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Abstract

Distributed energy resources ("DERs") are being adopted throughout the world. These technologies have the potential to not only deliver the valuable electricity services that have traditionally been provided by centralized generating units, but also new services enabled by their distributed nature. Aggregators are being lauded as critical in enabling DERs to provide these valuable electricity services at scale; in this light, regulatory and policy bodies are discussing the role of aggregators and even the need to support their market entry. In order to shed light on this debate, this paper reflects on the economic fundamentals of aggregators. We perform a critical review of the potential value of aggregators, defining the factors that is determining and will determine their role in power systems under different technological and regulatory scenarios. We identify three categories of value that aggregators may create: fundamental, transitory, and opportunistic. Fundamental value (e.g. economies of scale) is intrinsic to aggregation and is independent of the market or regulatory context. Transitory value may be diminished by technological or regulatory advances; for example, "energy boxes" that automate market interaction could mitigate the value in aggregators doing so. Opportunistic value emerges as a result of regulatory or market design flaws and may endanger the economic efficiency of the power system.

Keywords: *Value of Aggregators; Aggregation; Aggregators; Distributed Energy Resources; Fundamental Value; Transitory Value; Opportunistic Value; Regulation; Market Design; Solar PV; Demand Response; Energy Storage; Electricity Retail.*

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1 Introduction

Electricity systems are currently facing significant changes as a result of the deployment of information and communication technologies (ICTs), power electronics, and distributed energy resources (e.g., gas-fired distributed generation, solar PV, small wind farms, electric vehicles, energy storage, and demand response). Distributed energy sources (DERs), unlike "traditional" centralized generating units, are characterized by their small capacities, and their connection to low and medium voltage electricity distribution grids. These technologies have the potential to not only deliver the valuable electricity services that have traditionally been provided by centralized generating units, but also new services enabled by their distributed nature. Many industry stakeholders claim that DER aggregators create economic value by enabling DERs to provide these services at scale [1–5].

Citing the untapped value of aggregators, regulators and policy makers in both Europe and the United States are debating the role of aggregators. In Europe's liberalized retail markets, debate is centered around the functioning of retail markets, the ability of retailers[1] to deliver desired levels of consumer engagement and value-added services, and therefore the value or disvalue of superimposing third party aggregators over these retailers [5–7]. On the other hand, new independent aggregators are flourishing in U.S. markets, and stakeholders are attempting to design market rules to ensure these aggregators flourish due to true value creation and not regulatory arbitrage [8,9]. Clarifying these debates requires an understanding of the mechanisms by which aggregators create value, for it has implications for pertinent questions such as: should the power system accommodate many aggregators or only one centralized aggregator? Who can or should be an aggregator (transmission and distribution system operators, retailers, third parties, etc.)? What market design elements may need to be adapted or adopted to accommodate DERs? What is the "best feasible level of unbundling"?

To begin to answer these questions, this document establishes a "rational template" with which to analyze the role of aggregators in power systems. We argue that, in a hypothetical world with "perfect" information, economically rational agents,[2] and "perfect" regulations, aggregators will only create value

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[1] Retailers or retail electricity providers (REPs) are aggregators in that they aggregate a number of disperse consumers (and, at some times, producers) and act as a liaison between these agents and wholesale markets. These REPs also comply with power system regulations, perform hedging functions, and other activities on consumers' behalf. Some REPs, such as MP2 Energy in the U.S., are performing roles traditionally attributed to third party aggregators such as brokering demand response for capacity and ancillary services market participation [48].

[2] In this paper we refer to agents as opposed to consumers, producers, or the oft-referred to "prosumers." The term agent refers to all three of these possibilities. Agents can own and operate DERs and therefore they can become active parties in the power system.

by capitalizing on economies of scale and scope and by managing risks (we term these "fundamental values"). We note that maximizing the benefits of these sources of value could lead to a single, centralized aggregator, which might harm other power system objectives such as competition, agent engagement, and innovation; thus, the role of aggregators would be determined by analyzing the tradeoffs between fundamental values and the value of competition. Recognizing that we are far from this hypothetical perfect world, we identify "transitory" values of aggregation that may exist as power system technologies and regulations advance. Finally, we identify a number of regulations and market designs that create "opportunistic" aggregations; these opportunistic aggregations impair as opposed to enhance power system economic efficiency.

1.1 Defining aggregators

Aggregation is defined here as the act of grouping distinct agents in a power system (i.e. consumers, producers, prosumers, or any mix thereof) to act as a single entity when engaging in power system markets (both wholesale and retail) or selling services to the system operator(s). This paper adopts the definition of an aggregator promulgated by Ikäheimo, Evens, and Kärkkäinen [10][3]; in the context of this paper, *"an aggregator is a company who acts as an intermediary between electricity end-users and DER owners and the power system participants who wish to serve these end-users or exploit the services provided by these DERs"*. We recognize the existence of other definitions of aggregators; in practice, the definition of an aggregator can be restricted or expanded depending on regulations that define the roles and activities that aggregators can perform.

1.2 The present and future value of aggregation

One may hypothesize that, at some point in the future, the present limitations of the power sector (i.e. incomplete information, imperfect coordination of responses of all agents to economic signals, and economically irrational price responsivity) may disappear due to advanced regulation and technological innovation, among other reasons. It is possible that DER aggregators may only create value temporarily as the power system transitions to this ideal future. This document addresses the question of whether aggregators can provide value to the power system as a whole, or whether they provide

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[3] Ikäheimo et al. define an aggregator as "a company who acts as intermediator between electricity end-users, who provide distributed energy resources, and those power system participants who wish to exploit these services" [10]

value to a small set of agents while harming others. Furthermore, this document attempts to identify whether the value (or disvalue) created will exist temporarily or on a more fundamental basis.

To answer the question of for whom aggregation creates value, this paper discusses two types of economic value: private and system. Aggregation has system value if it increases the economic efficiency of the power system as a whole [11]. Private value is simply an increase in the economic wellbeing of a single agent or subset of agents. Private value creation may or may not align with system value creation; as we will demonstrate, aggregations with private value may create economic value for certain agents at the expense of system-wide economic efficiency. Alternatively, aggregation may simply lead to a rent transfer between market actors.

