Managing Distributed Energy Resources in a Smart Grid Environment: A review for incentives, aggregation and market design

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Keywords:

Tariffs, distributed generation, aggregation, incentives, decentralized systems

Highlights:

- Flexibility supply abilities are DER dependent
- Effective management of multiple DER require well-matched incentives
- Traditional markets do not support location dependent incentives for DER
- Decentralized electricity systems enable local balancing and geo-location based incentives

Abstract

In many places worldwide the amount of connected distributed energy resources (DER) at the distribution grids is increasing. The electricity feed-in and consumption of those resources requires an adaptation of the system management in order to secure reliability of supply. As it is the case already at high voltage levels under responsibility of the system operator, different trading options like contracts for ancillary services and balancing markets could provide opportunities for economic efficient supply of system flexibility services on lower voltage levels. In a situation with smart metering and real-time management of distribution networks, similar arrangements could be enabled for medium and low voltage levels. This paper reviews distributed energy resources from a technical perspective, the related system needs for electric flexibility and the economic and technical arrangements like load aggregation and tariffs to incentivize efficient operation of DER.

1 Introduction

Traditionally low voltage grids have been designed to transport electricity towards residential users for consumption. However, due to the increased penetration of distributed energy resources (DER), low voltage grids are increasingly used as carriers of bi-directional electricity flows. The penetration of DER such as distributed generation (DG), electric storage, electric vehicles (EVs) and demand response significantly affect the operations of distribution grids (Arriaga & Bharatkumar, 2014; Pudjianto, Ramsay, & Strbac, 2007). In Germany for example, the growth of Solar Photovoltaics (PV) reached a level of 38 GW installed in 2013 and affected grid stability in some local areas (von Appen, Braun, Stetz, Diwold, & Geibel, 2013). Large numbers of PV installations are noticed in The United States (US) within California, Arizona and Hawaii (Greentech Media & Solar Energy Industries

Association, 2013). Other examples of DER rises are a significant growth of EVs in Norway – where EVs stood for 12.5% of new car sales in 2014 – and California – with almost 130.000 plug-in vehicles on the roads by the end of 2014 – and CHP in Denmark (International Energy Agency, 2005).

On one hand, this DER development is positive due to reductions in CO_2 emissions with sustainable DG, decreased use of transmission lines, increased self-consumption and the increasing independence of customers from central grid power (Alanne & Saari, 2006). However, regardless of those, DER is potentially problematic for grid stability and reliability due to congestion and voltage issues (Eftekharnejad, Vittal, Heydt, Keel, & Loehr, 2012; Walling, Saint, Dugan, Burke, & Kojovic, 2008). These concerns are mostly posing effects on the distribution net which is under supervision of the DSO (in Europe) or central service utility (in the USA in some places) and system operator for maintaining the overall grid balance. The German example shows that due to local electricity over production at the sunny moments of the day, reliability of supply is endangered in distribution grids (EPIA, 2014; EPRI, 2014; von Appen et al., 2013; Yan, Braun, & Appen, 2011). In France, realistic forecasts count on 450.000 Plug-in Electric Vehicles on the roads by 2020 (RTE, 2014); if this objective is reached, simultaneous charging of these EVs could stand for between 5 to 20% of the annual peak load (RTE, 2014). Similar issues are found in … (add examples of challenges DER penetration; EVs, CHP, PV etc.).

Current research describes issues of DER penetration from both a technical perspective and market design perspective, including the solutions that could be proposed. For example, (Eftekharnejad et al., 2012) and (Dang, Petit, & Codani, 2015) discuss the impact of PV penetration on grid stability and the improving effects that storage would provide. An holistic approach of DER management has been briefly discussed for the Norway sector (Ottesen, 2012). A description of DER from a DSO perspective is provided in the report of Perez-Arriaga et al, describing the effects of DER on the financial position of the DSO (Pérez-Arriaga, Schwenen, & Glachant, 2013). Cossent described the way in which DSO charges should be set up to incorporate different DER (Cossent, 2013). More recently, evolving roles for the DSO with increasing penetration of DER and smart metering has been presented as well (EDSO, 2015; EvolvDSO, 2014).

However, an analysis of individual DER sources, their technical characteristics and the limitations that those technical issues cause for system use and economic trading of electric flexibility is lacking. Therefore, an interesting issue that remains is the ability of different DER sources to provide grid flexibility services and relate those to suited (price) incentives. Effective market design takes into account the technical complexity of DER management, the economic possibilities for designing markets for such services and eventual roles that should involve managing those transactions. Consequently, this paper presents a review of distributed energy resources from a technical perspective, the related system requirements for flexibility and the required incentives for DER management like (dynamic) tariffs and contractual arrangements. Depending on system status and policy objectives, some arrangements might better serve system purposes than others. Both in a liberalized and a vertical integrated sector this work is of interest for policy makers, electricity suppliers, network managers and emerging actors like aggregators and Energy Service Companies (ESCOs).

