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Energy Sustainability

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ABSTRACT: The integration of large amounts of distributed energy resources (DERs) as photovoltaic solar generation, micro-cogeneration, electric vehicles, distributed storage or demand response pose new challenges and opportunities on the power sector. In this paper, we review the current trends on: i) how consumers adopting DERs can self-provide energy services and provide other services at system level, ii) what can be expected at distribution networks and how retail markets will evolve with more proactive and market engaged consumers, iii) what are the effects and integration of DERs on wholesale markets, and iv) what are the challenges that DERs pose on cybersecurity and the opportunities for improving system resilience. Several recommendations are given for achieving an efficient integration of DERs. For instance, the design of a comprehensive system of prices and charges and the elimination of existing barriers for market participation are crucial reforms to achieve a level playing field between distributed and centralized resources when providing electricity services. This paper summarizes part of the work developed under the MIT Utility of the Future study.

JEL Codes: D4, L94, L95, L98

Keywords: Distributed energy resources, distribution networks, power systems, wholesale and retail electricity markets, locational marginal prices

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1 INTRODUCTION

The future landscape of the power system with a massive presence of distributed energy resources (DERs) as photovoltaic (PV) solar generation, distributed storage, commercial and residential cogeneration systems, electric vehicles, and demand response programs would present some relevant changes with respect today systems. DERs are connected at distribution networks and many of them at the consumer premises behind the meter. One of the implications of having distributed resources along the whole system would be the end of the traditional "trickling down" paradigm where top-down power flows from central generators to end consumers using first transmission and then distribution networks would be replaced by power flows in any direction top-down and bottom-up blurring the traditional boundaries between transmission and distribution networks. DERs would be another source for decentralized provision of services that should be considered in competition or collaboration with traditional centralized generators, for instance consumers may opt for producing energy from their own PV generators or to continue acquiring the service from the traditional utility. The massive utilization of information and communication technologies with capabilities of the Internet of Things empowering network users and facilitating the widespread of economics signals for services provision would contribute to make feasible this competition between DERs and centralized resources giving choice to customers. Dispersion and decentralization of service providers and new business models facilitated by a new structure of the power sector would appear in competition with or directly promoted by traditional incumbent utilities that in the end would change the current business panorama. The decentralization of trading among millions of agents using trading platforms different from the existing centralized approaches that today are mainly active in wholesale markets would be a new challenge with opportunities for new traders. Finally, the potential existence of agents, in some cases organized as energy communities, that decide to defect from the grid self-providing their energy needs would be another threat that appear for traditional utilities and challenge the current system. This new landscape poses the question, out of the scope of this paper, on whether incumbent utilities are prepared to lead this transformation.

A future vision in no more than a decade ahead with today´s technology leads us to households and buildings fully equipped with chips that control appliances, responding to prices under virtual energy boxes in the cloud. Those software platforms would optimize energy bills while preserving customer comfort and environmental preferences. There will be a range of possibilities for customers through specialized service providers to find trading opportunities, for instance, peer-to-peer transactions, maybe departing from the "classical marketplace paradigm".

Today this vision is becoming a reality through pilot projects and real experiences in countries with advanced regulations and proactive policies. The drivers for DER customer adoption , and the challenges and opportunities that the integration of DERs pose in current distribution networks and their implications on the functioning of wholesale and retail markets or in cybersecurity and resilience are illustrated in this paper mainly in the context of U.S. and Europe electricity markets. Section 2 presents how customers may select different DER technologies under an economic rationale benefiting from the savings and revenues derived from the provision of services. Section 3 proposes new ways of revisiting the conventional practices to plan and operate distribution networks and the new roles and functions to be adopted by distribution companies in the new landscape. Section 4 presents some of the challenges related to the effects and integration of DERs on the functioning of wholesale markets. Section 5 highlights the importance of increasing cybersecurity protection in the presence of DERs, and how, on the contrary, DERs may help to increase the resilience of the system in case of cyber-attacks or other natural disasters. Finally, Section 6 concludes with some recommendations for a more effective integration of DERs on power systems.

2 DER CUSTOMER ADOPTION

Customers by adopting distributed resources may self-provide energy services and deliver services for the system. For instance, residential customers may reduce their energy bill by installing PV generation and storage to self-provide energy and reduce peak consumption. Commercial buildings with high electricity consumption, large thermal mass and controllability of heating, ventilation and air conditioning (HVAC) providing demand response may participate in energy, capacity and ancillary service markets. The same for an electric vehicle (EV) aggregator by scheduling and controlling charging periods of a fleet of EVs while meeting the driving requirements of EV users. Energy communities may adopt multi-energy management systems to satisfy their energy needs under self-governance, energy efficiency, and net-zero emission strategies.

In this Section, different case studies illustrate how customers may select different DER technologies for the provision of electricity services.

2.1 Interplay between gas and electricity for space heating and cooling in residential buildings

Distributed energy resources for space heating and cooling comprise a set of varied technologies, ranging from mature well established systems such as furnaces, boilers, and air conditioning units to emerging ones such as micro combined heat and power (micro-CHPs), reversible heat pumps, and hybrid gas-electricity conditioning systems.

To illustrate the technical and economic performance of some of those technologies, we consider a single-family household of 150m^2 under two distinctive climatic conditions, namely cold and warm, and two combinations of energy prices based on their electricity-to-gas ratio, with values of 3.6 and 1.9 for high and low ratio scenarios, respectively. In term of technologies, we consider different type of fuel cells and reciprocating engines for micro-CHP and heat pumps (see Figure 1).

Figure 1 presents the annual energy cost savings and simple payback period for the various technologies being tested under several scenarios. We observe that energy prices have a great impact on potential energy savings, as well as the upfront costs on the economic viability of the various technologies.

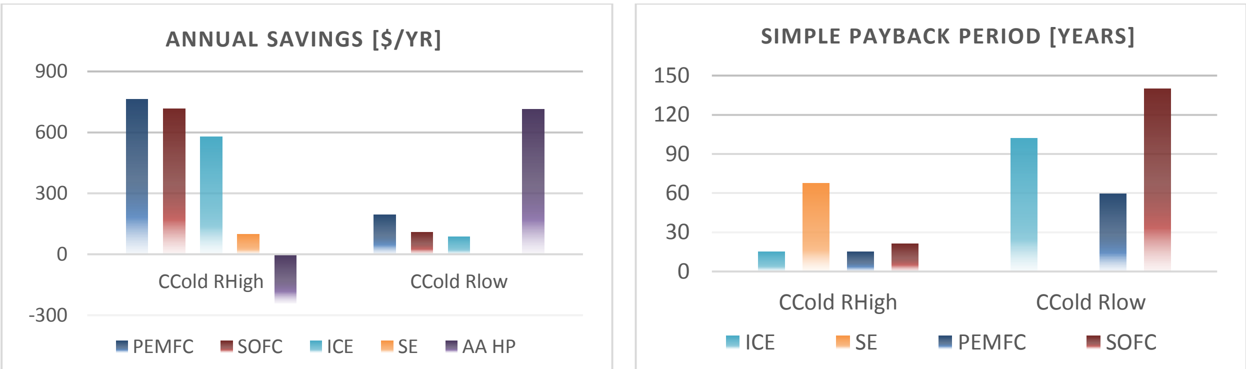

Figure 1.: Annual savings of different DERs with respect a high efficient gas-fired condensing boiler (reference case) and expected simple payback periods under cold climatic conditions and two electricity-to-gas ratio scenarios, with values of 3.6 and 1.9 for high and low ratios (PEMFC: Polymer electrolyte membrane fuel cell; SOFC: Solid oxide fuel cell; ICE: Internal combustion engine; SE: Stirling engine; AA HP: Heat pump)[1].