We can distinguish three broad categories of aggregation (see Figure 1-1). First, aggregations with *"fundamental"* or "intrinsic" value do not depend on the specific regulations, level of market awareness of consumers, or technologies in place in the power system, and will be permanent or near permanent in time. Aggregations with *"transitory"* value contribute to the better functioning of the power system under the present and near-future conditions; however, the value of transitory aggregations may wane as technical, managerial or regulatory conditions improve. Finally, aggregations with only *"opportunistic"* value emerge in response to regulatory or market design "flaws." Due to inherent tradeoffs in regulatory principles, there is no single ideal regulatory system. Regulations on system design and operations are inherently plagued by imperfect or asymmetric information, technology constraints, political interferences and conflictive regulatory principles, among other factors, which open the door to different levels of arbitrage. Different examples of these regulatory or market imperfections are present in different markets as shown in Figure 1-1. As indicated in the figure, aggregations creating transitory value may exist both now (under current regulatory and technology contexts) and in the future (under advanced but "imperfect" regulations and advanced technologies).

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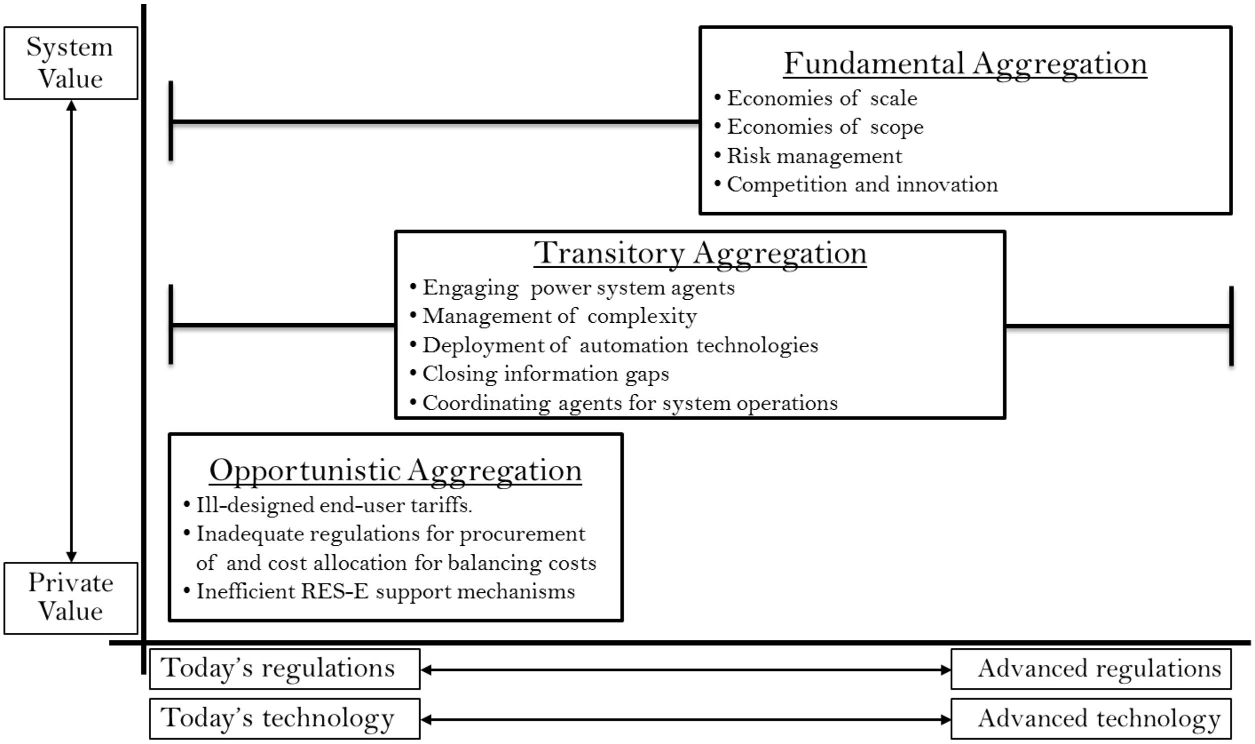
Figure 1-1: Value of aggregators based on technology and regulatory contexts



The following sections attempt to identify the ways in which aggregation can create fundamental, transitory, or opportunistic value. Where aggregation creates fundamental or transitory value, regulators or policy makers may want to take steps to remove barriers to its realization or to encourage it outright. However, where aggregation only creates private opportunistic value, regulations should be modified, unless this fact is explicitly acknowledged and desired as a form of subsidy.

2 The fundamental value of aggregation

Fundamental value stems from factors inherent to the act of aggregation itself. While regulation and policy may influence whether or not this value is captured and by whom, the value itself is regulation, policy, and agent-independent. In the context of the power system, aggregation may create fundamental value through capitalizing on economies of scale and scope and by managing uncertainty. However, these fundamental value streams must be weighed against transitory value streams that may emerge from the presence of competing aggregators. Competition may incentivize aggregators to provide customized and innovative solutions to agents, engage otherwise unengaged agents, enable the optimal adoption of DERs, and enable active participation in electricity markets. We discuss some of the benefits of competition below, and further discuss them in Section 3.

2.1 Economies of scale and scope

Participating in electricity services markets involves incurring certain unavoidable costs. First, one must acquire or engage the owner of one or more energy resources (either centralized or distributed resources); second, if these resources are to interact with the market, they must be equipped with some level of information and communications technologies (ICT); third, these resources and their owners must comply with power system regulations and market rules. Many of these costs include fixed and variable components. The existence of fixed costs may lead to the average cost of service provision being higher than the marginal cost of service provision and therefore declining average costs of service provision as the quantity of services provided increases. Thus, to the extent that there are fixed costs to participate in electricity services markets, there may be value in aggregation via economies of scale. Furthermore, to the extent that there are common technologies, transaction costs[4], acquisition costs, or knowledge-bases for the provision of multiple services or products, aggregation may create value through economies of scope.

There is no question about the economic reality of economies of scale and scope; the question is if these factors would dictate that aggregation should continue to the point where there is only a single aggregator (e.g. the ISO or DSO)[5], or if it is more efficient or desirable (e.g. for competition, innovation, limited economies of scale and scope, or other reasons) to have intermediate levels of aggregation from non-monopoly aggregators.

2.1.1 Sources of economies of scale[6]

There are often fixed transaction costs associated with participating in a market (both as a service provider and procurer), such as registering within a system or acquiring required insurance against economic losses. For example, Ofgem's Standard License Condition (SLC) 11.2 requires licensed electricity suppliers (i.e. retailers) to "become a party to and comply with the Master Registration

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[4] A transaction cost is any cost that an agent has to incur in making an economic transaction. These can involve searching costs (e.g. searching for information) and enforcement costs (e.g. ensuring that a certain amount of energy has actually been provided once contracted for), among others.

[5] Of course, regulations may dictate the maximum feasible level of aggregation. For example, because of unbundling regulations (in the European and in certain U.S. contexts), ISOs/ TSOs and DSOs may not be able to act as aggregators. Furthermore, the benefits of competition amongst multiple aggregators should be balanced against the benefits of economies of scale and scope.