This paper starts with a description of general changes in the electricity system in Section 2. Section 3 presents a review of the most common distributed energy sources and their technical characteristics. Section 4 presents an overview of centralized markets for flexibility trading. Next, Section 5 reviews incentives for DER management like tariffs, contracts and direct control. Lastly, Section 6 presents the discussion and Section 7 the conclusions and policy recommendations.

2 From Traditional to Smart electricity Systems

Worldwide, different developments in electricity sectors challenge the traditional centralized management of electricity systems. The increased *penetration of renewable energy sources* (RES), the *distribution of electricity production*, *the penetration of distributed energy resources* and the move towards smart-metering call for a different approach on electricity consumption and production.

Last years, supportive Feed-in-Tariffs in for example Germany incentivized the installation of small solar panels in the residential and commercial sector. In 2014 Germany had 38 GW capacity of Solar PV installed, with a large part, (more than 60%) located at low voltage levels (EPIA, 2014). Other examples of rapidly developing residential solar PV segment are found in Belgium (where 1 out of 13 households are equipped with a PV system), Denmark, Greece and the UK (EPIA, 2014). Likewise, large numbers of PV installations are noticed in The United States (US) in California, Arizona and Hawaii (Greentech Media & Solar Energy Industries Association, 2013). Electricity generation is thus increasingly placed at the distribution grid level as an alternative of transmission grid level. This affects the distributed nature of electricity generation (Alanne & Saari, 2006).

Demand response is a term that refers to "the changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized" (Aghaei & Alizadeh, 2013) meaning the electricity demand is being activated to respond on for example a price trigger. Regarding the terminology used, in this paper, we focus on price triggers and other incentives that could affect the "response" of the operation of different DER, including demand response itself.

Important system benefits related to the operation of renewable energy sources like wind and solar are decreased emissions and economic efficiency due to low marginal cost. However, for system operation, RES increase risks because of unpredictable production patterns due to their highly intermittent character. Therefore RES require flexibility services like back up generation to supply for balancing needs of the non-supplied demand. Next to those traditional methods of system balancing, demand response and storage can potentially supply the system with flexibility services. Storage units are potentially beneficial for electric energy time-shift, power supply capacity and transmission congestion relief (Eyer & Corey, 2010).

Next to the previous named developments regarding the variability of RES generation, the distributed nature of generation and the change of demand from static to responsive, other developments affect the way in which distribution grids require possible more decentralized management. The first one relates to the electrification of transport with the electric vehicle (EV). The EV development is important because EV charging significantly increases electricity consumption at distribution grids during peak periods, potentially jeopardizing security of supply due to congestion and voltage issues (Clement-Nyns, Haesen, & Driesen, 2011; Green eMotion, 2013).

3 Distributed Energy Resources as flexibility service providers within electricity systems

As described in the previous section, Distributed energy resources (DER) e.g. Electric Vehicles (EVs), combined heat and power (CHP) units, electric water heaters and storage units are potentially providers of flexibility services. Technically speaking, an electric flexibility product can be defined *as a power adjustment sustained for a given duration in order to balance supply and demand at a given* *moment in time*. Thus, a flexibility service is a service characterized by four attributes (see Figure 1): its *direction* (upward or downward) (a); its *electrical composition* in power (b); and its *temporal characteristics* defined by its starting time (c) and duration (d).

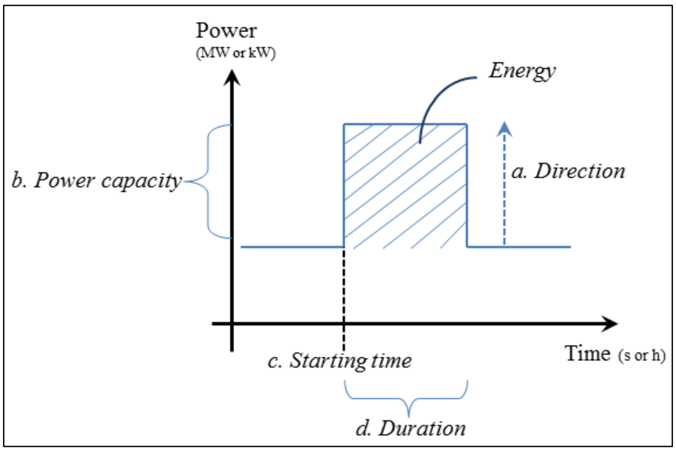


Figure 1: Characterization of flexibility products (Eid, Codani, Chen, Perez, & Hakvoort, 2015)

Some DER may have a single direction potential contribution (for instance typical household loads, such as water heaters, dishwashers and electric heaters), while others have bidirectional capabilities and could both act as a consuming and producing unit (e.g. EVs and storage units).

Furthermore, the electrical composition is of importance in order to state for what system flexibility needs the DER could serve, which calls for a differentiation between *power* and *energy* resources. The former have a rather low energy/power ratio. Those DER can provide the electricity system with a high power value, but are not able to maintain this power level for a long period of time. The latter have a high energy/power ratio and are more appropriate to maintain a change in power level for a longer period of time. The power resources are consequently better suited for short term markets (e.g. on the ancillary service markets) while energy resources are better suited for long term markets like for instance balancing mechanisms and trading DR in the bulk electricity market.

