See 山西电力市场规则体系V14.0, http://www.sx.sgcc.com.cn/lf/docs/202403/17105012804315O347.pdf.

Shanxi's market design has a three-settlement system, which means that day-ahead quantities (MWh) are settled incrementally relative to MLT quantities at day-ahead prices (yuan/MWh), and real-time quantities (15-minute MW) are settled incrementally relative to day-ahead quantities at real-time prices. When day-ahead energy prices are lower than MLT prices, the VPP can direct its aggregated loads to increase scheduled load; when day-ahead prices are higher than MLT prices, the VPP can direct its loads to reduce scheduled load. In other words, a VPP's changes in load are bounded by MLT contracts. If day-ahead changes in net load deviate too much from the MLT contracted amount (no more than 120% or less than 70% of the of the contracted amount), the VPP pays a penalty.

For instance, if MLT prices are 350 yuan/MWh, the day-ahead price (at a particular hour) is 200 yuan/MWh and real-time prices in that hour are 250 yuan/MWh (average hour-ahead forecast), a VPP with 50 MW of contracted MLT load and 10 MW of load flexibility would direct its customers to increase load by 10 MW and maintain load in real time. Its final settlement would be 20,000 yuan/h (= 350 yuan/MWh × 50 MW + 250 yuan/MWh × [60 MW – 50 MW] + [60 MW – 60 MW] × 250 yuan/MWh); relative to MLT prices (60 MW × 350 yuan/MWh = 21,000 yuan/h), the VPP will have saved its customers 1,000 yuan/h. The net income to VPPs for shifting load to respond to market prices will be a share of customer savings. In this model, VPPs thus play the role of a sophisticated retail provider.

In Shanxi and Shandong, VPPs can participate in day-ahead energy markets but are not settled at nodal prices, even though both provinces have nodal dispatch and LMPs. Instead, and as with loads, VPPs are settled using an aggregated weighted average of LMPs. Although this approach provides a foothold for direct participation by loads in wholesale markets, it does not compensate VPPs for the larger suite of services (including local services), resulting in less-than-ideal compensation for VPPs.

For instance, a VPP that can shift 1 MW of load for four hours per day capturing an average MLT-day-ahead price spread of 50 yuan/MWh in these hours over the course of a year will earn 73 yuan/kW/yr (= 1 MW × 4 h/d × 50 yuan/MWh × 365 d/y × 1 MW/1,000 kW), which is likely to be significantly less than it could earn through providing load shifting retail services (see *Retail compensation model*, above).[11]

Allowing VPPs to provide multiple local services (for example, a combination of local energy and local DR), with settlement based on more disaggregated LMPs and local DR needs, would likely better compensate VPPs for the true value of services that they provide – and thus expand the revenue streams available to VPPs.

[11] The example in the *Retail model* section is from Shanghai, which has higher electricity prices than Shanxi, but this hypothesis likely holds regardless. The main difference between retail and wholesale is that retail rates will generally include a larger amount of generation and transmission capacity-related costs relative to the inframarginal rents in nodal energy markets.

International example

New York's electricity market illustrates how locational price signals can be designed as part of wholesale generation capacity, energy and AS prices, and how VPPs can participate in these markets. NYISO's market rules allow VPPs and other demand-side aggregations to participate directly in capacity, energy and AS markets and be settled at local market prices.

Capacity market

The NYISO capacity market clears zonally, in each of 11 load zones. Due to transmission constraints among zones, some zones or groups of zones (such as New York City and Long Island) have a requirement to procure certain percentages of their capacity within their zones. This ensures that in transmission-constrained zones there are enough local capacity resources to meet peak demand.

As a result, the capacity prices vary across different localities, with prices in certain zones being significantly higher than in the rest of the state. VPPs that provide RA in these zones can earn higher revenues than those in other parts of the state, reflecting the higher value of RA capacity in these zones.

Ancillary services markets

NYISO's operating reserve markets include 10-minute spinning and non-synchronized reserves, 30-minute spinning and non-synchronized reserves, and frequency regulation reserves. VPPs are eligible to provide some of these reserves, depending on VPP dispatchability, characteristics and other obligations.

NYISO's operating reserve markets are based on zonal reserve requirements (also 11 zones) and clear zonally, which means that zones with higher reserve costs will tend to have higher AS prices. VPPs that provide AS in these zones can earn higher AS revenues than in other parts of the state.