[6] This section refers only to the sources of economies of scale that drive the aggregation for operations. Economies of scale are well documented in energy generating technologies. A generator may wish to "aggregate" customers such that it can sign long-term contracts with them and build a larger generating unit. However, this function of aggregation is not considered herein.

Agreement; the Distribution Connection and Use of System Agreement; the Connection and Use of System Code; and the Balancing and Settlement Code" [12]. The costs of complying with these codes[7], according to Ofgem, "are largely fixed and for a small supplier or DE [distributed energy resource] scheme represent a high transaction cost per unit of the output sold" [12]. Some of these costs may be unnecessary or inefficiently allocated; however, assuming that these costs are efficient, there will be fundamental value in increasing the quantity of services provided or procured per market agent and spreading fixed market and regulation costs across more agents.

ICTs are required to participate in market bidding and receive control signals. Economies of scale are well documented in the ICT industry [13,14]; there will therefore be opportunities to build larger ICT systems and aggregate customers onto a single system. Indeed, cloud computing and the centralization of computing power has been lauded as a potential enabler of a more efficient, low carbon power system [15]. This is particularly relevant for the conversation regarding energy boxes[8]. It may be more economically efficient for an aggregator to centralize computing power, allowing decentralized agents to use only inexpensive computing equipment (energy boxes) and receive simple control signals. EnerNOC, a U.S.-based demand response aggregator, is an example of this paradigm; EnerNOC has a centralized "Network Operating Center" for communicating with, and, in some cases, directly controlling its DR assets. The decentralized DR assets that EnerNOC leverages are equipped with simple control technologies, and all computing is done centrally.

2.1.2 Sources of economies of scope

Many of the same costs that drive economies of scale may also drive economies of scope. Economies of scope emerge when the provision of various services or products leverage a common set of business knowledge (e.g. market operations), technologies (e.g. ICTs), or engagement (e.g. customer acquisition) costs [16]. For example, market participation costs (as highlighted above) or other transaction costs may mean that it is more efficient for a single aggregator to bundle all required services for or from a customer (e.g. energy, operating reserves, voltage control, etc.), rather than having multiple aggregators, each procuring or delivering a single service.

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[7] These costs stem from insurance requirements and reporting requirements among other things.

[8] This energy box is a hypothetical device. The European Commission's ADDRESS project defines an energy box as "the interface between the consumer and an aggregator" [4]. It is capable of, receiving simple control signals, or, in a more computationally intensive manner, carrying out the optimization and the control of the loads and local distributed energy resources at the consumer's premises. It "represents the consumer from an aggregator's perspective"[49].

Economies of scope and product bundling are present not only for electricity services but also for adjacent service sectors such as heating, gas, energy efficiency solutions, telecommunications or internet. Given the inherent costs to a service provider of acquiring and engaging a customer, bundling services may lead to economies of scope. Furthermore, service bundling can create synergies and innovative solutions that adapt to consumers' needs. Telecommunications, internet, and energy management systems could exploit the use of common devices and communication protocols. For example, in Pennsylvania, cable television and electricity services are being offered as a bundle [17].

2.1.3 Aggregators in the presence of economies of scale and economies of scope

The question, again, is not whether value from economies of scale exists, but rather, at what level of aggregation are such economies exhausted. Taking this question one step further, do economies of scale and scope dictate that aggregators decrease system value by reducing the returns on these economies?

To make this discussion more concrete, consider a scenario with 100,000 distributed agents that are capable of sending availability information to and receiving dispatch signals from an aggregator. With rapidly exhausting economies of scale, the total cost of many aggregators providing market interaction may be nearly as low as having a single agent providing market interaction; this is due to the fact that the average cost for any given aggregator could be at or near the marginal cost. With economies of scale that diminish slowly with respect to scale, multiple aggregators may significantly increase the total cost of providing market interaction, as no single aggregator will be able to offer services near the cost of one large aggregator (e.g. if the system operator were to act as a centralized aggregator). Therefore, under the presence of strong economies of scale and scope, a centralized aggregator may be the most efficient industry structure. In practice, this centralized aggregator could be the system operator, a DSO, or another regional monopoly.

Codognet [18] argues that aggregators can reduce searching costs (i.e. transaction costs) for market agents, as the aggregator can benefit from its centrality in the marketplace and from economies of scale and scope in managing information. In addition, Codognet [18] argues that aggregators can realize economies of scale and scope by spreading transaction costs over a large number of products or a variety of products. However, it is not clear as to at what scale these benefits are exhausted (i.e. with complete aggregation by a single agent or with many competing aggregators).

2.2 Managing uncertainty and price risks

Market parties have different risk preferences and capabilities to hedge against risks. A small agent may not be able to hedge against price risks, while hedging products are often available for large agents (through contracts for differences, for example)[9]. Aggregators that act as intermediaries between small consumers/producers and volatile markets may provide hedging solutions to market players. For example, in retail markets, retail electricity providers (i.e. demand aggregators) offer stabilized prices to their consumers. The value of this type of risk hedging service is discussed in Littlechild [19]. In certain markets, established retailers are hedged against price volatility through vertical integration (i.e. owing generation). Certain scholars have argued that this vertical integration decreases incentives to exercise market power in wholesale electricity markets [20]; however, other scholars have noted that this vertical integration creates barriers to entry for retailers, reducing competition [21].

As with economies of scale, the question is not whether aggregation enables the above functions, but what level of aggregation is optimal. Aggregation mitigates uncertainty by gathering all data relevant to potential demand or generation, and translating this data into quantity bids in a market. This could be done by a number of small aggregators or by a single aggregator (e.g. a system operator) for all uncertain variables in a market (e.g. the output of variable generators or the behavior of a number of consumers). Assuming that a single aggregator (e.g. a system operator) could have access to the same quality of information as intermediary aggregators, intermediary aggregators could mitigate uncertainty and provide hedging as well as, but no better than, a single aggregator.

2.3 Competition and Innovation

The above discussion considers primarily static economic efficiency, and ignores other potential benefits of having many aggregators, such as the benefits of competition, innovation, and consumer engagement. These values should be considered, and the potential benefits of competition amongst many aggregators should be weighed against the potential increases in cost from the inclusion of intermediary aggregators (stemming from lower returns to economies of scale and scope).

In this light, the role of aggregators in the electricity sector is tightly linked to the discussion on the role of retail competition in electricity markets [19,22–24]. Indeed, as aforementioned, retailers are no more than aggregators.

The arguments in favor of retail competition, mainly defended by Stephen Littlechild, are particularly relevant in the context of cost-competitive DERs [19,25]. Littlechild argues that competition among retailers (i.e. aggregators) can, due to new technologies, provide value-added services such as demand

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[9] This may be due to a number of factors including a dearth of information or of financial products for small agents.