In order to compare the different DER on this criterion, we define the *max power temporal ratio* t_r (expressed in time) as the maximum duration a DER can sustain its maximum power variation with respect to its nominal power. For some DER types, this parameter can be computed by dividing the allowed energy range by the maximum power capacity (e.g. considering a stationary battery with a charging/discharging power equal to 10kW and an energy capacity equal to 50kWh, we find t_r = 5h). For some other DERs, it may be related to physical characteristics (for instance for a water heater with thermic inertia, we may find t_r = 30min). The lower this value, the more the DER can be considered as a *capacity type* DER, and vice-versa. This variable is intended to provide insights on differences between DER categories and is not a singular value for all DER in such category, simply because this is dependent on the specific technology.

What is more, the availability (in time) is a constraint that distinguishes the moment at which DER could provide services to the system. Some resources may only be available during specific periods of time – for instance EVs are most likely to be available from 6 PM to 6 AM. In order to compare the flexibility providing units on this criterion, we compute for each of the DER the ratio a_r defined as the average number of hours during which the unit is available divided by the total number of hours in a week. Also here, depending on the specific source (one EV differs from the other for example), in reality similar DER may offer different availability times, however we aim to provide insight in expected values.

Furthermore, the activation time refers to the aspect that some resources may be able to adjust their power much quicker than other sources. Generally, almost all electric appliances have a fast activation time, ranging from the order of a second to one minute, except for CHP units which have longer ramping times (Houwing, Negenborn, & De Schutter, 2010). Lastly, the geolocation of DER is of importance for the supplied nature of the required demand response. For example, geo-location based demand response could be of interest for local congestion management or distributed generation (DG) optimization. Table 1 provides an overview of the most common DER and their characteristics. The table is divided in different types of DER; consumption, bi-directional and generation.

	DER	Flexibility direction	Flexibility characteristic (power vs energy)	Availability ratio	Predictability	Technical response time	Grid[1]	Ref.
Electrical Consumption	**Lighting loads (W)**	Unidirectional	New LED systems: energy types older lightings: power types	20% < a_r < 50% during peak hours	Good	Second	DS	(Lee, Li, & Hui, 2011; Lu, Xie, Huang, Puyleart, & Yang, 2008; Samarakoon, Ekanayake, & Jenkins, 2012)
	Dispatchable, residential loads (washing machines, dishwasher)	Unidirectional	Power type 5s < t_r < 5min	a_r < 0.1 low *max power ratios* t_r due to max off time	High	Second	DS	(Lu et al., 2008; Samarakoon et al., 2012)
	Electrical heating/ Cooling (continuous loads)	Unidirectional	Power type $t_r \approx$ 15min	0.4 < a_r < 1	High	Second	DS	(Samarakoon et al., 2012; Tomiyama, Daniel, & Ihara, 1998)
Bi-directional	**Electrochemical Energy Storage (EES) (kW-MW)**	Bidirectional	Power & Energy types 4s < t_r < 10h	$a_r \approx$ 100%	Perfect	Second to Minute	DS or TS	(Divya & Østergaard, 2009; Yang et al., 2011)
	Electric Vehicle (kW)	Unidirectional or Bidirectional	Power & Energy types 30 min < t_r < 6 h	50% < a_r < 90%	High	Second	DS	(Kempton et al., 2009; Pearre, Kempton, Guensler, & Elango, 2011)
Generation	**PV Unit**	Unidirectional (production mode)	Not flexible	25%< a_r <41%	Good a few hours ahead	Minute	DS	(International Energy Agency, 2013)
	Micro-CHP unit (kW)	Unidirectional (production mode)	Energy type	$a_r \approx$ 100%	Perfect	Rather slow (0.15kW/min)	DS	(Houwing et al., 2010)

Table 1: The different DER and their technical characteristics

3.1 Consuming DER: residential loads

New generation LED lightings could adapt their power consumption to required grid power variations (Lee et al., 2011). Future LED systems could undergo system power variations up to 35% while humans would only perceive a variation of 15% in light intensity. This method would be particularly interesting for public lighting. On the contrary, older lighting systems do not have the same abilities (Lee et al., 2011; Samarakoon et al., 2012). Changing their power consumption would have serious impact on their luminous capability. LED lighting systems can maintain this power variation for a

[1] Where DS stands for distribution grid and TS for transmission grid

significant period of time and therefore can be considered as *energy type* flexibility resources. However, their potential power modulation is relatively low in absolute values. Their predictability is relatively good, while their availability highly depends on the usage considered. Typical lightings would be turned on from a few hours a day during peak hours to 12 hours a day, thus we have $0.2 < a_r < 0.5$. It is noticeable that this criterion is highly seasonal dependent.