The trade-off between electricity costs and fuel costs is key, as high electricity prices with high electricity-to-gas ratios clearly favor the economics of micro-CHPs over heat pumps. Markets with low prices and low electricity-to-gas differences favor electric heat pumps. Cold climates favor cogeneration systems, while mild ones favor heat pumps.

Regarding micro-CHP, reciprocating engines are the most mature and established technology in the market, with upfront costs lower than other cogeneration systems making them attractive for consumers. Fuel cell-based systems are promising given their high electrical efficiencies and low primary energy consumption. However, their high equipment costs continue to be a barrier for their further deployment.

2.2 Commercial buildings providing demand response in ancillary services markets

U.S. buildings use 74% of total electricity; nearly half of total building electricity consumption is from the commercial sector[2]. Within total consumption, electricity devoted to HVAC systems is the largest and frequently, most variable category. Materials used in commercial building envelopes and structures can provide energy storage when strategically heated or cooled. Enabling control technologies and software combined with HVAC systems that can facilitate more flexibility in building operation may result in commercial building participation in ancillary services markets while maintaining thermal comfort.

For instance, individual small and medium office buildings located in Boston, MA that pay wholesale ISO-NE locational marginal prices (LMPs) for electricity consumption and obtain revenues from the ISO-NE regulation and spinning reserves markets are simulated. Table 1 includes results of two July price scenarios A & B, Scenario A features higher ancillary services prices throughout the day compared to Scenario B, while the office paying either LMPs for energy cost or a July 2015 average retail rate of $14.50 ¢/kWh. The medium office buildings are able to recover 122-141% of electricity market expenditures for HVAC when paying the LMPs, resulting in a negative net operating cost. When paying an average retail rate for electricity, under both scenarios the medium office building still reduces its initial electricity cost by 13-26%.

	Scenario A	Scenario A Retail	Scenario B	Scenario B Retail
Optimal Energy Cost ($)	403	1436	323	1422
Optimal Regulation Revenue ($)	503	352	369	178
Optimal Spinning Reserves Revenue ($)	68	27	26	0
Reduction in Energy Cost ($)	571	379	395	178
Optimal Net Operating Cost ($)	-168	1057	-72	1243

Table 1. Monthly weekday scaled estimates for optimal energy cost, ancillary services revenue and net operating cost for two July price scenarios under which the medium office pays either the LMP or average retail rate for electricity[3].

It can be observed that the tariff design is also important on the response of the office building providing ancillary services. Under flat volumetric retail rates for electricity, less ancillary services are provided than under dynamic energy market prices (LMPs).

2.3 Competition between battery storage and demand response.

Two of the most prominent DERs – demand flexibility and battery energy storage – compete with each other providing the same type of services when adopted by residential consumers.

The analysis is conducted using a model that simulates the operation of DER technologies in response to electric tariffs, climate conditions, and technology cost and performance parameters. We simulate the case of a single-family household in New York and in Texas. The key variables tested include the amount of demand flexibility and the upfront cost of batteries.

Figures 2 & 3 depict the results in terms of the impact of different levels of demand flexibility and upfront battery costs on the profitability of the battery system. Demand flexibility is increased by expanding the comfort temperature dead-band and engaging more end energy uses, air conditioning (AC) and water heaters (WH).

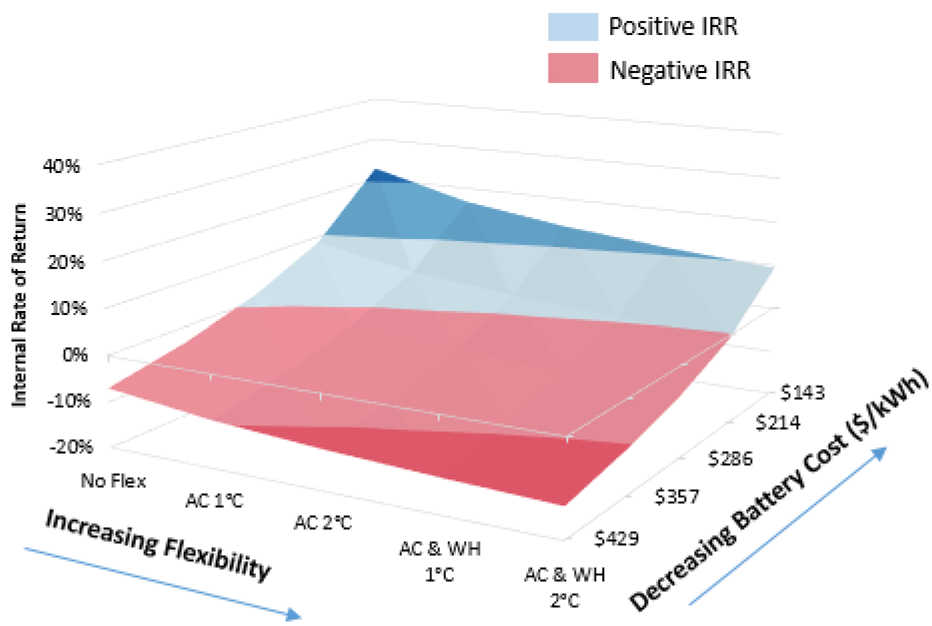

Figure 2. The impact of flexible demand and battery cost on battery profitability in New York

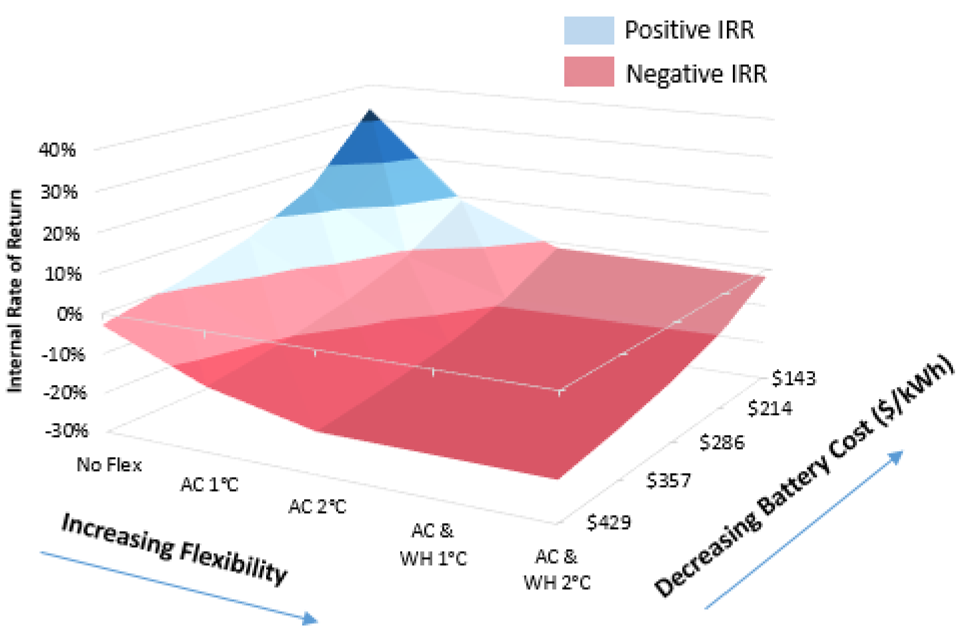

Figure 3.The impact of flexible demand and battery cost on battery profitability in Texas[4]

In both cases, we see that demand flexibility has a significant negative impact on the profitability of batteries. As the amount of flexibility increases, the cost of batteries must be much lower for them to be profitable, indicating that flexibility is cannibalizing the battery revenue streams.

The key difference between the cases is the availability of the thermal resource. The hotter climate in Texas leads to greater use of air conditioning, which in turn means greater potential for smart energy management strategies to reduce customer bills. Without flexible demand, batteries are profitable at a higher upfront cost in Texas, but like New York, any amount of flexibility quickly diminishes the revenue opportunities.
As conclusion, demand flexibility significantly reduces the profitability of batteries, but the size of the thermal resource and the structure of the tariff, not showed in the presented results, energy volumetric versus demand charges, are significant factors affecting the outcome.