Energy markets

NYISO energy markets clear nodally and have three components: marginal energy price, marginal loss price and marginal congestion price.

Market entities are settled using LMP at different spatial resolutions. Generators are settled at generator bus node prices; aggregators (including VPPs) are settled at transmission nodes (collections of designated load buses); and loads are settled at zonal prices, using the load-weighted average of nodal prices within the zone. These design choices attempt to balance the granularity of the locational price signal with practicality of implementation.[12]

For VPPs, settlement at transmission node prices means that VPPs that operate in transmission nodes (or load zones) that are influenced by significant congestion will have higher energy market revenues. A VPP in New York City, for instance, will have higher energy market revenues than a VPP in northern New York.

Programmatic model

In the programmatic model, VPPs earn revenues by providing DR and potentially other services to grid operators or retail companies in exchange for payments. As of now, in China most VPP revenues come from their participation in DR programmes.

Jiangsu Province provides a good illustration of how VPPs participate in DR programmes. Jiangsu's DR programme rules allow VPPs to respond to DR calls by provincial DR management centres, which are subsidiaries of the provincial grid company. Eligible VPPs must have a total dispatchable capability greater than 10 MW and be able to support DR events longer than two hours. At least on paper, municipal- and district-level development and reform commissions can also initiate DR calls when local supply conditions are tight.

Jiangsu's programme has three types of DR resources:

- Scheduled DR — mostly interruptible load that responds on a day-ahead timescale.
- Fast-ramping DR — responds within four hours of notice.
- Real-time DR — responds automatically or semi-automatically within 30 minutes of dispatch signal; usually includes resources like energy storage, EV charging, some industrial load, and smart thermostats.

The provincial DR management centre organizes DR supply auctions mainly to meet summer and winter peaks. In the auction process, DR resources submit their bids, and the provincial DR management centre creates a DR dispatch list in the order of increasing bid price. DR resources are compensated per kWh according to their bids except for real-time DR, which receives an additional 10 yuan/kW capacity payment (paid even if not actually dispatched; if dispatched, the payment is performance-based). Funding for DR payments mostly comes from a summer critical peak adder in the TOU rate.

DR programmes like Jiangsu's can provide an adequate compensation model for VPPs as long as supply conditions are tight and DR calls are semi-regular. However, when DR calls are less frequent, VPP revenues will also be intermittent, creating financial challenges for VPPs.

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[12] Kumar, S. (2024). *Locational based marginal pricing.* NYISO. https://www.nyiso.com/documents/20142/3037451/3-LMBP.pdf/f7682e03-e921-eaab-09bf-690524b5ade6.

Additional sources of revenue – such as price arbitrage of retail rates or wholesale market prices or AS provision – could help to support VPPs when DR calls are less frequent. For instance, a VPP that earns 200 yuan/kWh of DR, that is called five times per year and provides four hours of DR per call, will earn 4,000 yuan/kW/yr (= 400 yuan/kWh × 4 h/call × 5 calls/y); but if this all occurs in year three of a five-year time horizon and the VPP has no revenues in other years, its discounted annual revenues will be only around 800 yuan/kW/yr (assuming a 10% discount rate).

An alternative approach to direct VPP participation in wholesale markets might be a wholesale market tariff (also called real-time tariff) for VPPs, which links the tariff with the near-real-time market clearing price, described below in the context of New York. For VPPs that do not yet participate directly in wholesale markets, a wholesale tariff that includes local values could be a reasonable way to approximate the value they bring to the grid.

International example

New York has several programmes that VPPs and other demand-side resources can participate in, including a wholesale tariff and DR programmes. New York's Value of DER (VDER) tariff is a wholesale tariff used to compensate distributed energy resources for the value they provide to the transmission and distribution grids. Table 3 describes each value in the VDER 'value stack.'

Table 3. New York VDER Components

Component	Targeted value to capture	Calculation methods
Energy value	Energy commodity offset by each kWh	Day-ahead hourly location-based marginal pricing (LBMP)
Capacity value	Installed capacity purchase requirement offset	Capacity market prices
Environmental value	Renewable energy certificate compliance cost offset	Renewable energy certificate procurement price or social cost of carbon
Demand reduction value (DRV)	Distribution upgrade costs offset	Based on utility cost of services studies. Utility defines total avoided distribution upgrade costs and spreads the cost in peak hour windows. Similar to critical peak pricing.
Locational system relief value (LSRV)	Higher, more locational specific distribution costs offset	Based on utility cost of services studies. Available only in locations where the utility has been identified as having needs that can be addressed by DERs. DERs are credited based on dispatch during at least 10 peak-period calls per year. Similar to variable critical peak pricing.