Residential appliances, such as water heaters, washing machines, electrical heaters, air conditioners etc., have rather low *max power temporal ratios* t_r (many of those units are off or stand-by most of the time). The latter can range from a few seconds (e.g. for cookers) to a dozen of minutes (electric space heaters) (Samarakoon et al., 2012), thus providing a *maximum temporal ratio* of $5s < t_r < 15min$. Their availability depends a lot on the appliance considered: whereas electric space heaters have a good availability, therefore named continuous loads here ($0.4 < a_r < 1$) while washing machines have a very limited one ($a_r < 0.1$). Similar rationale applies for their predictability (Tomiyama et al., 1998; Wong & Pelland, 2013). Heat pumps coupled with thermal energy storage stand out in this category: indeed, their *max power temporal ratio* can reach up to 3h without any inconvenience for end-users (Arteconi, Hewitt, & Polonara, 2013), making those units suited for longer grid services such as peak shaving.

3.2 Bi-directional DER: Electrochemical storage and EVs

Storage units are potentially beneficial for electric energy time-shift, power supply capacity and transmission congestion relief (Eyer & Corey, 2010). Electrochemical Energy Storage (EES) units have a perfect availability and predictability ($a_r \approx 1$). Whether they should be considered as *energy type* or *power type* resources depend on their power density and energy density characteristics, both parameters being much related to the type of battery technology (Li-ion, Ni-MH, Ni-Cd, etc.) (Yang et al., 2011). Thus, it is possible to find EES units for all kind of applications, from very-fast high-power responding units (such as supercapacitors, $t_r \approx 4s$) to energy type chemical batteries (such as Li-ion batteries, $t_r \approx 10h$).

Most Electric Vehicles that are on the roads today have a battery capacity around 20kWh[2]. Their *max power temporal ratio* depends on the power of the charging station they are plugged in. Typical charging station powers range from 3kW to 50kW, leading to approximately $30\ min < t_r < 6\ h$. Because EVs are primarily used for transportation, capacity type services that would not empty the battery should be encouraged. Privately owned EVs are mainly available during nighttime and week-ends ($a_r \approx 0.5$), but the availability could rise up to $a_r > 0.9$ if charging points are installed at working places. Company fleets have slightly different usage patterns and could also be available in the afternoons ($a_r \approx 0.8$). Their predictability patterns are easily foreseeable (Pearre et al., 2011), especially considering a fleet of EVs and not a single vehicle.

3.3 Producing DER: Micro CHP and PV units

Micro-CHP units are small heat and electricity generating entities. They have a large availability and predictability since they are dedicated to heat and electricity production ($a_r \approx 1$). It is more difficult to define a *max power temporal ratio* for micro-CHP units because they could produce electricity at maximum power continuously, as far as they are being supplied in primary energy source (mainly gas). Rather, their availability to maintain a change in their electricity production will be based on economics considerations. The control strategies of micro-CHP units are likely to take into account energy costs (Houwing et al., 2010) in their economic balance. Therefore, micro-CHP units would fit in the *energy type* category.

[2] Nissan Leaf: 24kWh; Renault Zoe: 22kWh; BMW i3: 19kWh

PV units are different from the others, in the sense that their production output cannot be controlled – only, they can be curtailed in a few minutes in case of extreme network conditions. They are available in daytime, so between 6 hours and ten hours a day depending on their location. Good predictability is difficult to achieve, and is dependent on the method used and the desired spatial resolution. Generally speaking, we can say that acceptable forecasts can be achieved a few hours a-head (International Energy Agency, 2013).

4 Markets for electric flexibility trading

Traditional electricity systems are managed in a top-down manner, meaning that generally large generation units connected at high voltage levels feed in electricity for electricity consumers that are located at all other voltage levels. Flexible generation units (mostly hydro units, gas and coal fired plants) are besides providers of bulk electricity supply, also providers of electric flexibility by means of upward and downwards adjustments. Those adjustments could be incentivized by for example capacity contracts with the SO for automatic adjustments.

Beside generation, also consuming units might be suppliers of electric flexibility. France and the United Kingdom (UK) are important frontrunners regarding demand response developments in Europe (SEDC, 2014). In France, already before sector liberalization, demand response activity was triggered by the electricity utility EDF for industrial electricity customers. These units received dynamic tariffs that incentivized consumption shifting. Table 2 provides an overview of the most common traditional markets for electricity trading in the short and long term, based on the French system. The next sections describe in further detail the presented examples.

4.1 DER trading for ancillary services

Ancillary service markets are in place in order to manage transaction for system balancing in the short to very short term. These markets are organized very close to real-time and require automated load adjustment. In France ancillary service markets are organized shorter than 30 seconds before real-time for Frequency Containment reserves (FCR, also named primary reserve), below 15 minutes for frequency restauration reserves (FRR, also named secondary reserve) and lastly replacement reserves (RR, tertiary reserve) for system balancing between 13-2h before real time (see Table 2). In the United States (US) and UK different projects present examples of DER flexibility provision within ancillary service markets (dynamicDemand, 2005; Kempton et al., 2009). Due to the fact that individual DER do not provide sufficient reliable electric flexibility to be tradable in markets, aggregation is required in order to trade in organized markets. The US example of EV trading is the Delware project where an EV aggregator acts as an intermediary firm between PJM (the local SO) and flexibility service providing EVs. This aggregator sells a certain amount of capacity to the grid operator and bids this in the hourly auction for frequency regulation and for the available power capacity ($/MW-h) (Kempton, 2014; Kempton et al., 2009). When participating in this frequency regulation, EVs receive a dispatch signal from the local TSO (PJM) and are remunerated accordingly. If the regulation service offered by the Delaware EV aggregator has not met with the performance thresholds over a specified time period in terms of correlation (delay) and precision, PJM is able to disqualify the aggregator (Chris, 2013).