2.4 Aggregators managing the charging of a fleet of electric vehicles

Electric vehicles (EVs) are expected to play a crucial role in decarbonizing the transportation sector. Public policies are actively promoting the adoption of EVs all over the world[5]. The increasing penetration of EVs in the electricity system will increase the electricity demand. However, due to EV demand flexibility, EVs are parked most of the time, and possibly plugged-in, it would be possible to meet this load growth at minimum cost, for both the system and EVs' owners. In addition, EVs could even sell energy back to the grid and provide electricity services, whenever they are incentivized to do so.

In order to reduce electricity purchase costs and even obtain revenues from providing electricity services to the system, such as balancing energy or operating reserves, smart EV charging strategies would be crucial. An independent agent, an aggregator, can coordinate the charging of a fleet of electric vehicles, or alternatively, a smart charging system can automatically charge each EV independently.

The costs and benefits of EV charging strategies would depend on a number of factors that vary from the markets where EVs participate, specific market regulations, degree of smartness of charging strategies and technology available, mobility patterns of EVs, among others.

For instance, Figure 4 compares the average annual costs per vehicle charging under different imbalance pricing market rules, and charging strategies. Single versus dual imbalance pricing rules are compared. In addition, dumb charging, referring to start charging whenever the EV is connected, versus smart charging, either through an aggregator or through individual smart charging systems, are analyzed.

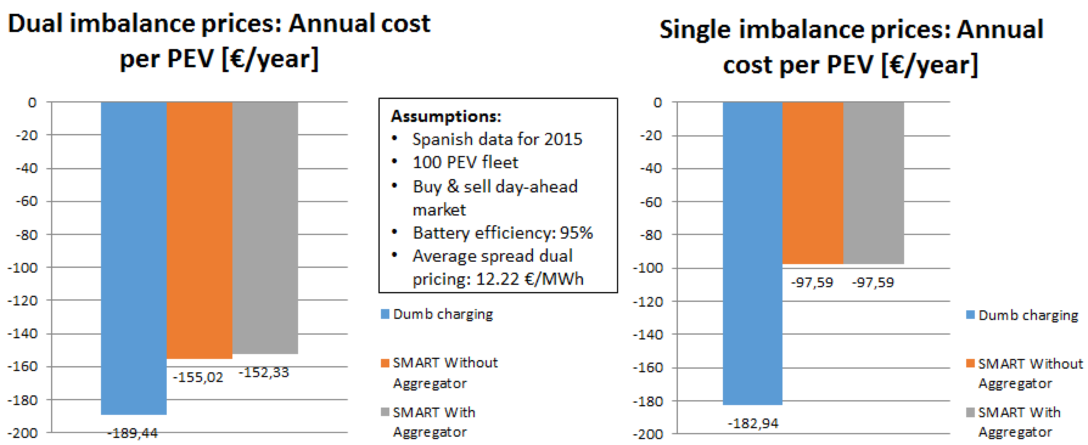

Figure 1 Value of aggregation depending on the imbalance pricing mechanism[6]

The results show that smart strategies, charging EVs whenever wholesale prices are low and selling energy back to the grid when prices are high, result in around 40% lower costs than dumb charging. In markets with dual imbalance prices, and due to EV unforeseen energy imbalances, the cost of EVs charging would be almost 50% more expensive than in markets with single imbalance prices. Furthermore, in markets with single imbalance prices there would not be additional benefits of aggregating EVs and netting energy imbalances among them.

In summary, smart EV charging strategies responding to time varying price signals can significantly decrease EV charging costs. Furthermore, the profitability of aggregators, assuming alternative individual EV smart charging strategies, is strictly related to market pricing rules, which in certain cases, such as the presence of dual imbalance prices, create opportunistic value for EV aggregation. However, charging of EVs through an aggregator can reduce entry barriers for participation in markets, such as the one related to meeting minimum size requirements.

2.5 Multi-energy services in integrated energy communities.

Integrated Community Energy Systems (ICESs) are multifaceted smart energy systems, which optimize the use of local DERs, dealing effectively with a changing local energy landscape and local communities[7]. ICESs organization may emerge because of economic reasons, but in some other cases, even if these alternatives are more expensive, customers may be willing to self-organize and contribute towards a sustainable energy transition through local provision of renewable and energy efficiency solutions. Currently there are 2,800 energy co-operatives in Europe which indicates huge potential for community energy systems[8]. The recent surge of DERs is providing the enabling environment for ICES. Yet, there are uncertainties on how ICES can emerge under currently centralized institutional settings and what value they would have for local communities as well as for the whole energy system.

Figure 5 presents the annualized total energy costs of different alternatives to supply the energy needs to a community of 12 households, first in the base case with no DER installations and then assuming both individual household and community DER investment. Although the major cost savings comes from technological change from natural gas-based heating systems to heat pumps, the savings in energy costs because of self-consumed energy by solar PV, and consequent reduction of payments for policy costs, taxes and network costs are also significant. Network costs are mainly recovered through contracted individual peak capacity charges. Due to non-coincidental loads among households in the ICES, network charges can be reduced as the community peak demand is lower than the sum of the individual peak consumptions. Volumetric tariffs also allow savings in energy costs, policy costs and taxes. Overall, the cost savings with individual and community DER investment are 37 % and 43 %, respectively. In terms of CO_2 emissions, they are also reduced from 55 (base case) to 16 and 12 tons, respectively.

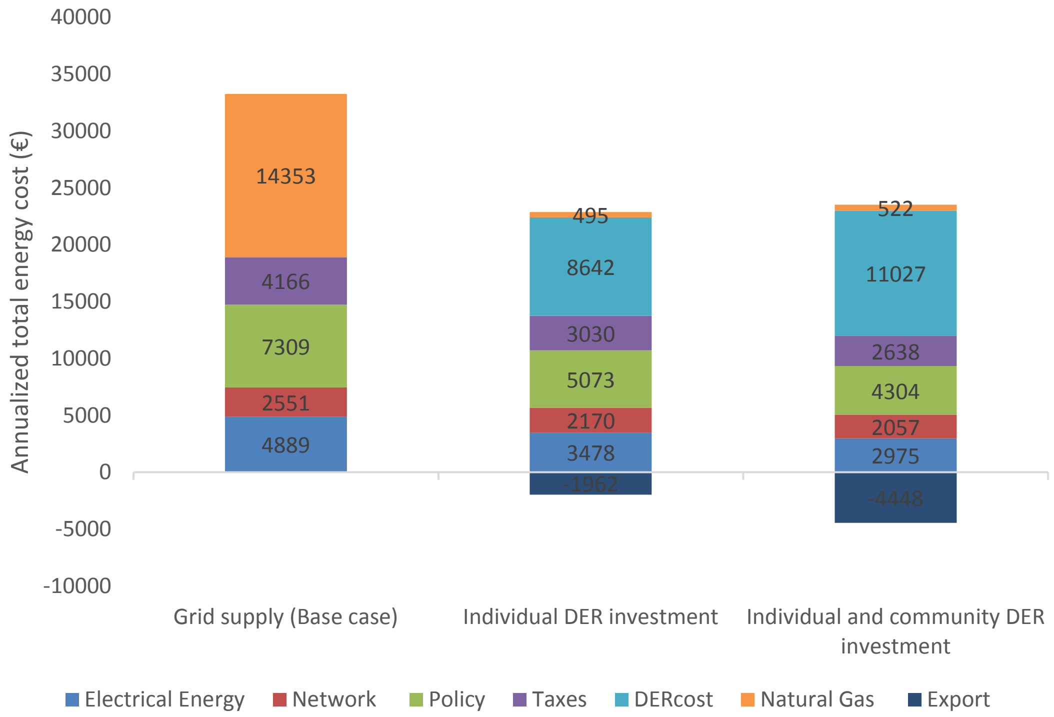

Figure 5. Cost-savings through ICES in grid-connected systems[9]

In summary, under current energy prices and regulated charges, ICESs are attractive over the solely grid-supplied option. Diversity of demand as well as generation profiles among the households within ICES lead to increased local exchanges. However, some of the cost reductions achieved are on policy or network payments that do not create system efficiency. By the contrary, they may create spill-over effects on the remaining passive customers that will see progressive energy bill increments. On the other hand, ICESs also have potential to provide energy services to the bulk power system such as ancillary services increasing their revenues, as it has been commented for the case of commercial buildings in Boston.