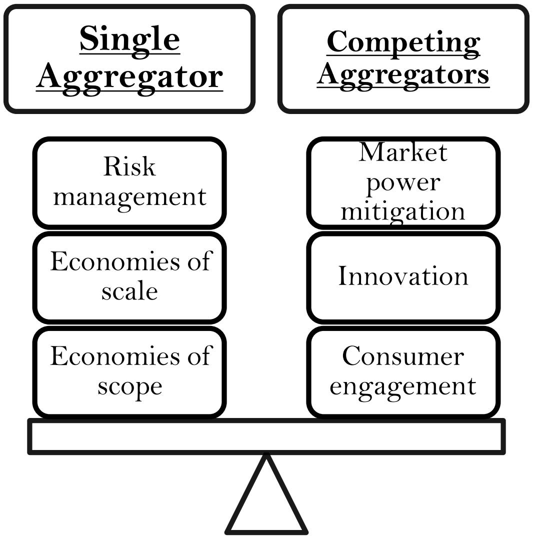
monitoring, advice, and energy efficiency products. As noted by Defeuilley [23], the role of retailers depends on the technological paradigm; in the long term, greater integration of DERs and ICT technologies will create opportunities for innovation to expand considerably [23]. With the emergence of DERs, aggregators therefore have the ability to provide a new and unexplored set of services. As aforementioned, economies of scope and product bundling with adjacent sectors (e.g. gas, heating, telecommunications and internet) enable an even wider range of innovative solutions. However, these benefits may not be available to a single aggregator (e.g. the system operator), as the single aggregator may be constrained by regulation to perform only certain functions (e.g. under today's regulations, system operators cannot control heating) or it may lack the necessary expertise or incentives.

Competitive forces should incentivize aggregators to deliver competitive prices, DERs, customized products, and other innovations where they are desired and economically viable [19,25]. These innovations can stimulate consumers to become active market players, creating further system value. For example, by utilizing existing DERs, consumers may increase their demand elasticity and mitigate market power [19]. Moreover, DERs, either directly or through aggregators, may compete with centralized generators to improve competition in supply. Traditional anti-competitive flaws such as unilateral market power, vertical integration, and barriers to entry or expand can be mitigated through DER integration [19].

However, Joskow [22], among others, was skeptical of the benefits of retail competition (i.e. the benefits of demand aggregators); he argued that additional costs for consumers would emerge from marketing activities, and that retailers would create few value-added services. Indeed, the extent to which innovations have been realized is quite uncertain. Borenstein and Bushnell [26] argue that innovations in retail electricity supply have largely failed to materialize due to a number of factors including technical constraints (e.g. advanced metering systems), as well as regulatory constraints (e.g. universal reliability requirements). Kim et al. [27] further find a decrease in electricity sector wide R&D attributable to retail competition, while Jamasb and Pollitt [28] find a decrease in electricity network R&D following the introduction of competition.

Many of the costs of competition derive from the perennial lack of a proper market structure, which results in market advantages for incumbents, insufficient or a complete lack of unbundling, and other challenges [24]. Given the aforementioned vertical integration between retail and generation, incumbent retailers may have a natural disincentive to boost the deployment of demand response and other sources alternative to conventional generation. Driving electricity markets towards "perfect" competition is an ongoing challenge that highlights the difficulties in choosing the ideal role for aggregators to play. In conclusion, based on the magnitude of each of the sources of fundamental value of aggregators (Figure 2-1), regulatory actions may need to be taken to establish a single regulated agent or guarantee a level playing field for aggregators to compete in the market.

Figure 2-1: Regulatory options based on sources of fundamental value of aggregators



3 The transitory value of aggregators

Aggregators may create value as the power system transitions from current regulations and technologies to a more advanced or idealized future. Temporary value is not inherent to aggregation, but may be unlocked by aggregators.

3.1 Complexity, information gaps, and agent engagement

Opportunities for agents in the distribution system to increase system efficiency by engaging with the bulk power system are increasing as ICTs enable loads to become more price-responsive and as DERs are increasingly deployed. However, market complexities, information gaps, lack of engagement, and other biases may prevent the value in these distributed assets from being unlocked. Aggregators may create system value by managing or eliminating these factors.

3.1.1 Information gaps and the value of aggregation

An agent may be capable of providing a service (or set of services) to the system but may lack the information required to do so effectively. For example, consumers often lack information on when system peaks may occur, what the prices for the various services they consume are, what available technologies may help them control their consumption, what the prices of these technologies are, etc.

Additionally, consumers may lack the ability to forecast this information into the future, which is critical for hedging risk or scheduling bids and consumption. Finally, power system operations and planning require the provision of many energy services; these services need to be priced in a manner that incentivizes efficient behavior. However, current power system technology is not capable of calculating and communicating the multiplicity of price signals at theoretically optimal levels of temporal and spatial granularity. An aggregator may be able to intervene to close information gaps between the system operator and various agents on system operating conditions. Consider, for example, the hypothetical system in Figure 3-1 below. The number and complexity of signals that an aggregator will send to agents will depend on the available ICTs (e.g. the capabilities of energy boxes), the types of DERs responding to price signals, the contractual arrangements between the aggregator and the agent, and the regulatory and market context.