4.2 DER trading for system balancing and network congestion management

Balancing services are arranged a bit longer before real-time than ancillary services and in different places in Europe they are open for aggregation and demand response. In Germany many industrial loads are directly participating in the balancing mechanism, however for aggregated loads still many barriers exist to participate within the balancing markets (Koliou, Eid, Chaves-Ávila, & Hakvoort, 2014). In the French system such barriers have been lowered by reduction of the minimum bidding capacities for balancing services from 50 to 10 MW. This has been done in order to motivate the entrance of smaller entities like aggregators to participate in balancing mechanisms (SEDC, 2014).

Differently, for network congestion management a French example of small load aggregation is the aggregator named Voltalis[3]. Customers contracted with Voltalis receive a free box installed in their home named Bluepod, which reduces their electric heating device operation in short time intervals when Voltalis receives a signal from the TSO. The dispatch signal is mostly related to endangered electricity supply sufficiency in Brittany (a French region poorly interconnected to the other ones) and network limitations. Customers who have the box installed are automatically enrolled, but can opt-out at any time by pushing a button on the device and use their electric heater as usually. Voltalis as an aggregator is able to trade the aggregated flexibility in different markets like balancing markets and demand response mechanisms of the TSO. The customers do not receive any financial benefit when their heating device reduces their load, but observe a reduction of their normal electricity bill due to those interruptions in electricity consumption for heating.

In Sweden the DSO can incentivize load shifts by the provision of Time of Use (TOU) prices in order to deter network investments or decrease congestion by incentivizing the customer to shift the load away from peak moments (Bartusch & Alvehag, 2014; Bartusch, Wallin, Odlare, Vassileva, & Wester, 2011). Different from the previous examples, the DSO does not trade this flexibility within a market for congestion management or deterred network investments, but this is a direct incentive arrangement between the DSO and electricity users.

4.3 DER trading in spot markets and generation capacity markets

As the first one in Europe, the French system provides a possibility for demand response trading within spot markets. This is possible since 2014 wherein demand response can be traded in the day-ahead market through the NEBEF mechanism[4]. In 2017 it is foreseen that demand response will also be tradable in capacity markets in France (RTE, 2013a). Furthermore the French TSO organizes an annual tender dedicated to specifically to Demand Response providers. Other possibilities of spot market and capacity trading markets for DR? Check.

[3] Information on Voltalis via: www.voltalis.fr

[4] See https://clients.rte-france.com/lang/fr/clients_distributeurs/services_clients/effacements.jsp

Time frame	Technical system flex need	Trading mechanism	Capacity or Energy trade?	Notification[5] before real time	Suited DER type	Location[6] DER connection	Examples of DER trading/incentive in traditional centralized markets
Short Term	Ancillary Services	Primary Reserves (FCR)	Capacity	<30s (automatic)	EV's, residential loads, continuous loads, EES	Transmission and Distribution	UK: dynamic demand project with dynamically-controlled refrigerators (dynamicDemand, 2005)
		Secondary Reserves (FRR)	Capacity	<15 minutes (automatic)	EV's, residential continuous loads, electrical heating, EES	Transmission and Distribution	USA: EVs for frequency regulation in Delaware (Kempton et al., 2009)
Medium Term	Real time system balancing	Balancing mechanism (Tertiary reserves, RR)	Energy and/or Capacity	13 min - 2 h	EV's, EES, CHP units	Transmission and Distribution	Germany: industrial loads participate in balancing mechanism (Koliou et al., 2014)
	Network constraints / Network capacity planning	Transmission congestion management	Energy	13 min - 2 h with balancing mechanism or separate	large EV coalitions, EES, CHP units	Transmission and Distribution	France: congestion management is traded in balancing market (CRE, 2015) And the Voltalis load management of residential heating devices (Eid et al., 2015)
		Distribution congestion management **(not existing)**	Energy or Capacity	Not existing	EV's, residential loads, electrical heating, EES	Distribution	Sweden: distribution time of use for residential use. (Bartusch et al., 2011)
	Spot market energy trading	Intraday market	Energy	1 - 24 h	Aggregated loads	Transmission and Distribution	n.a.
		Day ahead market	Energy	24 - 48 h	Aggregated loads	Transmission and Distribution	France: The NEBEF mechanism allows trading of DR in spot market (RTE, 2013b)
Long Term	Generation Capacity planning	Capacity Market	Capacity	Year ahead	Aggregated loads	Transmission and Distribution	France: Foreseen in 2017 that demand response will be tradable in capacity markets. (RTE, 2013a)
		Capacity Payments	Capacity	Year ahead	Aggregated loads	Transmission and Distribution	n.a.