3 DERs AT DISTRIBUTION

The development of DERs would drive a change in paradigm thus require revisiting the conventional ways to plan and operate distribution networks, send locational economic signals to network users, and define new functions and roles for traditional distribution utilities.

3.1 Fit and forget versus active network management

Traditionally, distribution network planning and operation have been carried out as two almost fully decoupled tasks. Firstly, long-term network planning consisted in forecasting the peak demand over the planning horizon on a regional basis and reinforcing the grid accordingly. At this stage, the main goal was to ensure that no operational constraints, thermal limits or voltage problems in network installations, would be encountered during day-to-day operations. As a consequence, the grid was passively operated with very low levels of monitoring and control.

Likewise, the progressive connection of new network users, including DER installations, has been so far managed under this paradigm by reinforcing the network whenever the existing grid capacity was not enough to ensure that the most unfavorable conditions foreseen can be coped with. Thus, all potential problems were tackled at the time of network connection. Hence, this is usually referred to as a "fit & forget" approach. This network management approach has proven to be effective and cost-efficient in a conventional centralized environment. However, the development of DER is questioning the suitability of such a model as the power system becomes more and more decentralized.

For instance, the UK Smart Grids Forum, participated by public authorities, industry and other stakeholders, carried out an analysis of the distribution network investment needs to accommodate DER in different scenarios for the year 2050[10] A business as usual (BAU) scenario, where only conventional "iron-and-copper" investments are considered, is compared to the implementation of smart distribution grid solutions. In this regard, both a large-scale top-down and a progressive or incremental deployment of smart grid solutions were considered. The results, depicted in Figure 6, show that the implementation of smarter distribution grids and active network management provide much lower costs as compared to the conventional "fit and forget" or BAU paradigm.

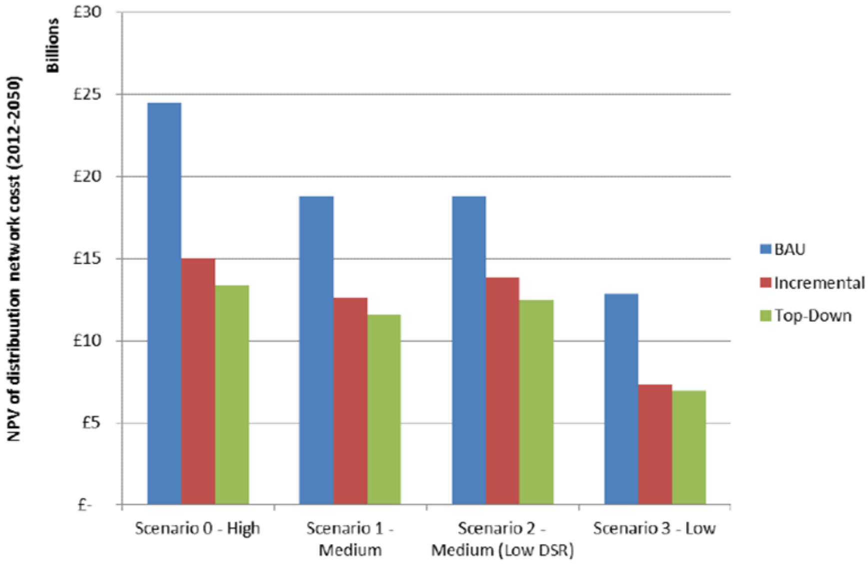

Figure 6: Network investment needs to connect different rates of low carbon technologies to the British distribution system by 2050. Source: EA Technology, 2012

In a nutshell, a passive grid operation and a fit & forget approach to connect new network users is bound to lead to an important cost increase, particularly when large shares of DER are to be connected. Oftentimes, costly grid reinforcements would be triggered by situations that, at most, would only happen a few times per year; for example, when there is a very high solar irradiation. Moreover, the need to reinforce the grid can result in long lead times for connecting new network users. Therefore, distribution companies will need to adopt innovative ways to manage their networks in order to facilitate an efficient transition to a decentralized system.

This necessarily implies bringing network planning and operation closer together so that network thermal and voltage limits are tackled not only at the planning and connection stage, but also during real-time operation. This active network management approach ultimately relies on smarter distribution grids, which integrate an extensive use of ICTs to enable advanced monitoring and control capabilities. However, despite the fact that the implementation of smart grid solutions implies a deep change in paradigm for distribution utilities, these companies are facing an even greater challenge in this transition.

Distribution companies will no longer manage network elements alone. Instead, they will need to interact closely with DER to operate the distribution grid. Thus, DER flexibilities may become essential for day to day network operation. Accordingly, distribution companies will become system operators, which acquire network services from DER such as voltage control or congestion management.

Early examples of such transformation can be already seen in some countries. For instance, since 2012 German distribution companies can remotely limit the injection of PV installations above 30kW in case of local network constraints in exchange for an economic compensation. Smaller PV units may either follow the same instructions as larger plants or permanently limit their injection to 70% of their rated withdrawal capacity[11]. Similarly some regulators are promoting such a change in planning and operation practices. The UK is an example of this, since distribution companies are required to follow common methodologies and indicators to justify their long-term investment plans based on benefit-cost analyses and including innovative grid solutions[12].

3.2 Benefits of DER on network operation and planning by responding to prices

In addition to a more active management of distribution networks, we will need a comprehensive system of prices that motivate efficient responses by network users from a system perspective.

DERs may create value in very different ways and are therefore likely to have very different impacts on distribution network operations and in the end in planning. Using a detailed model of a distribution network, we compare the network impacts from customer DER investment decisions in response to different economic signals, specifically flat average prices (Flat), hourly time varying prices at substation level (Substation LMP), and distribution locational energy prices calculated at each node of the distribution network (DLMP). Results suggest that the type and location of DERs likely to emerge on the distribution network are very sensitive to the structure of energy prices. Furthermore, locational prices can effectively align customer DER investment decisions with network benefits, potentially relieving network constraints at a cost that is less than traditional 'iron-and-copper' solutions.

Figure 7 shows the location and technology type of the most profitable DER investments– solar PV, HVAC controls, or batteries – under different energy price structures. Customers adopt the most profitable investments according to the implemented energy price structure. Each panel corresponds to the same distribution network (dots are network users and lines are distribution wires), with the network congested region highlighted in the upper left. Flat prices, for example, lead to investments in solar PV with no discernable geographical pattern that do not help to solve the congestion in the network. In contrast, distribution locational marginal prices (DLMP) lead to investments in HVAC controls that are clustered around the area of congestion and help to solve the problem by demand reduction in those critical hours when the network is congested.

In summary, flat, volumetric energy rates resulted in solar PV being more profitable from a customer perspective relative to either demand management or battery technologies. Energy prices that varied over time, but not location, resulted in demand management technologies being the most attractive, while prices that varied across both time and location also resulted in demand management technologies being the most attractive, but coordinated around congested areas of the network.

