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Review on the main flexible residential loads with potential to participate in Demand Response Programmes

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Abstract

Demand Response programmes represent an important component in the establishment of smart grids, since the management of load flexibility enables demand to be dynamically adjusted according to fluctuations in the price of electricity in the wholesale energy market, or according to the supply of distributed energy generation from renewable sources. Given the importance of load flexibility for the optimised management of smart grids, this paper argues that it is essential to carry out a technical characterisation of the main flexible residential loads with potential to participate in Demand Response programmes. For that, the scientific literature was reviewed. This review carried out in this study aimed to point out different approaches in the selection of flexible residential loads with potential to participate in DR programmers, as defined by 6 different authors. The main conclusion that can be drawn from the review of the studies selected in this paper is that there is a consensus on the main flexible residential loads with potential to participate in DR programmes. In conclusion, this study argues that there is the need to design and implement real case studies that examines the impact of the selected flexible residential loads under different scenarios and under real-market conditions to access the new market potential in this field. It is only through the successful implementation of innovative DR programme models (followed by the scaling up from pilots to commercial deployments) that the benefits of demand flexibility will be truly known.

Keywords: demand response, flexibility, load management, smart grid

1. Introduction

As evidenced by Yin et al. (2016) [1] and Tulabing et al. (2016) [2], the high penetration of renewable resources in the energy grid is increasingly driving the need to promote ancillary services as means to absorb potential interruptions of power supply caused by the intermittency of distributed energy generation, thus reducing critical peaks in energy demand. In view of this, the comprehensive management of load flexibility from the demand side through Demand Response (DR) programmes represents a low-cost alternative for the provision of ancillary services to the energy grid in comparison to the management of flexibility from the supply side through reserve generation units, which represent costly non-renewable sources of uninterrupted power to the grid that are activated during emergencies in power supply.

In view of this, DR programmes represent an important component in the establishment of smart grids, since the management of load flexibility (through mechanisms of load shedding or load shifting) enables demand to be dynamically adjusted according to fluctuations in the price of electricity in the wholesale energy market, or according to the supply of distributed energy generation from renewable sources [1] [2].

As pointed out by the abovementioned authors, the emergence of DR programmes was made possible in part by technological advances in Information & Communication systems, as it allows the optimal management and aggregation of distinct flexible loads in real-time, enabling in this way the transaction of these aggregated flexible loads in the wholesale energy market.

Dyson et al. (2015) [3] explains that DR programmes in liberalised energy markets could represent a major benefit for utilities, energy suppliers, aggregators, Distribution System Operators (DSOs) and Transmission System Operators (TSOs), since the balancing of supply and demand promoted by these programmes results in the reduction of the costs of maintenance of the energy grid infrastructure and in the reduction of the electricity price fluctuations in the energy market. In this sense, in order to remain competitive in the new paradigm brought forward by smart grids and distributed energy resources, these traditional big players need to develop new business models and learn from pilot programmes to design new services focused on the final customers that lead to behavioural changes related to the flexible consumption of energy, as means to encompass the new value proposition derived from DR programmes and create new revenue opportunities outside of traditional utility offerings.

In this sense, Dyson et al. (2015) [3] and Goldenberg et al. (2018) [4] suggest that policy makers should support the introduction of new incentives that facilitate public-private partnerships (PPPs), thereby fostering innovation in the energy sector. Furthermore, the authors also suggest that policy makers should support the creation of new regulatory frameworks that ensure investment recovery for those utilities that invest in the adoption of load flexibility management as a power grid balance asset. These developments may come in the form of new tariff models that reflect the marginal costs of utilities, ensuring that the reduction of the final customer's invoice (and hence the reduction of the utility's own revenue) also takes into account the significant cost reduction of network maintenance. Finally, the authors suggest that policy makers should support the creation of incentives (i.e., monetary incentives, such as rebates; and non-monetary incentives, such as automation and DR programmes) that facilitates the purchase of flexibility-enabling technologies to increase end-user involvement in DR programmes.

Given the importance of load flexibility for the optimised management of smart grids, this paper argues that it is essential to carry out a technical characterisation of the main flexible residential loads with potential to participate in DR programmes. For that, the scientific literature was reviewed.

2. Literature review

This review carried out in this study aims to point out different typologies of flexible residential loads with potential to participate in DR programmers, as defined by different authors. When loads were not clearly grouped and categorised, they were listed as individual loads.