Table 2: Traditional markets for balancing from a single node perspective (based on the French case study)

5 Incentives for efficient operation of Distributed Energy Resources

As the distribution system transitions from a passive network of consumers to a more actively managed system of network users with diverse consumption and production behaviors, price signals

[5] Note that these values relate to the French system and are very system dependent.
[6] This paper focuses mainly on DER connected at distribution level, however demand response from large industrial units which is mostly connected at high voltage levels can be also seen as a part of DER and therefore taken into account here.

will play a crucial role in shaping the interactions between the physical components of the distribution system and network users (Arriaga & Bharatkumar, 2014). There are different ways to create efficient interaction in electricity systems; tariffs are one of the incentive methods that are being described in this section.

A one-sided economic approach on settlement of incentives for DER management would be the application of real-time nodal pricing that would incorporate both grid and supply constraints at each moment in time, incentivizing upward or downward adjustments for all DER (Sotkiewicz & Vignolo, 2006). However, due to the fact that each flexibility source has its own technical requirements and abilities to provide flexibility services, non-singular approach; a combination of tariffs, contracts and direct control.

Broadly speaking, a distinction is made between **price based** and **controllable** methods for demand response (Pfeifenberger & Hajos, 2011), also referred to as price based and interruptible demand response (Muratori, Schuelke-Leech, & Rizzoni, 2014) or as direct and indirect methods of load modification. Next to tariffs therefore, direct control and other contract arrangements are methods by which efficient operation of DER could be incentivized.

5.1 Price based methods for DER management

Price-based demand response is incentivized by exposing the DER user to a time-varying electricity rate, also called a dynamic rate. The theory of dynamic tariffs for demand response has already been discussed in 1989 by David and Lee for large industrial electricity users (David & Lee, 1989). Table 3 presents an overview of those tariff options with definitions. In this table a distinction is made between basic dynamic pricing options and those which specifically incentivize adjustments of users' normal consumption patterns (also called baseline consumption adjustments). The basic pricing options leave most freedom to the user, without requiring extra information on baseline consumption levels. Options for such pricing methods are 1) Time-of-Use pricing (TOU), 2) Real-Time Pricing (RTP) and 3) Critical Peak Pricing (CPP). The more specific incentives for baseline adjustments are 4) Peak Time Rebates (PTR), 5) Interruptible capacity programs (ICAP) and 6) Emergency demand response (Newsham & Bowker, 2010). Those options require baseline consumption information penalizing or remunerating for specific load adjustments. With RTP, the user receives a changing price per time step (for example 15 minutes) and the customer will shift electricity consumption accordingly. With critical peak pricing, only in specific hours per day a higher price is presented to the customer. Electricity customers receive an ex-ante notice of these moments in time and can therefore plan their consumption (Koliou, Eid, & Hakvoort, 2013). Critical peak pricing toghether with the options for baseline adjustments are specifically incentivizing the shift of electricity consumption away from a specific moment in time. A driver for such incentives could relate to the for example high wholesale market prices or jeopardized system reliability (Koliou et al., 2013).

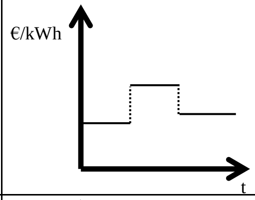
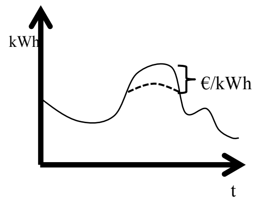
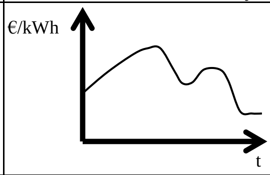
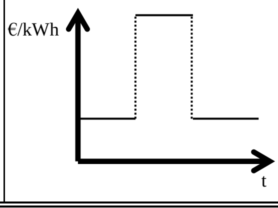
Basic Dynamic Pricing Options			Specific incentives for baseline adjustment		
Time-Of-Use (TOU)	Fixed electricity prices for different time blocks within a time period		**Peak time rebates (PTR)**	A rebate when electricity is reduced compared to baseline consumption, within certain hours in a year.	
Real-Time-Pricing (RTP)	An hourly rate depending on the day ahead real-time price of electricity		**Interruptible Capacity Program (ICAP), Interruptible load**	A rebate when electricity is reduced below a baseline value.	
Critical Peak Pricing (CPP)	High electricity price periods for certain (fixed) days of time within a year		**Emergency Demand Response**	Mandatory commitment to reduce load, with penalties if not supplied.	