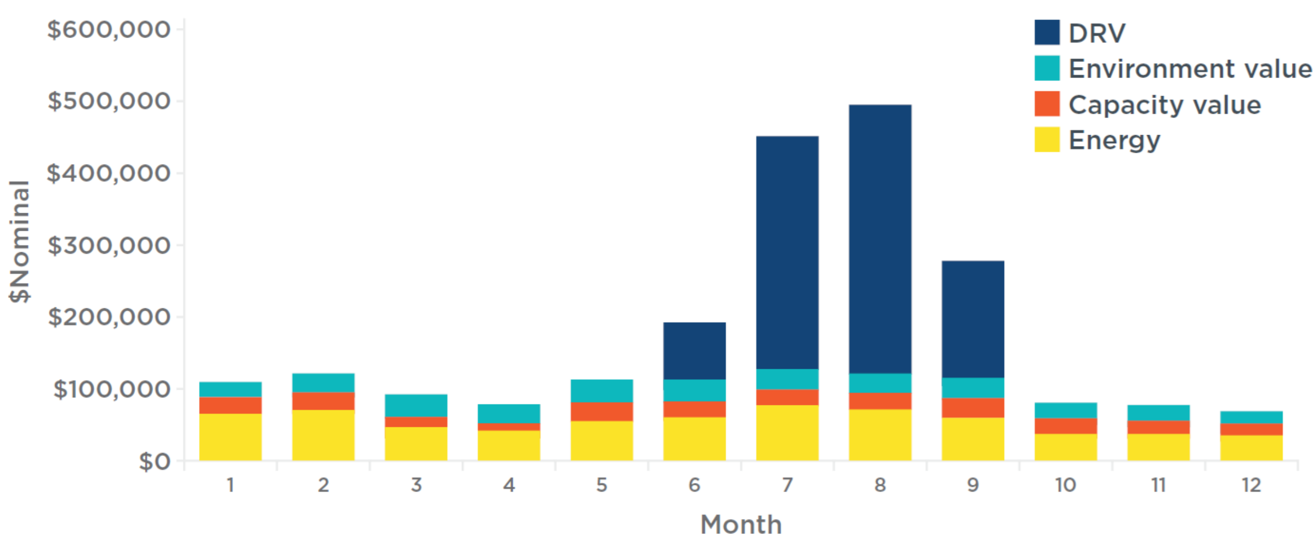
All of the components of VDER include local value — energy value is based on LBMPs, capacity value is based on zonal capacity prices, demand reduction and locational system relief also capture locational marginal transmission and distribution costs. Although VDER has mostly been used for distributed generation, it could in principle be applied to any form of VPP.

VPP participation in wholesale tariffs like VDER can be combined with participation in other programmes, but programme design should ensure that VPPs are not over-compensated; for instance, if RA capacity value is already included in a wholesale tariff, VPPs should not also be compensated for participation in DR programmes.

In New York, utilities typically also run DR and other programmes. Utilities sign up customers to participate in these programmes by offering incentives, which are based on avoided (reduced) costs to customers. For instance, if capacity market prices are expected to be USD 10/kW/month in summer months, the utility might sign up customers who are willing to reduce load during specified time periods in those summer months for less than USD 10/kW/month. Because capacity market prices are zonal, utilities in import-constrained zones with higher prices are willing to spend more on DR and other programmes than other utilities.