2.1 Classification proposed by Tulabing et al. (2016)

Tulabing et al. (2016) [2] developed a load aggregation prioritisation algorithm based on the flexibility response characteristics of different typologies of residential loads. For this, the authors categorised different residential loads into 3 different typologies of flexible loads and 1 typology of non-flexible loads, as detailed in Table 1.

The study simulated 3 different scenarios to test out the proposed load aggregation prioritisation algorithm. For the simulations, battery-based energy storage technologies were left aside, and electric vehicles were taken solely as a load and not as a battery that supplies power to the grid. This was done to highlight the potential of the aggregation methodology to balance the grid without the need to rely on energy storage devices. In view of this, the 3 different scenarios are presented:

- Mitigation of system peak demand: the prioritised mechanism deployed in this scenario was load shifting capacity from electric vehicle charging, refrigeraton and non-urgent TCLs;
- Mitigation of distributed energy resources disruptions: the prioritised mechanism deployed in this scenario was load shedding capacity from HVAC systems, freezers and refrigerations;
- Mitigation of market price fluctuations: the prioritised mechanism deployed in this scenario was load shedding capacity from electric vehicle charging, non-urgent TCLs, fridges, and freezers.

Table 1: Definition of each typology of flexible residential loads with potential to participate in DR programmes proposed by Tulabing et al. (2016)[1].

Typology		Types of loads	Definition
Battery-based loads		Electric vehicles; stationary batteries	These loads are considered flexible since they can store chemical energy and can be recharged. They are also considered to be interruptive since they can be delayed as long as they meet the charging requirements set by the end-user. In this sense, the recharge can be interrupted when there is insufficient power in the network, which consequently approximates the "expected time to complete the recharge" to the "last available time to finish its recharge operation in time, as required by the end-user." Within these specifications, whenever there is a surplus electricity available in the network, recharging can resume automatically
Thermostatically Controlled Loads (TCLs)		HVAC systems; water heaters; refrigerators; freezers	These loads are considered flexible since they have the capacity to store thermal energy. These loads are prioritised according to the temperature deviations from their predefined setpoint – i.e., tolerance for temperature deviation (deadband). In this sense, loads with higher deadbands must be used first. The flexibility of TCLs is also achieved by maintaining the flexibility values below the established maximum temperature value (in the case of the cooling mode) or higher than the established minimum temperature value (in the case of the heating mode) even though it is still within the thermal zone of the deadband. In the case of HVAC systems, it is noted that load shifting mechanisms (i.e., precooling) are more efficient than load shedding, since the former can keep the thermal comfort of the interior of buildings for longer periods of time
Non-TCLs	Non-urgent	Dishwashers; clothes washers; Clothes dryers	This category includes non-urgent loads that are considered flexible since they can be started after some admissible time. Given that these loads can be delayed, they provide room for flexibility between "the expected end time based on the duration of its operation" and "the last time required to complete its operation on time, as required by the end-user." Unlike the batteries, the operations of these loads cannot be interrupted once they are started- Therefore, the prioritisation of the flexibility of this type of loads is to avoid exceeding the last time necessary to finish its operation in time, as required by the end-user
	Urgent	Entertainment (e.g., computers, televisions, video games, etc.); cleaning; cooking; lighting	These loads are not flexible since they need to respond instantly to the end-user's request as soon as the equipment's switch is turned on. Thus, they should have the highest priority and be addressed first among all types of flexibility, in order to allow end-users to have their daily routines affected as little as possible by DR programmes

2.2 Classification proposed by Hoogsteen et al. (2016)

Hoogsteen et al. (2016) [5] developed a mechanism for the creation of artificial residential load flexibility profiles, which allowed the evaluation of different approaches for DR programmes in smart grids. Specifically, the authors categorised the main flexible residential loads into 4 distinct classes: timeshiftables, buffer-timeshiftables, buffers and curtailable, as explained in Table 2.

On the other hand, non-flexible loads were divided into 6 different categories: stand-by loads, electronic equipment, lighting, induction equipment (ventilation), refrigerators and others.

[1] Source: Adapted from Tulabing et al. (2016).

Table 2: Definition of each typology of flexible residential loads with potential to participate in DR programmes proposed by Hoogsteen et al. (2016) [2].