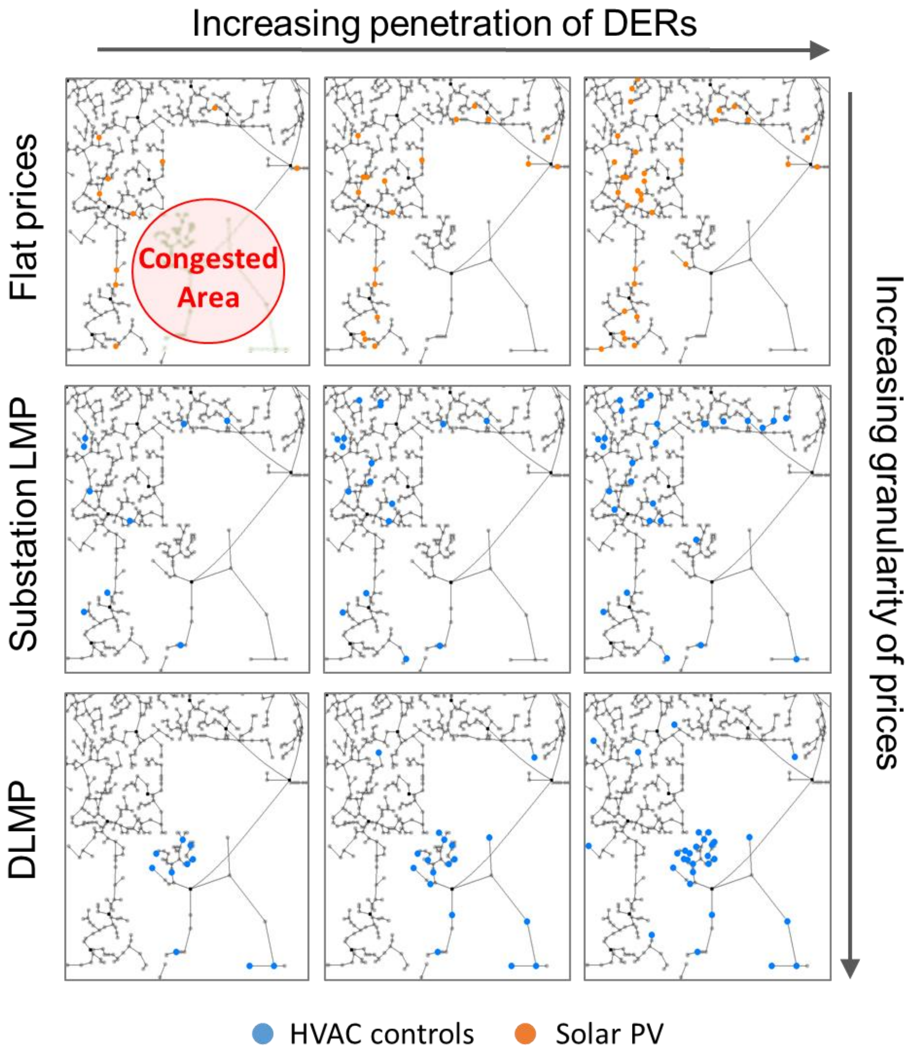

Figure 7 | Most profitable DER investments under different energy price structures[13]

Figure 8 compares the net cost of addressing the network congestion with DERs and traditional 'iron and copper' solutions. Cases are listed in order of least costly to most costly. Three network cost drivers are included in the final metric: losses, non-served energy (NSE), and investments (either DERs or transformer replacement). Cost reductions (benefits) appear as negative bars, while cost increases (e.g., investment) appear as positive bars. A red line for each case represents the net cost.

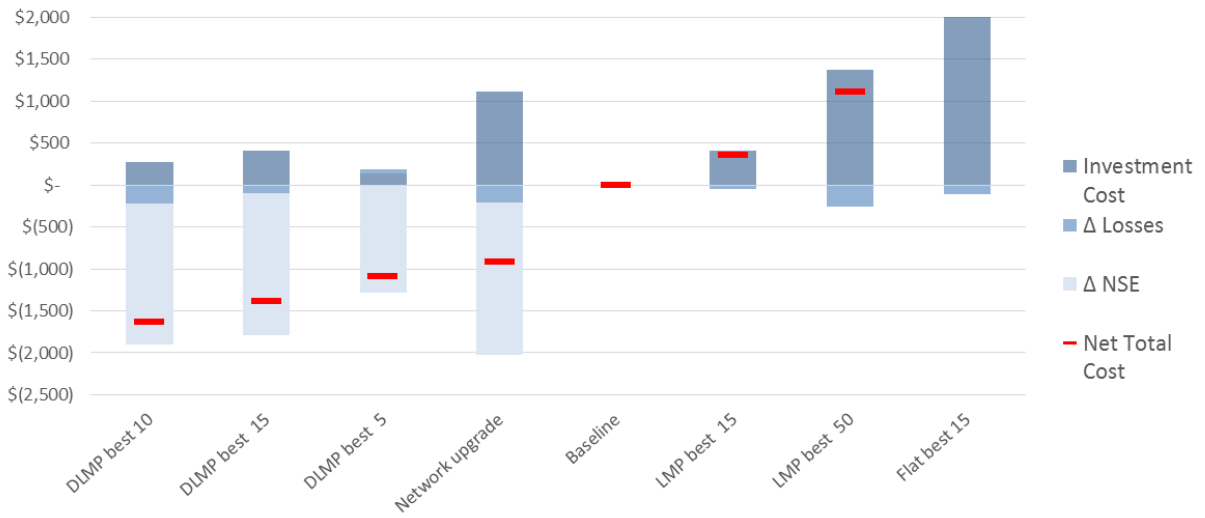

Figure 8. Net cost of DERs addressing network constraint[14]

As shown in Figure 8, the lowest cost solution occurs when the best 10 DER investments are installed under the DLMP pricing scenario. Looking back at Figure 7 shows that those investments are HVAC controls, all located in the area of congestion. The traditional utility solution upgrading the network – replacing the transformer – actually results in greater benefits in the form of reduced non-served energy and losses, but carries a higher upfront investment cost, making the total net cost higher than the best DER solutions. DER investments that emerge under Flat and LMP prices result in some reduction in losses, but because they are located outside of the congested region (see Figure 7), do not reduce non-served energy, making their net cost much higher.

In summary, DLMPs can effectively align customer incentives for DER investment with network benefits, and DERs can potentially solve network constraints at a cost that is below traditional network reinforcement solutions.

3.3 New roles of distribution utilities and interactions with DERs

The progressive decentralization of the power system, together with the massive deployment of ICTs and enhanced consumer awareness, will require distribution companies to adopt new roles.

First, we have shown how relevant it will be for distribution companies to take into account the flexibility potential of DER when doing network planning and operation. Distribution utilities may adopt a new role as active system operators. Distribution companies may additionally need to enhance their role as neutral market facilitators, both in terms of retail competition, in those jurisdictions with such feature, i.e. as data managers, and providing non-discriminatory access of DER to local and upstream markets and services by enhancing their interaction with other stakeholders including: market operators, transmission or independent system operators, suppliers, and aggregators. Finally, distribution companies could play an essential role in enabling or directly deploying innovative technologies such as smart metering, distribution storage or electric vehicle (EV) recharging infrastructure. In the following, we will introduce the drivers for the adoption of these new roles as well as the most relevant implications.

The interaction between distribution network utilities and network users has been conventionally limited to the one-off grid connection process, phone calls in case of a supply interruption and, depending on the specific regulation, metering and billing. However, as discussed above, the implementation of active network management approaches entails exploiting the existing DER flexibility potential by actively managing the resources connected to the grid.