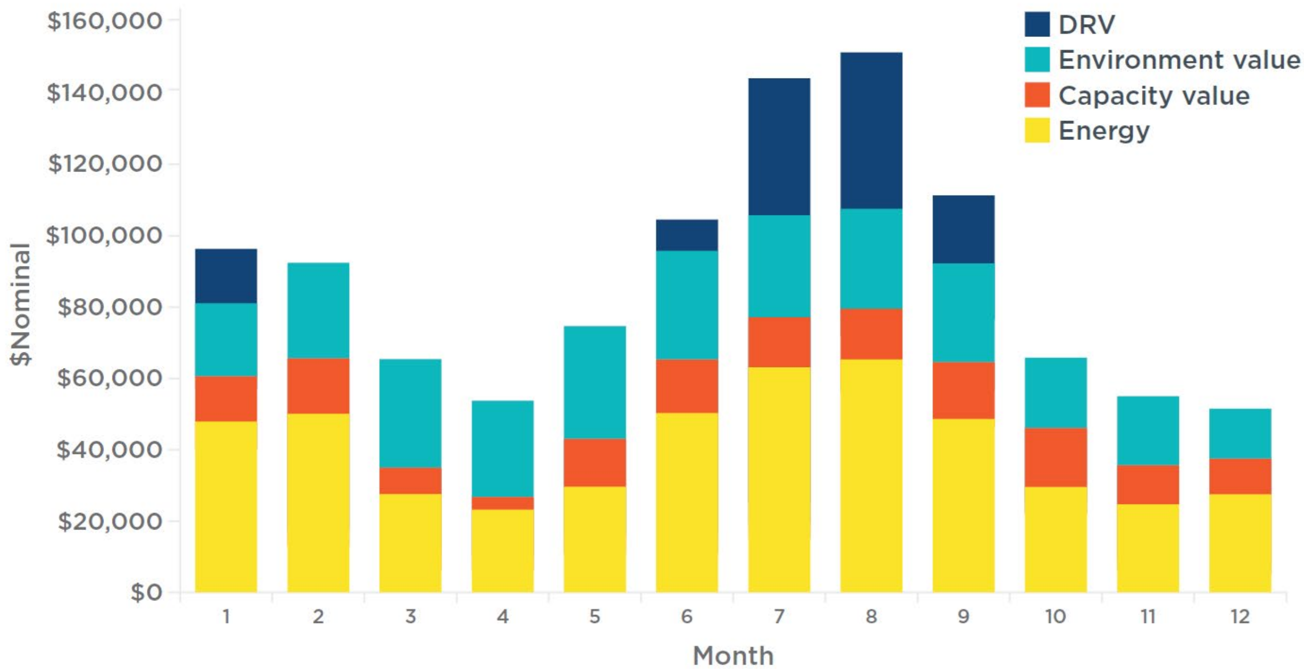
In the United States, most DR and other utility programmes are targeted at the capacity constraints of the transmission system rather than the distribution system. On the distribution system, utility operators in the past have felt that DR was not concentrated or dependable enough to manage real-time operating constraints. However, following improvements in grid technologies (monitoring, communications and control) and customer engagement, some utilities are now considering or designing DR programmes that target distribution-level constraints, in order to defer distribution investments. Figures 1a and 1b show the full-stack value of a VPP consisting of 5,000 kW of solar and 12,000 kWh of battery storage located in New York City (1a, top) and Central Zone (1b, bottom), generated using NY-ISO's Value Stack Calculator developed by E3.[13]

Figure 1a. Monthly variation in project value by value stack component in NYISO New York City Zone



[13] NY-ISO. (2024). *Value stack calculator.* https://www.nyserda.ny.gov/All-Programs/NY-Sun/Contractors/Value-of-Distributed-Energy-Resources/Value-Stack-Calculator

Figure 1b. Monthly variation in project value by value stack component in NYISO Central Zone



As an illustration, despite differences in energy and capacity values due to grid constraints, one significant differential in values for identical VPPs in New York City and somewhere in central New York State is the demand reduction value (DRV), or the avoided distribution system upgrade costs. For the month of August, the avoided distribution costs in New York City are roughly 20 times higher than those in central New York State. While this is a stylized example, it is clear that if the local values of VPPs are not compensated fairly, there will be little to no incentive for investors to set up VPPs in places that could benefit the most from them.

Summary and recommendations

VPPs in China provide valuable services and, if fully compensated, can grow significantly, lowering system costs and emissions and improving reliability. New compensation models, however, may be needed to accelerate and sustain their commercial scale-up. A critical barrier is the lack of sustainable funding, due in part to the fact that current compensation models do not fully compensate the multiple, especially local, values that VPPs can provide to the transmission and distribution systems. This paper explores potential solutions to this challenge in three kinds of VPP compensation models: retail, wholesale and programmatic. For each model, we identify VPPs' value proposition and outline concrete steps to unlock the value of VPPs in the context of China's electricity markets, regulation and industry structure. In some instances, VPPs may be able to combine multiple models, as we describe below.