Typology of flexible loads	Types of loads	Definition
Timeshiftable	Dishwashers; clothes washers; clothes dryers	Load flexibility is specified through operations with predefined start and end times. In this way, operations cannot be started before the start time nor finalised after the end time that were predefined
Buffer-timeshiftable	Electric vehicles	Load flexibility is specified by operations with a predefined start time, deadline and required energy demand. Electric vehicles have both their maximum power consumption capacity and buffer capacity fixed
Buffer	Stationary batteries; water heaters	These equipment have specified their maximum power consumption, production level and capacity
Curtailable	Photovoltaic panels	Load flexibility is defined through operations that establish a fixed profile of consumption and production, as well as the amount of energy that can be reduced

2.3 Analysis carried out by Yin et al. (2016)

Although the study conducted by Yin et al. (2016) [1] did not specifically focus on the categorisation of different categories of flexible residential loads, it presented promising results for DR estimation models targeting Thermostatically Controlled Loads - namely, heating, ventilation and air conditioning (in the case of commercial buildings) and multi-dwelling unit, single unit, water heaters and refrigerators (in the case of residential buildings).

Through the aggregation of the different flexible loads of these equipment, the proposed model quantified the DR potential (i.e., load shifting) for both commercial and residential sectors, as well as quantified the energy savings that could have been obtained through the creation of different scenarios of setpoint adjustment. The study concluded that HVAC systems represent a good asset for DR programmes for the following reasons:

- HVAC systems account for a substantial share of the electrical consumption of buildings;
- The “thermal flywheel” behaviour of indoor building environments allows HVAC systems to be temporarily switched off (i.e. load shedding) without immediate impact on the comfort of the building’s occupants;
- DR programmes targeting HVAC systems can be at least partially automated with smart management and control systems, thus reducing user responsibility for the implementation of the flexibility programmes.

2.4 Analysis carried out by Dyson et al. (2015)

The study conducted by Dyson et al. (2015) [3] performed an economic analysis of five main types of flexible residential loads, namely: air-conditioning; residential water heater; electric vehicle charging; clothes dryer; and battery energy storage. Specifically, this analysis designed different models for load shifting, taking into account the impact of distinct climates, tariff structures as well as PV production on load flexibility.

2.5 Analysis carried out by Goldenberg et al. (2018)

The study conducted by Goldenberg et al. (2018) [4] demonstrated that flexibility management of 8 different types of flexible loads through DR programmes (i.e., load shifting to periods of high availability of renewable energy in the grid) can level the load demand curve and reduce peak loads. The flexible loads selected for this study were: residential water heater; commercial water heater; residential air-conditioner;

[2] Source: Adapted from Hoogsteen et al. (2016) .

commercial air conditioner; residential heater; commercial heater; residential plug loads; and electric vehicles.

This study concluded that DR programmes of such magnitude can reduce the contingency (i.e., curtailment) of distributed generation by 40%; this increases the value of renewable energy by more than 30% when compared to a system with inflexible demand, thus transforming renewable energy into a more attractive asset for the deployment of smart grids. In addition, DR programmes can reduce energy demand during peak periods by 24%, as well as reduce the average magnitude of the multi-hour peaks (i.e., the "duck curve") by 56%.

2.6 Analysis carried out by Pipattanasomporn et al. (2014)

The study conducted by Pipattanasomporn et al. (2014) [6] trialled the potential of 11 different residential loads from two American households to participate in DR programmes. Specifically, the focus of this study was to elaborate an extensive dataset of the consumption profiles of these equipment.

The selected equipment is presented in Table 1, as well as their respective flexibility potential to participate in DR programmes.

Table 3: Potential of 11 different residential loads to participate in DR programmes[3].

Appliance type	Average peak power consumption in a cycle (W)	Average min power consumption if DR is performed (W)	Load reduction potential (W / %)	Possible interruption/ deferral period	DR potential	DR potential rank
House 1						
Clothes dryer	2,950	185	2760W-2950W / 94%–100%	Up to 30min/ Up to several hours	High	1
Air conditioner	1,150	0	1,150W / 100%	Vary	Medium	2
Clothes washer	580	0	580W / 100%	None/ Up to several hours	Low	3
Refrigerator	365/135	0	365W / 100%	Up to several hours (defrost cycle)	Low	4
House 2						
Clothes dryer	5,760	226	5,534W-5,760W / 96% - 100%	Up to 30min/ Up to several hours	High	1
Water heater	4,500	0	4,500W / 100%	Vary	High	2
Air conditioner	2,000	0	2,000W / 100%	Vary	Med	3
Dishwasher	1,180	0	1,180W / 100%	None/ Up to several hours	Med	4
Refrigerator	500 - 145	0	500W / 100%	Up to several hours (defrost cycle)	Low	5
Clothes washer	200	0	200W / 100%	None/ Up to several hours	Low	6
Oven	1,300 – 3,000	0	0	None	None	None

[3] Source: Adapted from Pipattanasomporn et al. (2014).