Table 3: Possible dynamic pricing options for DER management (David & Lee, 1989; Faruqui & Sergici, 2009; Hakvoort & Koliou, 2014)

5.2 Direct load control for DER management

With controllable or incentive-based demand response, a central actor like the system operator, aggregator or even retailer could make the end-user agree to automatically curtail its electricity demand under certain circumstances. This means that a central actor has direct access to the load and is able to reduce or increase this as required for the system or for portfolio management purposes. Load shedding refers to the "switching off" of entire network zones from electricity supply in order to sustain total system operation (Newsham & Bowker, 2010). With brown outs, the system operator slightly reduces voltage frequency in order reduce the needed electricity transport capacity and generation capacity but to maintain electricity supply quality within limitations (Blume, 2007). The named approaches are more contractual and introduce constraints for the supplied flexibility, while the price-based approaches described in Section 5.1 leave the customer to decide in real-time regarding the supply of flexibility (DOE, 2006). Consequently, direct control methods are probably more suited for short term services, or services which require a very precise location of activation like voltage control and congestion management. Table 4 provides an overview of different incentives presented in Section 5 and relates them to their suitability to DER types and markets for flexibility.

5.3 Techno-economic alignment of incentives

Depending on the type of consumer and the DER installed, a specific contract or price incentive might be appropriate to incentivize DER interactions that are efficient for the overall system. With focus on the technical activation time of DER and possible incentives, Table 4 provides an overview of possible arrangements. For grid interactions which require response between 1 to 30 minutes before real-time direct load control would be suited in order to secure reliability of supply. Appropriate DER for such short notification time periods would be most DER except for CHP units due to their longer response times. For longer notification times of 30 min to 1 hour all other pricing methods could be suited and decisions should be further depend on socio-technical issues like the urge of required response, the direction and user characteristics like price elasticity and the availability of home automation for example. All DER types would be appropriate for supplying flexibility for longer than 1 hour of activation time. For the very long term, critical peak pricing and time of use pricing is appropriate due to the possibility to settle those prices on a yearly basis, as the case in France with the tempo tariff[7]. Differently, PV units provide in some way possible flexibility but in combination with storage unit their reliability would be improved.

Notification time <u>before real-time</u>	**Appropriate incentives or control method for <u>DER management</u>**	**Related markets for electric flexibility trading[8]**	**Appropriate DER**
< One minute	Direct load control (DLC)	Frequency control (primary, secondary, tertiary reserves), voltage control	*EV, Continuous loads (heating/cooling, lightning), EES*
1- 15 minutes	Direct load control	Network restauration, voltage control	*EV, Continuous loads (heating/cooling) , EES*
15- 30 min	Direct load control	Network restauration (HV/LV), Balancing market, Portfolio balancing	*EV, EES, CHP units Continuous loads (heating/cooling), dispatchable loads*
1 hour	ICAP, Emergency demand response, Real time pricing, Direct load control, Peak time rebates, Critical Peak Pricing	Balancing market	*EV, EES, CHP units Continuous loads (heating/cooling), dispatchable loads*
1 - 48 hour	ICAP, Emergency demand response, Real time pricing, Direct load control, Peak time rebates, Critical Peak Pricing	Spot Market (Day ahead and Intraday market)	*EV, EES, CHP units Continuous loads (heating/cooling), dispatchable loads, PV units with storage*
Year ahead	Critical peak pricing, Time of use pricing	Deferring network investments (HV/LV), generation investment peak reduction	*EV, EES, CHP units Continuous loads (heating/cooling), dispatchable loads, PV units with storage*

Table 4: Relationship of notification times, appropriate incentives and markets for DER flexibility trading

6 Discussion

This paper provided an overview of different DER and their technical abilities to provide flexibility services to the central grid. The activation of the demand side is technically bounded by the technical abilities, but furthermore should take into account other variables which are discussed here.

6.1 Socio-economic effects on appropriate incentives

The presented work provides a good starting point of deciding between appropriate DER for flexibility management in electricity systems. However, in reality, appropriate incentives are not only technical-economic dependent, but also socio-economic affected by individual factors like consumption behavior, sustainability drive, relative price differences and price elasticity of the user (Goulden, Bedwell, Rennick-egglestone, Rodden, & Spence, 2014). This work did not look into those issues but pilot projects which takes into account those variables could provide more insight in those issues and could furthermore specifically direct which incentive would be most appropriate depending on consumer and DER characteristics.

6.2 Transitioning towards decentralized system operation

Beside the socio-economic context, also the regulatory environment of the electricity system at stake will affect the decisions for deciding on appropriate incentives. Flexibility trading options presented in Table 2 are all presented in the framework of centralized system management, generally managed

[7] See http://residential.edf.com/energy-at-home/offers/electricity/tarif-bleu-56121.html
[8] Composed with insight from report (International Energy, 2008)

by a system operator. However, as discussed by others, decentralized management approach could open up possibilities for locational pricing, local balancing and optimization at community level with virtual power plant (VPP) approach (Alanne & Saari, 2006; Kamat, Oren, Hall, & Oren, 2002; Pudjianto et al., 2007). For example, distribution congestion management and distribution balancing are not possible within centralized market designs and till now these externalities have been integrated in the final electricity price. Consequently, DER penetration could call for parallel a decentral arrangement of trading in markets which could enable flexibility trading for electricity flows from different voltage levels and time periods. Beside the fact that decentralized management would yield benefits for more cost-causality based incentives, it is discussed by Goulden et al. that moving away from centralized system towards decentralized system furthermore encourages a new approach on consumption, moving from "*passive energy consumer*" towards an "*active energy citizen*" (Goulden et al., 2014). Therefore the use of current markets for DER management might be a transition phase possibly towards a decentralized techno-economic management approach of the electricity system. Figure 2 presents a conceptual presentation of the arrangement of such a decentralized system based on arising system challenges and opportunities with DER integration.