The regulatory needs to enable this interaction depend largely on the power sector organization and structure. In the absence of unbundling requirements, distribution companies may directly own and operate DER both for network support and market participation. For instance, in the State of California, the Regulatory Commission has mandated large investor-owned utilities to deploy a certain storage capacity by 2020 for several applications, including distribution network support. This storage capacity may be owned either by the utilities themselves (no more than 50% of the total capacity) or by third-parties[15].

The main challenges arise precisely when the DER are not directly owned and operated by the distribution company. This may happen either because, unbundling rules forbid so, as in the case of Europe, or simply because other stakeholders decided to invest in such installations for commercial or other reasons, e.g. prosumers, independent renewable producers or EV charging stations. In these cases, a level playing field for all types of DER should be established. For that purpose, a neutral platform enabling the commercial transactions can be an alternative. For instance, New York authorities, under the on-going reform of the electricity sector regulation, envision future utilities as becoming Distributed System Platform Providers[16] .

A key missing link for this to happen is that of suitable regulatory mechanisms that would allow distribution companies to acquire services from DER in a transparent and non-discriminatory manner. The challenge is then how to turn DER flexibility into an additional tool for distribution companies in addition to network investments. Some of the main existing mechanisms, beyond mandatory requirements, can be broadly categorized into[17] [18]:

- Bilateral flexibility contracts: this scheme would consist in an agreement between the distribution company and DER owners, or the corresponding aggregator, to provide a flexibility service. In exchange, the DER would receive a reduced grid connection charge or an agreed fee. These contracts are sometimes referred to as flexibility contracts, variable access contracts or non-firm connection agreements.

- Local flexibility markets: in case distribution companies are able to foresee and contract in advance the required amount of flexibility, they could organize local markets for this service (i.e. periodical auctions to allocate flexibility contracts). For instance, this mechanism may be applied to solve expected network overloads in a year-ahead horizon in a distribution area where distributed generation (DG), demand response or storage could compete to contract such service.

It is important to highlight that the implementation of network services at distribution level, in combination with a system of prices with locational differentiation, will offer DER additional revenue streams. This will pave the way for new business opportunities for agents such as aggregators that combine the flexibilities of a large number of DER to respond to the needs of distribution companies.

Regarding the deployment of innovative technologies, such as distributed storage, EV recharging infrastructure or smart metering, the main question to be addressed by policy makers and regulators is whether these technologies should be treated as distribution assets, thus regulated as a natural monopoly, or, on the contrary, consider them open to free market competition, limiting the role of distribution companies at connecting them to the network. The selection of one alternative or the other will be thus largely influenced by existing unbundling rules.

For instance, smart metering infrastructure is a key enabling technology in a low-carbon decentralized power sector, and it is driven by several factors: development of prosumers, increased awareness from end consumers, need for flexible demand response, or the desire to promote retail competition. Traditionally, metering deployment and ownership has been part of the activities and remuneration of distribution utilities. The corresponding costs would be recouped via the tariff or a specific rental fee. Hence, it may seem straightforward that distribution companies remain in charge of deploying smart metering infrastructure. However, there are a few relevant nuances and alternatives to this.

EU countries have predominantly opted for a conventional model for smart metering roll-out where distribution companies perform a centralized large-scale deployment, although there are a few exceptions to this rule[19] . For instance, German consumers may choose any metering operator (or remain with their conventional meter). Metering operators may compete among them to provide this service, albeit distribution companies would remain as the default metering operator. In the UK, a large-scale smart meters roll-out has been mandated. The main difference with respect to the conventional approach is that it is the responsibility of suppliers to carry out this deployment.

Another added difficulty that has been faced in some jurisdictions is the opposition to smart metering due to privacy or health concerns from the population. In these cases, some regulators have decided to introduce opt-out clauses in their roll-out programs. This has been the case, for instance, of The Netherlands or California[20] .

Another innovative technology are distributed storage systems connected to the distribution network. They offer new possibilities for distribution companies. However, going from demonstration projects to actual deployment raises two main regulatory concerns: i) whether distribution utilities may own and operate storage systems (considering unbundling rules), and ii) how distribution companies may influence the location of storage so that it can provide grid support services where they are needed.

In case distribution utilities were entitled to own the storage systems, as in the aforementioned case of California, they could locate these systems where the grid actually needs the flexibility. However, the benefits from the provision of grid support services alone may not be enough to yield a positive business case. Moreover, given that network constraints may arise only a few times per year, the storage systems could be underutilized. This can be avoided by allowing distribution companies to participate in upstream markets for price arbitrage or the provision of balancing services. However, this may be hampered or undesirable when a strong emphasis is placed on unbundling. Regulators may explore intermediate approaches that could allow reconciling these two opposing principles of appropriate storage location and sizing, and respecting unbundling rules. These may include enabling distribution companies to own storage assets only under certain conditions (e.g. size limitations or limited to non-competitive activities) or to organize auctions for the installation of storage at certain locations by third parties.

4 DERs AND INTERACTIONS WITH THE BULK POWER SYSTEM

The integration of large amounts of DERs pose several challenges in the functioning of present wholesale markets and the need of reviewing some market rules to achieve a level playing field among centralized generators and distributed resources. In addition, the participation of DERs in wholesale markets in combination with the provision of valuable network services require a more close coordination between transmission system operator (TSO) and distribution system operator(DSO) functions.

4.1 DER active participation in wholesale markets

The integration of large amounts of DERs in wholesale markets present several challenges related to their effects on the functioning of these markets and on the other hand, the elimination of current barriers, that difficult their participation on equal footing than conventional centralized technologies.
Technologies consisting of variable renewable energy (VRE) sources, both utility-scale centralized and distributed customer-adopted installations, such as wind and solar, have a great potential to grow in the upcoming years.
The main challenge for the integration of these technologies is indeed its intermittency, which requires other resources to rapidly adapt their power output in order to keep the instantaneous balance of generation and demand. Both expected and unexpected variations in VRE power output will increase the need for flexible generation capacity in power systems. The fact that a rapid change in VRE generation can be better predicted does not eliminate the need for fast ramping resources. This is well illustrated by the Californian "duck-curve" (Figure 9). Increasing solar penetration in the Californian system results in a net load curve that produces significant ramping needs in the evening, and at the same time requires thermal generators to drastically reduce their output during the day.

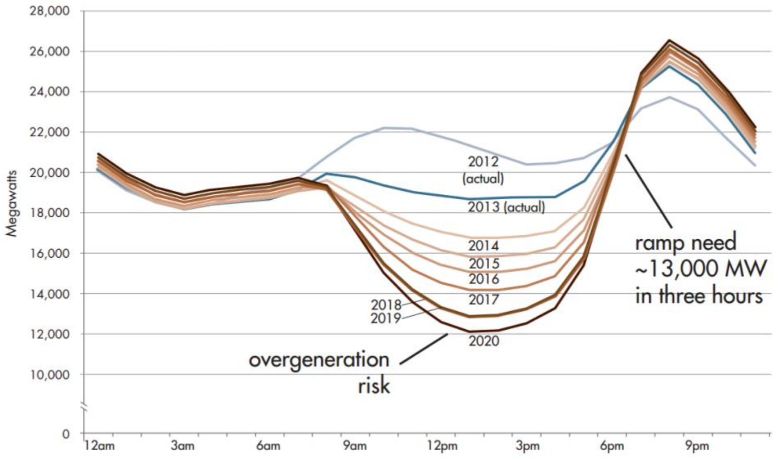

Figure 9: Duck Curve. CAISO 2013[21].

The most notorious result of a large penetration of VRE is probably the so-called merit order effect; solar and wind zero variable cost generation displaces other generating technologies with higher variable costs, having the immediate effect of reducing wholesale market prices. Because VRE are only intermittently available, the reduction in prices only affects those periods when solar or wind generation is available, although it can result in lower prices on average.
In power systems where most of the variability of VRE will be absorbed by thermal generation, these thermal units will be forced to rapidly change their output and to more frequently start-up and shut-down. Consequently, generation costs associated to thermal plants cycling will increase and, for a large

penetration of VRE the merit-order effect may be offset by thermal cycling costs increasing energy prices. Figure 10 depicts this effect in a simulation of the solar generation impact in the ERCOT system.