Table 3 compares the energy consumption of the different equipment, as well as their potential to reduce peak power, their load shedding/ shifting capacity (without affecting end-user comfort) and potential to participate in DR programmes.

As can be seen for House 1, the equipment that presented the highest potential for load reduction during peak hours through DR programmes was the clothes dryer, followed by the air conditioner, clothes washer and refrigerator.

In the case of House 2, the equipment that presented the highest potential for load reduction during peak hours through DR programmes was also the clothes dryer, followed by the water heater, the air conditioner, dishwasher, refrigerator and, finally, the clothes washer.

In view of these results, the authors reached the following conclusions:

- Clothes dryers represent the residential loads with the greatest flexibility potential to participate in DR programmes amongst all loads selected in this study. This is because the load shedding or shifting of this typology of flexible residential load has the potential to considerably reduce the total electric consumption of a household. Load shedding can be performed using hardware devices that disconnect the heating coils of the machines, thus allowing them to dry the clothes without heating. However, this interruption should not exceed 30 minutes to avoid excessive heat loss. Load shifting can also be performed using automated management and control systems that delay the start time of their drying cycles. The deadband to carry out the load shifting mechanisms can be of several hours, depending on the level of urgency of the end user in having the drying cycle completed;
- Water heaters can offer the second greatest flexibility potential to participate in DR programmes (namely load shifting performed through direct load control programmes – i.e., network operators have the right to directly change the load profiles and operating setpoints of electrical equipment according to the requirements of each end-user). To perform direct management and control of the water heating process without affecting end-user comfort, it is necessary to perform real-time monitoring of the water temperature inside the heating tank so that the interruption of the water heating operation takes place only within a predefined water temperature limit set by the end user. Thus, whenever the water temperature in the heating tank exceeds this limit, the heating operation of the water is resumed;
- Air conditioners offer a medium flexibility potential to participate in DR programmes, since their automated control can reduce approximately 1 kW of peak power consumption (in the case of splits) and 2 to 4 kW of peak power consumption (in the case of centralised HVAC systems). The simplest way to implement DR programmes with air conditioners is by adjusting their temperature setpoints. In this case, all DR programmes are carried out within the comfort limits set by end-users. Thus, while the indoor environment temperature is within the specified comfort range, the operation of the equipment may be interrupted;
- Dishwashers can reduce their load demand by up to 1 kW through load shifting mechanisms performed using automated management and control systems that delay the start time of their washing cycles. The deadband to carry out the load shifting mechanisms can be of several hours, depending on the level of urgency of the end user in having the washing cycle completed. However, these machines cannot have their washing cycles stopped once they are started, thus requiring a higher degree of rigor of DR programmes;
- Clothes washers and refrigerators have low potential to participate in DR programmes due to two reasons: firstly, both equipment do not have high consumption profiles; secondly, there are not many smart models available in the market that allow the automated shifting of the start of the washing, rinsing and spin cycles (in the case of clothes washers) or the defrost cycle (in the case of refrigerators);
- Ovens do not offer any load flexibility for DR programmes, since the shedding or shifting of their load significantly affects the comfort and convenience of end-users.

3. Conclusion

The main conclusion that can be drawn from the review of the studies selected in this paper is that there is a consensus on the main flexible residential loads with potential to participate in DR programmes. Specifically, the flexible loads that appear the most in the scientific literature under analysis were (by order of magnitude): water heaters (6); HVAC systems (5); electric vehicles charging and clothes dryers (4); clothes washers, dishwashers, refrigerators and stationary batteries (3); and, finally, freezer and residential plug loads (1).

As for the impact of each type of flexible residential load in DR programmes, results vary greatly from study to study since it depends on a wide array of factors, such as: the purpose of the DR programme (e.g., mitigation of system peak demand, of distributed energy resources disruptions or of market price fluctuations); load aggregation (or not); use of algorithms for load prioritisation (or not); climate; available tariff structures; integration of distributed energy resources; overall demand profile; etc.

Finally, this study argues that there is the need to design and implement real case studies that examines the impact of the selected flexible residential loads under different scenarios and under real-market conditions to access the new market potential in this field. It is only through the successful implementation of innovative DR programme models (followed by the scaling up from pilots to commercial deployments) that the benefits of demand flexibility will be truly known.

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