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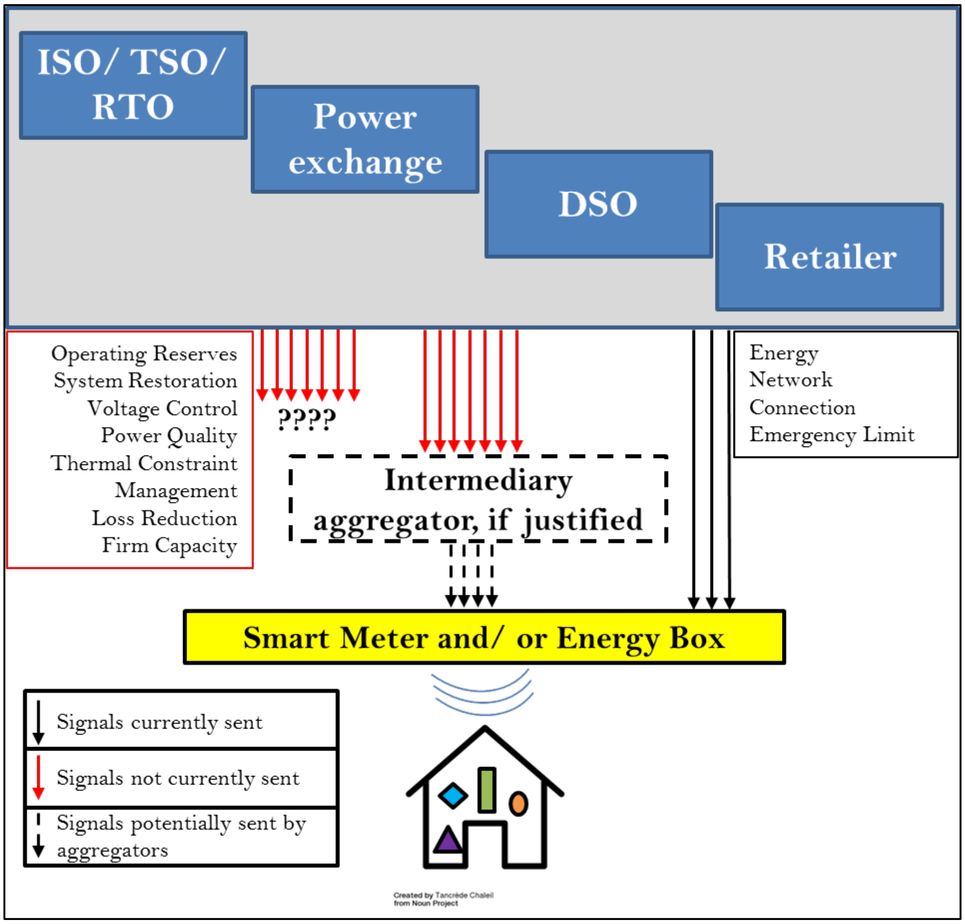
Figure 3-1: Current Power System Information Gaps & the Potential Role of an Aggregator[10]



As depicted in Figure 3-1, presently most residential and small commercial consumers typically only see a flat retail or stair-stepped time-of-use tariffs, and are not exposed to actual wholesale energy prices (even though these prices are typically calculated and available). This situation is rapidly changing with the deployment of advanced hourly (or semi-hourly, or even faster) meters in many countries; nonetheless, only one signal – the current energy price – is typically sent. Aggregators, however, can access and relay not only real time energy price information on behalf of smaller agents, but also price signals for a host of other services such as operating reserves or voltage control. This is exactly the role of many of today's demand aggregators (e.g. EnerNOC, Comverge, Enbala or others); these aggregators send signals that enable historically static consumers to participate in operating reserve and capacity markets [29].

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[10] Notice that, as discussed earlier, a retailer can substitute the function of an aggregator and therefore, price signals would go directly from the system operators to the retailer.

In the case of real time pricing information, retailers or vertically integrated utilities can aid in closing information gaps. For example, Commonwealth Edison ("ComEd") in Illinois and Electricité de France ("EDF") offer real-time pricing programs to their consumers, and offers services such as automatic curtailment during high price periods. Retailers in the E.U. have offered real time or time variant pricing packages for many years, and certain retailers are beginning to offer similar pricing schemes in the U.S. For example, TruSmart Energy, a competitive retailer in Texas, offers its users free electricity on nights and weekends, attempting to encourage its customers to consume when energy prices are typically low. In Spain, all consumers are charged real-time hourly prices by default, unless they freely contract another pricing scheme with a retailer. While competing aggregators are not a necessary ingredient for the communication of real-time pricing information to distributed agents, the flexibility enabled by a lighter regulatory burden in pricing decisions combined with competitive incentives may create more opportunities for the relaying of efficient price signals (this was a key argument in favor of retail competition in the early days of restructuring) [19].

3.1.2 Agent engagement and the value of aggregation and automation

Agents may be difficult to motivate to action due to the small sums of money that can be gained and the complexity of required action. However, when taken in sum, significant system value can be created. For example, Opower achieves peak energy reductions by communicating when and how energy should be saved. Opower estimates that, in Nevada, an average customer may save $33 per year (the estimated national average is $28 per customer per year). This equates to just over $2 in savings per month. Without intervention, a customer may not be motivated to take the actions to save this small sum on his or her own. However, Opower estimates that they have the potential to avoid over 140MW of generating capacity in Nevada and over 4.5GW nationally [30].

The problem of small sums of money is exacerbated by system complexities. Navigating the power system's various rules and codes may prove very difficult for an agent that has not historically engaged in power system operations. An aggregator may be able to navigate the complexities on an agent's behalf. Many companies, such as EnerNOC and Comverge, handle the complex registration and bidding processes on behalf of the agents they serve, enabling both the system to benefit from the services that the agents provide, and enabling the agents to benefit from previously untapped revenue streams. The value here stems from engaging an otherwise unengaged customer, but aggregators may, and often do, provide this engagement. Indeed, the mere existence of demand response aggregators in restructured and traditional markets signals that, in many cases, retailers or incumbents are not providing competitive agent engagement services[11].

Automation of energy consumption or production decisions may decrease the burdens of agent engagement, provide optimal responses, and lower transaction costs. EcoFactor, a U.S. demand response company, demonstrated customer bill savings of roughly $100 per customer per year in Nevada through automated energy management programs. In comparison to Opower's $33 per customer per year, this number is rather high; however, it amounts to only $8.33 per month, which may not motivate a customer to take action unless engaged and motivated (or automated) [31]. Competitive aggregators (such as EnerNOC or EcoFactor) have a profit motive to engage consumers and act as the provider of automation services. Automation, supported –temporarily, at least– by aggregators and the technological innovations associated with the "Internet of Things" is the future of an enhanced and more comprehensive vision of demand response.

3.2 Aggregation as a tool for managing coordination issues

Power system operators (ISOs or TSOs) are required to dispatch generation, storage, or demand response resources to match supply and demand at all times. Traditionally, these resources have taken the form of a discrete set of large and easy-to-centralize resources. DERs therefore represent a new challenge for utilities: coordinating and controlling DERs involves bidirectional communication with an order of magnitude larger number of resources. Aggregators may create transitory value by coordinating information exchange between various power system actors [18].

Ultimately, if a DER is going to be dispatched to meet system needs, a signal must be sent from the system operator (SO) to the DER and vice versa in some fashion. This signal may be sent directly or through an aggregator[12]. For example, in a system with 500,000 DERs, the SO can send control/ dispatch signals to only five aggregators with 100,000 DERs each under control, or the SO can send

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[11] There may be many factors driving this dearth of action from retail aggregators including vertical integration with generation [25]; this is an area that requires further research.

[12] Certain services, such as reactive power or frequency control can be provided with automated responses based on localized sensing of voltage or frequency levels. For example, frequency droop control provided by PV inverters is provided simply by the inverter detecting the frequency of the power it is receiving and reacting accordingly. However, participating in energy markets and capacity markets as well as operating reserve markets requires that a discrete communication signal be sent from the SO to the DES and vice versa (potentially through an such as an aggregator). We are ignoring here the possibility of certain decentralized/collaborative computing solutions.

control/ dispatch signals to the 500,000 DERs directly. While these two actions may produce the same result, they have different consequences. From the SO's perspective, it is likely easier and less costly to coordinate a small number of aggregators; the question is whether eliminating aggregators and relying solely on the SO for coordination would increase system value.