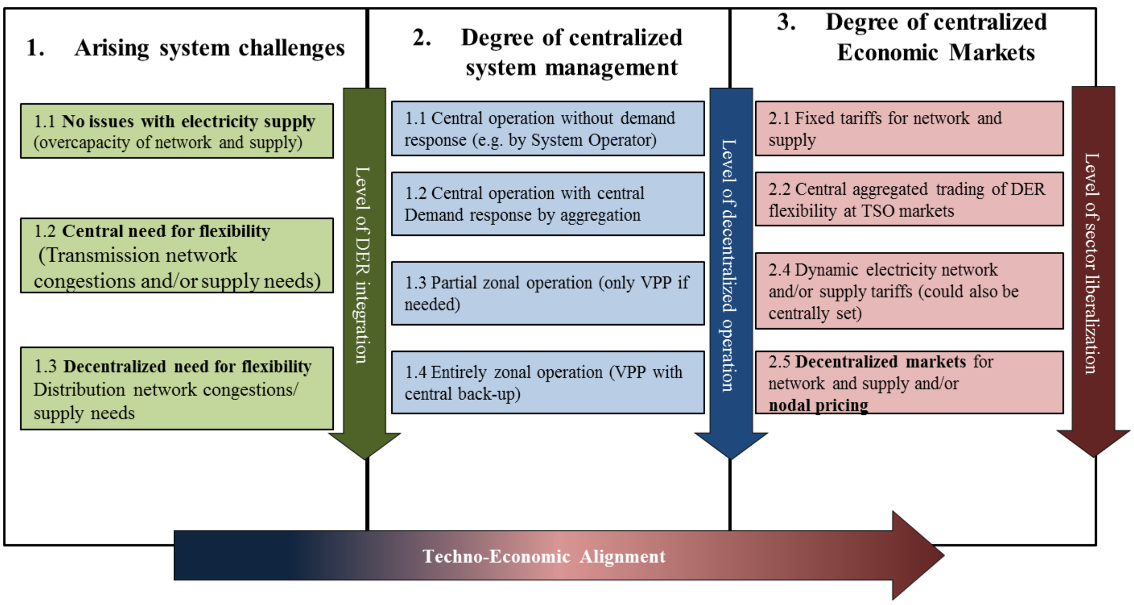


Figure 2: Conceptual presentation of relationships between electricity system needs and decentralization

6.3 Settlement of incentives and control: which roles for different actors?

Depending on the electricity market design and the level of sector liberalization, one or more of the actors in the sector could decide on tariffs, control and other incentives. Therefore insight in the role(s) of the DSO, electricity retailer, supplier, (independent) aggregator and other involved third parties are crucial in order to understand the process of incentive settlement. Challenges that arise have not been dealt before with, for example the ones related to load aggregation. Due to the fact that there are minimum trading values for the balancing and other free markets, DER should be bundled to simultaneously provide significant tradable amounts of flexibility in those other markets. However, challenges arise when this is done by independent actors due to competing plans of electricity suppliers and demand response aggregators (Eurelectric, 2015).

7 Conclusions and Policy Recommendations

This paper presented a review of existing Distributed Energy Resources’ (DER) abilities to provide flexibility services and options to incentivize such interactions. With a central management approach on the electricity system, flexibility services from DER could be traded within traditional centrally arranged markets for flexibility for securing reliability of supply. A one-sided economic approach on settlement of incentives for DER management would be the application of real-time nodal pricing that would incorporate both grid and supply constraints in order to incentivize efficient interactions for upward or downward adjustments at each moment in time for every DER. However, due to the fact that each flexibility source has its own technical requirements and abilities to provide flexibility services, the authors of this paper argue that DER require a non-singular approach; a combination of tariffs, contracts and direct control.

Next to central management of DER, also decentralized management of DER could be possible through for example local aggregators and/or virtual power plant arrangements. The potential for this type of management is arising, especially with the increasing roll-out of smart meters, sensing and control at distribution level and upcoming risks due to over-voltage and congestions with the penetration distributed generation (DG). Decentralized management of the system could reduce local needs for expenses in the network and support the reliability of supply with high level of DG. Consequently, the options presented in this paper are suited for a transition phase of centralized towards more decentralized operation, but further decentralization might require new market design. Therefore future research should take into account such options of market design and the roles of traditional and new actors within such markets. Depending on the current and expected challenges within electricity systems, policy should anticipate the required DER transactions and design markets that incentivize arrangements that will benefit the system from an economic, sustainability and reliability perspective.

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