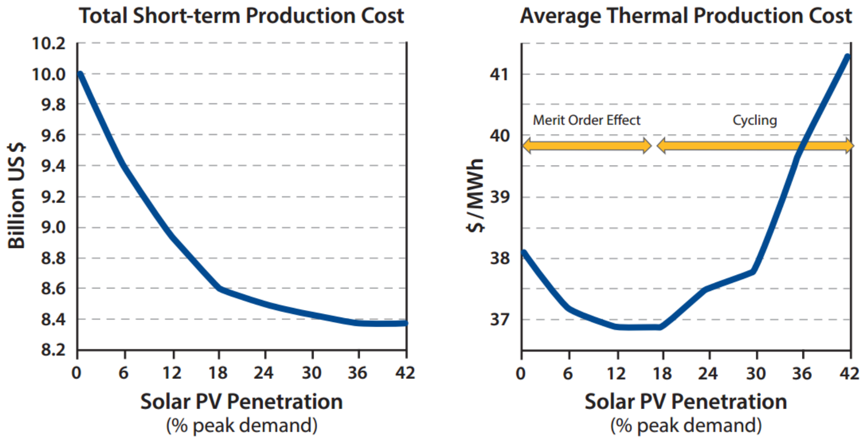

Figure 10: System and thermal production cost for increasing solar penetration in a thermal-dominated system (MIT, 2015)[22]

The effect of VER on spot prices is, therefore, twofold. Prices can increase due to the cost of thermal generation cycling in some periods, while they can drop when VRE production displaces more expensive generation. In those latter cases, prices can reach negative values, negative prices reflect the excess in electricity supply, when inflexible thermal generators find impossible or uneconomical to come offline. This effect will be more pronounced due to VRE priority of dispatch rules or production subsidies. All these lead to higher price volatility in spot electricity markets, which combined with the unpredictability of VRE, also makes electricity prices diverge between different sequential markets, such as day-ahead and intraday or real-time markets.

On the other hand, facilitating the potential of DERs to provide electricity services in wholesale markets requires properly designed markets that shall ensure the efficient deployment and operation of DERs. However, current electricity markets present numerous barriers to the participation of DERs. In most cases, these barriers are simply the result of technology evolving at a faster pace than electricity market rules and regulations. For example, the participation of DERs may be hindered by a lack of clear rules, or by rules that were designed with large traditional resources in mind, and have not been updated ever since.

Pioneering experiences in DER integration show the most urgent changes needed in wholesale markets to allow for DER participation. In the following, we concentrate on size-related and product definition barriers.

In general, most of the current electricity markets require a minimum size for market participation. This limitation is sometimes justified by the computational complexity of market clearing algorithms. This is especially true for short-term markets that may not be able to post results in time if the number of participating bids is too large.

Even if there are no limitations to the bid size, market platforms may impose fixed entry fees to participants, which may be easily offset by profits for large resources, but can impede the business case for small participants.

The most common approach to remove these two barriers is to permit the aggregation of DERs. This allows the participation of DER in current market platforms with minimal changes, managing aggregated resources as conventional ones, and "outsourcing" the disaggregation of market payments and dispatch instructions to individual resources. For instance, in 2016, the California Independent System Operator has been the first ISO in the US approved by the Federal Energy Regulatory Commission (FERC) to allow providers to group various distributed energy resources to reach the threshold for market participation currently at 0.5 MW[23].

Another existing barrier for DER participation in markets is the current definition of some market products. In markets that allow the participation of DERs, their involvement may still be hindered by market products that were designed with the capabilities of conventional resources in mind, and do not fully reflect the needs of the power system. In addition, the remuneration for these products may not be able to capture the additional value of, for example, a more flexible resource than a traditional thermal power plant.

The challenges associated with DER participation can be widely different between each of the market segments. For example, in capacity markets, the key challenge is how to assess the contribution to firm capacity made by resources with very different technical characteristics. Those markets were initially thought for the participation of only conventional generators, more recently demand response offering peak-load reductions is increasingly been allowed to participate, but still VRE and storage are the technologies that find more barriers for participation in these markets.

An illustrative example of demand response participation in markets is given by the annual mapping that the Smart Energy Demand Coalition (SEDC) makes in Europe. SEDC acknowledges the progress made with the inclusion of demand response in European network codes, but still grades some member states very negatively due to five main regulatory barriers: 1) Demand response may not be accepted as a resource, 2) Inadequate and/or non-standardized baselines, 3) Technology biased program requirements, 4) Aggregation services are not fully enabled, and 5) Lack of standardized processes between balancing responsible parties and aggregators[24].

4.2 The importance of locational economic signals

As it has been stated in previous sections, in a more decentralized system, , economic signals will play a crucial role in coordinating interactions amongst power system users. Active system users with DERs may contribute to not only mitigate negative system impacts but enhance power system efficiency over the entire power grid.

Locational marginal prices (LMPs) of energy changing in time and network location reflect costs of production, as well as of the impacts of network losses and technical constraints in those costs. Presently LMPs are only used in some countries, mainly in the U.S: and Latin America countries, and exclusively at transmission level. While in distribution, they are not used yet. Extending the calculation of LMPs to the distribution network appears to be conceptually simple, although difficult computational issues appear when the distribution network and DERs response are represented in detail[25]. In Figure 11, the streamlined equivalent to the complete Spanish distribution network in terms of the share of losses at the different voltage levels is represented. It can be observed that differences in energy prices of up to 40% are shown to exist, which can make all the difference in the viability of investing in a given DER or whether to operate it or not at a given time. Note that in the operating conditions shown in the figure the power flows trickle down and the lower the voltage the higher the LMP. The situation would be exactly the opposite in an exporting, instead of importing, mode[26].