Establishing the ability to send coordinating signals requires some costs to be incurred. These costs include ICT investments and investments in manpower (knowledge). These costs can be borne by the SO or by aggregators (or some combination thereof). Given that the SO is a monopoly and its costs are typically recovered through regulated charges, the SO would be remunerated for making any investments required for coordination. Regulators may wish that competitive aggregators perform the majority of coordination actions; the extent to which coordination costs borne by aggregators are passed along to aggregated agents is at the discretion of the aggregators.

Aggregators therefore have value in coordination if it is believed that competitive agents are better positioned to deliver and bear the costs of coordination than a SO. If coordination technologies are changing rapidly, etc., it may be desirable for non-monopoly agents (e.g. non-SO) to invest in the infrastructure necessary for coordination. A regulator may determine that aggregators should exist because their presence limits the risk that customers are exposed to if a SO makes a poor investment in the ICT infrastructure necessary, etc.

If fixed costs of ICT infrastructure required to coordinate actions are significant, then there is value in larger aggregations of end-users on a common ICT platform derived from economies of scale (discussed above). If the returns on economies of scale do not diminish significantly, it may be the case that it is most economically efficient for one agent to perform all coordinating actions.

Due in part to coordination costs, system operators create standardized products that may leave certain agents out of the market. Aggregators may be able to mobilize these agents. For example, an industrial customer may be able (or willing) to participate in a demand response program, but may require that it curbs demand only once per month (due to a production constraint, for example). It may be difficult for this constrained resource to participate in a DR market due to minimum size, duration, or other market rules and constraints (discussed below). However, as part of a portfolio, an aggregator may be able to call on this constrained resource once per month, while calling on other similar resources to meet the grid operator's or regulator's requirements. Automation via an aggregator may help here as well, as automation may eliminate all required action from the asset owner.

4 Opportunistic value of aggregation

Opportunistic aggregation may emerge as a response to regulatory "flaws." Opportunistic aggregation is aggregation of different agents or DERs owned by an agent in one or several sites, to obtain private value without increasing the economic efficiency of the system; furthermore, opportunistic aggregation may restrict competition, especially for small agents. We identify three categories of rules which can create opportunistic aggregation: rules related to the procurement of balancing services, rules related to allocation of balancing costs to agents, and inefficient locational price signals and inefficient network charges.

4.1 Regulations for the procurement of balancing services

4.1.1 Penalties for lack of response in the provision of balancing services

The activation of committed reserves requires available capacity to increase or decrease production or consumption of energy. Units that provide this availability receive a payment based on the capacity provided or on the capacity made available to the SO. In a second step, these units may be required by the SO to increase or reduce energy in real time. If a unit that has committed reserve capacity to the SO is not able to provide energy when called upon, an additional penalty may be applied beyond the marginal cost of activated reserves. If an aggregator has multiple flexible units within a portfolio, and one unit is not able to respond to dispatch in real time, another could do so at lower cost than the cost of reserves plus the associated penalty set by the SO. Consider, for example, an aggregator with a portfolio of two resources, A and B, that have marginal costs MC_A and MC_B, where $MC_B > MC_A$. Consider that unit A is committed to provide reserves, and the marginal cost of activated reserves MC_{ACT} is $MC_B > MC_{ACT} > MC_A$. Under a system with a penalty, if the aggregator is unable to dispatch unit A, it will be charged some penalty P plus MC_{ACT}. If $(P + MC_{ACT}) > MC_B$, the aggregator will deploy resource B, to avoid the penalty due to unavailability of A, even though the cost of deploying resource B is higher than the marginal cost of other resources in the system – a clear inefficiency. Therefore, aggregation of resources can reduce the penalties associated with a failure to respond to SO needs. Further, the design of those penalties can prevent small agents from directly providing balancing services unless they are aggregated.

4.2.1 Symmetric bidding requirements

Furthermore, in many markets, the provision of operating reserves requires symmetrical products for upward and downward regulation or reserves (that is, if a unit offers 5 MW of upward ramping capability, it must also offer 5 MW of downward ramping capability) [32,33]. Symmetrical bid requirements are also in place in some US markets such as MISO and NYISO, but are not in place in others such as ERCOT [34]. This requirement can be costly for a single agent to fulfill. For instance, solar or wind power can provide downward regulation, but it would be costly to provide the same amount of upward regulation, as this would force solar or wind generators to produce below their maximum output. Aggregation of units capable of providing upward and downward regulation would fulfill the symmetric bid requirement. This unnecessary regulatory restriction may incentivize some agents to make inefficient decisions from the global power system viewpoint.

For example, imagine that there are two locations, A and B, and that an investor owns a solar PV plant at location A. The energy revenues at location B are expected to be greater than those at location A. The same investor is considering investing in a new generator, and is considering whether to place it at location A or B. The best decision from the perspective of system efficiency would be to install the generator at location B. However, the optimal decision from the investor's perspective may be to install at location A if the revenues associated with unlocking the downward reserve capacity of the PV plant outweigh the increased energy revenues earned at location B. In a system without the symmetric reserve requirement, any capable unit may provide reserves in one direction. Therefore, symmetric bid requirements restrict flexibility of certain units and add additional costs for reserve provision.

4.2 Market imperfections associated with the allocation of balancing costs

In real time, deviations from scheduled supply and demand need to be solved by the SO through the activation of operating reserves (regardless of the exact term used for this service). The concept of imbalance settlements refers to how imbalances (i.e. how many MWh and at what time) and imbalance prices (i.e. how the balancing costs are allocated per deviated MWh) are determined. The method for allocating these costs to market parties plays an important role in terms of encouraging economic efficiency and creating incentives for market parties to support the system supply-demand balance. The method for allocating balancing costs differs widely among countries, and may create an opportunistic value for aggregation.

4.2.1 Balance Responsibility

Balance responsibility defines which market participants (e.g. generators, suppliers, consumers, and traders) are obligated to submit individual or portfolio schedules (for consumption and/or production) to the SO, and defines the method with which the economic settlement of the deviations from those schedules is performed.

In Europe, energy imbalances and the corresponding imbalance costs can be computed for an aggregation of different generating units. Under a portfolio balancing scheme, aggregations of units can net imbalances, even if the costs to the system of the imbalances are dramatically different across locations. For example, under a portfolio scheme, if one unit produced 5 MW less than scheduled, and one unit produces 6 MW more than scheduled, the net imbalance is only positive 1 MW. In the US, energy imbalances and imbalance costs are typically computed for each individual centralized generating unit. Under a unit-by-unit scheme, if one unit produced 5 MW less than scheduled, and one unit produced 6 MW more than scheduled, the imbalance would be 5 MW for the first unit and 6 MW for the second unit.