Retail model

In the retail model, VPPs earn revenues by decreasing net load (load + storage charge – distributed generation – distributed storage discharge) during periods of high retail prices and demand charges, and shifting net load from higher to lower retail price hours. VPPs can already operate using the retail compensation model in most of China — and, in a few cases, TOU rates and demand charges are already high enough to enable substantial revenues for VPPs. However, in most provinces TOU price differentials and demand charges may not yet be high enough to support VPPs, and retail rates do not incorporate local costs. To better compensate the local value of VPPs, provincial governments can consider the following steps:

- *Enhance existing TOU rates*. Consider larger TOU price differentials by ensuring the rates fully reflect the marginal costs of new generation, transmission and distribution capacity. This can provide a stronger price signal for VPPs to shift net load.

- *Refine existing demand charges*. Base demand charges on locational marginal costs for generation, transmission and distribution, and on coincident peak (rather than individual customer peak) demand. This would align demand charges more closely with actual grid stress points and marginal costs.

- *Implement localized retail pricing*. Develop city- and district-level TOU rates that accurately reflect local grid operation and investment costs, particularly in areas with transmission constraints. Local retail rates would more closely align prices with local costs.

- *Exempt residential customers if necessary*. If applying complex rate structures to all customers proves challenging, design multi-part (fixed + demand + volumetric charges) retail rate VPPs that target big industrial and commercial consumers first. VPPs are, by definition, able to optimize net load around retail price differences that most customers would not be able to respond to.

Wholesale model

In the wholesale model, VPPs earn revenues by providing RA, energy, AS and other grid services through wholesale markets. At least two provinces now allow VPPs to participate in MLT and day-ahead energy markets. However, annual revenues from arbitraging average MLT and day-ahead energy market prices — as the mechanisms are currently designed — may be too low to support viable business models for VPPs. To more fully compensate VPPs (and enable higher and more diverse revenue streams), provincial governments can consider the following steps:

- *Enable settlement at LMPs*. Ideally, VPPs should be settled at local market (nodal) prices, which would provide more accurate locational price signals and encourage more efficient resource allocation, especially in transmission-constrained regions. However, settlement granularity must be balanced with practical constraints, including the challenges of aggregating resources at individual nodes and cost-shifting considerations. As in New York, VPPs in China could be settled at aggregations of nodes (e.g., at sub-provincial zones) rather than provincial average prices, though in general the more the aggregation the less precise the price signals.

- *Allow VPPs to provide and be compensated for multiple services*. Allowing VPPs to provide and be compensated for other services, in addition to energy arbitrage, would strengthen the VPP business model. Provinces in China do not yet have competitive capacity markets open to VPPs. In addition, VPPs could participate in wholesale energy markets and provide programmatic DR. Doing so would help to diversify revenue sources for VPPs and expand their services. If provinces do develop capacity markets, programmatic DR could be transferred to capacity markets. If VPPs are eligible to provide capacity, energy, AS and programmatic DR, market rules will need to ensure that VPP capacity is not being used for energy and reserves at the same time, or for conflicting transmission and distribution services at the same time. These are likely longer-term considerations.

Programmatic model

In the programmatic model, VPPs provide services — typically DR services, currently — to grid companies or retail providers through programmes in which the grid company or retail provider pays the VPP for services. DR programmes are widespread in China and VPPs are often allowed to participate in them. However, DR programmes are not often used for local needs — for instance, a transmission-constrained city that is also supply-constrained. Local DR programmes could provide additional revenue for VPPs and help them to target areas that are transmission and supply-constrained. Additionally, other kinds of programmes, such as wholesale tariffs, could help to support business models for VPPs. To expand the benefits of VPP participation in programmes, provincial and local governments can consider the following steps:

- *Localize existing DR programmes*. Experiment with municipal or district DR programmes in areas that have higher-than-average rates of load curtailment. Local DR programmes could be deployed when local demand exceeds local supply, if transmission import constraints bind, or when system demand exceeds system supply. Local DR programmes would, in principle, increase the number of DR calls and thus would increase VPP revenues.

- *Implement a wholesale tariff*. Consider implementing a wholesale tariff for VPPs, similar to New York's VDER tariff. This tariff could include local capacity, local energy, environmental, local transmission and distribution values. VPPs could participate in the tariff and other programmes, but government agencies should ensure that VPPs are not compensated more than once for the same service (e.g., for RA capacity in the tariff and in DR programmes).

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