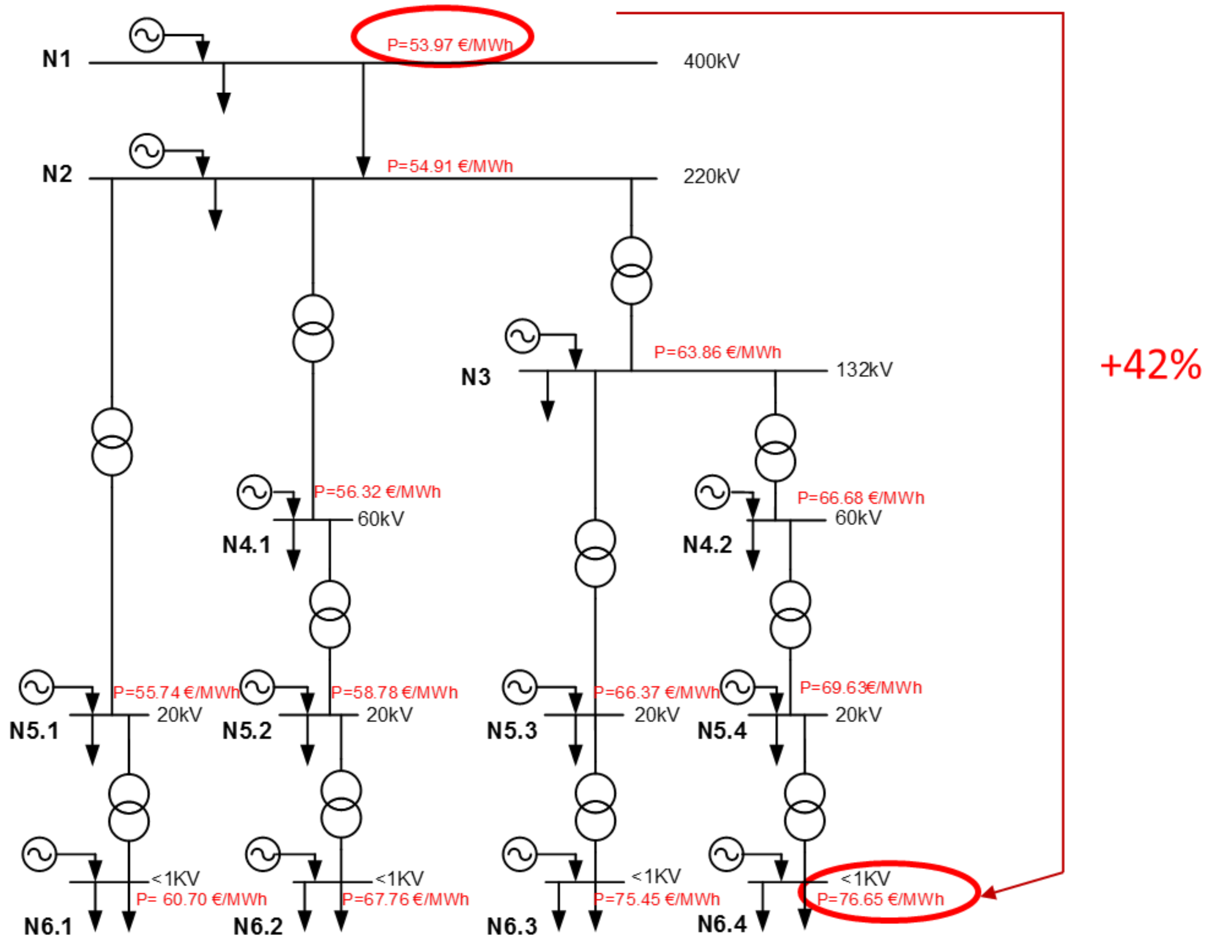

Figure 11. Distribution locational marginal prices considering aggregated distribution losses for the Spanish system.

In summary, it is clear that in the context of decentralization of services, sending time and locational differentiated energy prices and cost-reflective network charges will be relevant for bringing system efficiency in operation and planning stages. This efficiency will be the result of a decentralization economic rational making decision process where customers adopt DER in their own benefit.

4.3 TSO-DSO coordination in presence of large amounts of DERs

DERs can contribute to the provision of all of the electricity services at transmission and distribution. As it has been presented in previous sections, the efficient participation of DERs can only take place if they receive the right economic signals and have access to the different markets where these services are traded. The key institutions that mange those services are the system operators at transmission (TSO) and distribution (DSO) levels, and their coordination is of essence.

DERs can provide services, such as, but not limited to congestion relief, reactive power and voltage control, and frequency reserves. The roles of TSOs and DSOs will be evolving in kind as more DERs start to change load and generation patterns. With increasing penetration of DERs, the coordination between system operators will expand, in terms of information exchange, monitoring and analytic capabilities, computation of prices of electricity services, forecasting, scheduling and activation of resources, as well as system operator responsibilities. DSOs and TSOs must be able to monitor and engage resources as well as study and share information in a timely manner to enable efficient markets and reliable system operations. The coordination between TSOs and DSOs is of utmost importance for the grid to obtain the full value from services provided by DERs.

The evolution of the DSO/TSO coordination can be foreseen as a two-phase process. In the initial phase, DERs would provide services mostly to the TSO in established markets without violating constraints within the distribution networks, since these networks would have enough margin to manage flows and DSOs would not buy services from DERs. There would be challenges with respect to the effectiveness of DERs providing TSO services and the need to extend price signals further into distribution networks to guarantee a level playing field between centralized and distributed resources. The deployment of advanced metering infrastructure (AMI) would still be low. In the second phase, a higher integration of DERs and AMI is expected and new services can be provided by DERs and purchased by both TSOs and DSOs, leading to potential conflicts. New roles for DSOs have to be established, as well as the mechanisms for purchasing distribution services, which must be coherent and coordinated with those managed by the TSO. The developments of both phases are contingent upon many system specific factors and, in particular, the evolution of the regulatory frameworks[27].

Different actions are currently under development worldwide to efficiently integrate DERs into the power system and to reform the roles of the agents involved in the transformation. The European Commission (EC) and the New York State Department of Public Service in Reforming the Energy Vision (REV) are two examples of institutions actively pursuing increased coordination between the DSOs or Utilities and the TSOs or Independent System Operators (ISOs), respectively. ENTSO-E (European Network of Transmission System Operators for electricity), ISGAN (International Smart Grid Action Networks), CIRED (International Conference on Electricity Distribution), EDSOs (European Distribution System Operators) have task forces and working groups investigating future roles, relationships, markets and coordination requirements for and between the operators[28].

5 CYBERSECURITY, RESILIENCE AND PRIVACY WITH DERs

Widespread connection of DERs in power systems, tied to transactional energy markets, will increase digital complexity and attack surfaces, and require more widespread and intensive cybersecurity protection. Cyber incidents can cause loss of grid control or damaged equipment from deliberate tampering with data, firmware, algorithms, or communications; false data injection into pricing or demand systems; data exfiltration; and ransom demands to restore access to data[29].

Utilities and DER providers need to develop approaches to defend against cyber-attacks, and recover from possible cyber and physical attacks. To keep up with rapidly evolving cybersecurity threats against large and complex electric utility grids, electric utilities, vendors, law enforcement, and governments need quickly and effectively to share current cyber threat information. Understanding of costs to meet future standards for cybersecurity and resilience is needed. In this direction, regulators and policy makers could introduce specific regulation with incentives for utilities to work in practical and advanced implementations of pilot projects addressed to improve the level of protection and, in case of successful attacks, the resilience of the system.

Moreover, to maintain the integrity and correct operation of the power system is important to adopt minimum cybersecurity regulatory standards for all components of the interconnected network. From bulk power central generation and transmission, through distribution systems and distributed energy resources, to end connection points in buildings and industrial facilities with smart meters and electrical equipment with information connections for the "Internet of Things".

On the other hand, future power systems with high penetration of DERs are envisioned to have features that would be favorable for their resilient operation. For instance, microgrids with distributed energy resources and islanding capabilities would be helpful for increase system resilience in case of system blackouts. Microgrids with islanding capabilities can provide black-start services and continue local operations if the power bulk transmission grid goes down due to a cyber or physical incident.

Finally, with expanding connection of electric and telecommunications devices, and vastly more information become available, privacy is also a growing concern issue. Private personal and corporate information is gathered and stored by utilities and their affiliated companies and shared with other market participants and interested parties. Specific procedures to protect data breaches and exfiltration of information will be needed. For instance, in the EU a General Data Protection Regulation[30] has been passed that applies to all sectors, including electric utilities. It sets the basic principles for the protection of personal data, including security and "privacy by design". In the electricity sector, DG Energy within the European Commission and the Joint Research Centre developed a Data Protection Impact Analysis[31], a template to help utilities assess smart grids when evaluating privacy and data protection issues.

6 CONCLUSION

In this paper we have provided visions of how a future with DERs may look like and how DER may transform the power sector. The challenges and opportunities that the integration of DERs pose in current distribution networks and their implications on the functioning of wholesale and retail markets or in cybersecurity and resilience are illustrated with case studies and evidences collected in U.S. and Europe. Customers adopting DER technologies, self-providing services and becoming active participants in markets, would drive the fundamental transformation. The analyzed challenges ahead that would involve a deep reform in our current power systems can be summarized in two main stream lines: i) identify and eliminate inefficient technical, economic, and regulatory existing barriers for the deployment of DERs, and ii) design a system of economic signals that would create efficiency for the combination of both centralized and decentralized resources in a level playing field.

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