Intermittent renewable sources have significant uncertainties with regard to their generation schedules, which may result in the increased use of balancing resources [35,36]. The inherent uncertainty in the generation of intermittent sources has motivated some regulatory bodies to apply special conditions to intermittent units. For example, in many European countries, wind power producers have different levels of financial responsibility for energy imbalances in relation to other technologies [37]. In liberalized US markets, wind and solar have special treatment with respect to energy imbalances and imbalance penalties. For instance, no penalties are applied to deviations within 5% of the scheduled amount in PJM; exemptions from uplift costs[13] are set for wind in ISO-NE; wind and solar are exempt from under-generation penalties up to 3,300 MW in NYISO; and ERCOT and MISO have set tolerance margins for energy imbalances from wind and dispatchable intermittent resources[14], respectively [38]. Creating thresholds of imbalances under which imbalance penalties are not applied creates an opportunistic value of aggregation; aggregating intermittent units (either in one location in the U.S. context, or across locations in the EU context) may decrease the net imbalance of the aggregation, thereby allowing the aggregation to avoid imbalance penalties.

Imbalances are usually computed per retailer or Load-Serving Entity in both the EU and U.S. However, in absence of hourly meters, imbalance costs are usually socialized among all consumers (often without a transparent methodology). Furthermore, provision of electricity services by aggregators (e.g. by changes on initial positions) without facing balance responsibility from energy deviations (i.e.

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[13] Uplift costs (as applied in US markets) are a result of payments made to resources whose commitment and dispatch by an RTO or ISO result in a shortfall between the market clearing price and the resources' offer in the markets. The SO may make an uplift payment to fill the delta between the resource's bid and the market clearing price [50].

[14] That is, intermittent resources which are equipped to be capable of being dispatched by the SO.

aggregator being a different party than energy provider) may lead to opportunistic aggregation strategies that should be avoided by regulation [7].

As a general conclusion, all units, independently of their source, should face the imbalance costs. Furthermore, imbalance costs assigned at end-user level (i.e. per connection point) do not discriminate between market parties' size, and are therefore preferred.

4.2.2 Imbalance Pricing Schemes

Generally speaking, in Europe, two main approaches for imbalance pricing exist: single and dual. Under a single pricing approach, imbalance prices are based on the marginal cost of activated reserves. With dual pricing, the imbalance price depends on the direction of the market party imbalance with respect to the direction of the net system imbalance. If the market party deviation is in the opposite direction of the net system imbalance, it usually receives the day-ahead price. On the other hand, if the market party has an imbalance in the same direction as the net system imbalance, it typically pays the marginal or average energy price of the activated reserves (typically higher than the real-time or day-ahead energy price, in case of upward reserves). Note that, in some countries (e.g. Nordic countries), generators and consumers are differentially charged for imbalances [39].

Germany, the Netherlands, and Belgium (after 2012) apply a single pricing scheme. On the other hand, the Nordic countries (for generation units), France, the UK, and Spain apply a dual pricing scheme. Imbalance pricing rules have been demonstrated to impact the bidding strategies for wind generators [37]. In general terms, dual pricing penalizes energy deviations, creating opportunistic incentives for aggregation derived from the netting of imbalances among different units. However, single pricing schemes do not create this opportunistic value, as an agent will always be penalized or paid the marginal cost of activated reserves, regardless of whether this activated unit is in the aggregator's portfolio.

For example, consider a system in which the marginal energy cost is \$50/MWh. Consider an aggregator with two generation resources, A and B, of 40 MW and 50 MW respectively, and with marginal costs MC_A = \$50/MWh and MC_B = \$55/MWh. In this scenario, MC_A is dispatched and MC_B is not. Assume now that unit A has an unexpected outage of 40MW. Consider that this system has a net negative imbalance (i.e. lack of 10 MWh). Under a dual imbalance pricing scheme, increasing generation would cost \$60/MWh (MC_C), since this is the marginal cost of another unit that has participated in the reserve market. An aggregator could dispatch unit B to generate 40 MWh; this would compensate for the imbalance of A and allow the aggregator to get paid \$2,000 (40 MWh × \$50/MWh). While the aggregator would have a loss of \$200 with respect to the marginal costs of unit B, as $MC_B < MC_C$, the aggregator would still have a net gain of $200 (by having a balanced position) with respect to paying the imbalance cost. If unit B were fully dispatched to balance the system, the system would save $50 (as $MC_B < MC_C$). However, this may not happen under a dual pricing scheme. This is obviously inefficient for the system.

In the US, energy imbalance prices are set largely by the clearing price of real-time energy markets (i.e. single imbalance pricing). Remaining imbalances (relative to scheduled dispatch in real time) are managed by ISOs through the activation of operating reserves. The costs of operating reserves (which in Europe are usually included in the computation of imbalance prices) are allocated to consumers through an energy charge to Load-Serving Entities on the basis of the relative shares of these loads [40][15].

Real time markets enable market participants to minimize imbalances within the system and are therefore preferred. Additional reserve costs not reflected in the real time prices should be allocated based on cost causality principle. Furthermore, as demand becomes more price-responsive, it should be subjected to the same imbalance prices as supply.

4.3 Inefficient locational price signals and inefficient network charges

As aforementioned, accurate price signals are nearly universally not communicated to agents in the distribution system. The failure to communicate price signals accurately to distributed agents can provide incentives for aggregation without increasing system economic efficiency.

4.3.1 Inconsistent price signals

Strong theory backs the usage of locational marginal prices for energy in the transmission system [41,42]. Emerging theory indicates that similar benefits could be realized through the use of LMPs in the distribution system [43,44]. Furthermore, new methods for pricing operating reserves may reveal the locational value of these resources in a manner that limits economically distorting arbitrage opportunities [45]. The goal of this paper is not to delve into these highly complex issues, but rather to note that failing to implement these models creates opportunities for distortionary aggregation.

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[15] Cost allocation to variable renewable energy resources has been debated, with market participants arguing that these sources can potentially game from exemptions of reserve costs (Further discussion on regulatory aspects of integration of variable resources in US markets can be found in: www.ferc.gov/whats-new/comm-meet/2012/122012/E-1.pdf). FERC order No. 764 A "leaves adequate room for a public utility transmission provider to demonstrate that inaccurate data are leading to increased reserve costs and the public utility transmission provider should be able to recover such costs from customers causing them".

Indeed, many power systems have price signals that are locationally or otherwise inconsistent with the true cost of energy at a given location or time. A common example is loads that are charged a rate representing a weighted average over an area, while generators in the same area are paid the appropriate nodal LMP (for instance New York and California markets). Other examples include national markets with locational marginal congestion prices for generators only (as is the case in some EU countries). Finally, perhaps the most common example is retail tariffs that, through the use of volumetric network tariffs, create an artificially high apparent price for energy in the distribution network.

These inconsistencies create clear opportunistic aggregations. Consider, for example, the zonal prices for load combined with nodal prices for generation (as is currently the case in CAISO) [9]. An aggregator with load and generation resources may find it profitable to increase demand, driving LMPs for its generation resources up, while paying dampened zonal prices for the increased demand. A more salient example for the U.S. market is that of net-metering. By aggregating load and generation resources at a single site, net-metered facilities receive an artificially high price for the energy produced. Any number of possible arbitrage opportunities emerge in the face of inconsistent pricing that this paper will not enumerate them all.

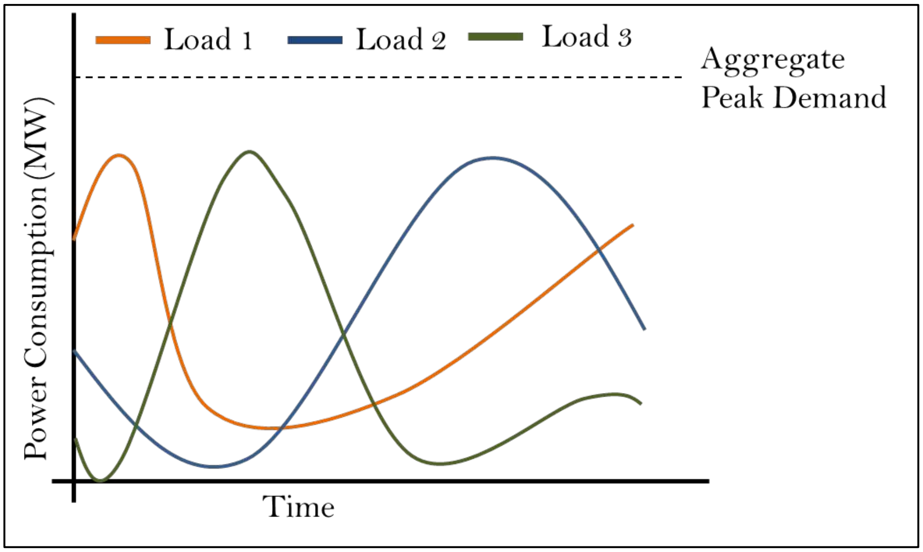
4.3.2 Netting peak consumption through aggregation

In certain countries, part of the network charges paid by consumers is based on contracted or observed peak electric consumption at the network connection point. This is the case in countries such as France, Italy, Spain and the Netherlands [46]. This regulation incentivizes consumers to reduce their contribution to the peak demand and to invest in DERs to reduce their peak consumption and the associated charges. First, if improperly designed, demand charges or contracted demand payments could over-incentivize DER investment. Second, many users who have a similar peak demand in magnitude, but whose peak demands are offset in time, may be aggregated. This aggregated unit may have a similar aggregate peak demand as each individual customer. Aggregation in this case creates private value, as it allows the aggregated units to pay a smaller demand charge while not decreasing the aggregation's impact on network costs. For example, in Figure 4-1, the aggregation of loads one, two, and three has a peak demand similar to that of any given load; assuming a constant demand charge, the network operator will recover only one third of the costs relative to each load being charged independently. Aggregation of different consumers has been already developed to create a microgrid with a point of common coupling with the main grid and even islanding capability, for instance the microgrid project

Delete

Mannheim-Wallstadt in Germany[16]. Regulation should prevent the aggregation different consumers to reduce their peak consumption charges when consumers are not connected at the same connection point.

Figure 4-1: Stylized Peak Demand Aggregation



The arbitrage of regulation to decrease a consumer's payment may jeopardize the financial viability of network providers. Network use-of-system charges should therefore be designed to reflect each individual user's contribution to network costs. Novel network tariff designs can incentivize more efficient DER location and operation decisions, and can eliminate this regulatory arbitrage opportunity [47].

5 Conclusions

The value of aggregators in power systems changes dynamically with regulations and technologies. In a hypothetical future scenario with "perfect" regulations and markets that expose the full marginal costs of providing or consuming services coupled with advanced end-user energy management systems (energy boxes), the only value of aggregators will stem from the fundamental value drivers identified herein. However, power systems may never reach these "perfect" conditions of complete information, perfect coordination, rational behavior, and perfect regulation. As such, we highlight areas where aggregators may create system-wide economic value even as the power system transitions to an

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[16] More information can be found in: https://building-microgrid.lbl.gov/mannheim-wallstadt

idealized future. Furthermore, we identify a series of flawed regulations that encourage aggregations that have the potential to harm power system economic efficiency.

Fundamental value stems from factors inherent to the act of aggregation itself. While regulation and policy may influence whether or not this value is captured and by whom, the value itself is regulation, policy, and agent-independent. In the context of the power system, aggregation may create fundamental value through capitalizing on economies of scale and scope and by mitigating uncertainty. Furthermore, competition amongst aggregators may create value through driving agent engagement (enabling the participation and optimization of DERs), and potentially mitigating market power.

Aggregators may create value to the power system transitions from the near future scenario to the reference future scenario. Temporary value is not necessarily inherent to aggregation, but may be unlocked by aggregation. Temporary value, by definition, may exist only for a period of time until superior solutions emerge. We highlight that transitory value comes from closing information gaps (i.e. related to price signals, complexity of power system) as well as agent engagement.

Finally, opportunistic aggregation may emerge as a response to regulatory "flaws." This opportunism may create private value without increasing the economic efficiency of the system; furthermore, this opportunism may restrict competition, especially for small agents. We highlight different regulations that may create opportunistic aggregations: rules related to the procurement of balancing services, rules allocation of balancing costs to agents, and inconsistent locational price signals and network charges. We propose alternatives to those regulations to avoid opportunistic actions.

Where aggregation creates fundamental or transitory value, regulators or policy makers may want to take steps to remove barriers to its realization or to encourage it outright. However, where aggregation only creates private opportunistic value, regulations should be modified, unless this fact is explicitly acknowledged and desired as a form of subsidy. We discuss that capitalizing on the value of aggregation (e.g. economies of scale, scope and uncertainty management) could lead to a single, centralized aggregator; but it may harm other power system objectives such as competition, agent engagement, and innovation. We thus make explicit the tradeoffs between these values that aggregators may provide to the system which may have important consequences for the overall power system structure.

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