Energy Policy 182 (2023) 113745

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Prosumers integration in aggregated demand response systems

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A R T I C L E I N F O

Keywords:
Cooperative demand response
Energy communities
Prosumers
Renewable energy resources
Microgeneration
Aggregators

A B S T R A C T

In recent years, the increasing popularity of renewable energy and energy-efficient technologies is creating a new movement towards more sustainable communities. Understanding energy consumption is important for the optimisation of resources and the implementation of ecological trends. This paper integrates electricity consumers into a cooperative framework for planning sustainable smart communities through aggregators, which reallocates consumers' demand according to available renewable energy supply collected from consumers and service providers. The aggregated demand response also includes consumers involved in energy production activities through microgeneration capabilities. A characterisation study of the different types of demand preferences is performed by defining scenarios of communities and consumers' behaviours, which are validated through a reputation factor. The results show that the system adequately manages demand reallocation following the preferences and contribution of consumers and/or prosumers. Besides, this research analyses the current energy policy concerning demand flexibility, demand aggregation and microgeneration capacity, and their regulations in Spain. Finally, microgeneration acceptance, the role of aggregators and prosumers in the scheduling process is also investigated through a series of surveys.

1. Introduction

Recent Intergovernmental Panel on Climate Change (IPCC) reports drawn attention about the state of scientific, technical knowledge on climate change and the options for mitigating its impact. In this context, cities, smart communities and residential energy demands offer significant opportunities for sustainable energy transition and CO_2 emissions reductions. The customer participation in the energy market and the integration of Information and Communication Technology (ICT) in smart grids are deemed to become an integral part of residential energy systems evolution (Camarinha-Matos, 2016).

Three global challenges affect the residential sector: 40% of CO_2 emissions come from the residential field (Eds, 2022); more than 30% of needed energy in buildings is wasted (EPA, 2021); and approximately 90% of our time is spent indoors (Hallen, 2021). In addition, the increase in global demand has grown by around 20% over the last 20 years and this trend will increase at an annual rate of approximately 1.8% over the period 2020–2030 (Brugger et al., 2021). Furthermore, the current situation of rising prices on the energy market is taking place in a context of health crisis caused by COVID-19, which had a huge impact on the economic activity. The high electricity expenditure leads to higher prices, and consequently, means regressive effects on households (Ine, 2021). The rising electricity prices is mainly due (70%) to the international increase in gas price and CO_2 emission rights.

The European Union (EU) is taking actions to adapt to the impacts of climate change with initiatives under the Green Deal. For instance, the EU has set energy policy objectives as the *Fit for 55* package (Silviu, 2022) based on climate or energy policies to reduce greenhouse gas emissions by at least 55% until 2030. Therefore, Brussels is increasing pressure on emissions despite their impact on electricity prices. Stable energy prices will only come with an increase in renewable generation and a less dependence of fossil fuels. In this regard, the Spanish framework for energy and climate sets an objective to reach a national climate neutrality and 97% renewable energy in the total energy mix by 2050. Beyond the electricity sector, the Spanish government also plan to expand self-consumption of renewables and distributed generation, as well as promote and encourage the use of renewables in the residential sector.

Smart community is gaining importance as a promising solution to the challenge of sustainable energy communities providing a minimal impact on environment and citizen lifestyles (Bibri and Krogstie, 2017). Consumers behaviour focused by patterns may be the most preeminent city asset in smart and sustainable power grids. For instance, Kramers et al. (2014) explore opportunities for the reduction of energy consumption in cities through an intelligent aggregation of anticipated demand

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https://doi.org/10.1016/j.enpol.2023.113745
Received 11 September 2022; Received in revised form 13 April 2023; Accepted 29 July 2023
Available online 9 August 2023

Nomenclature

$\mathcal{D}_f$	Fixed demand
$\mathcal{D}_v$	Variable demand
$\mathcal{N}$	Consumer number
DR	Demand Response
DRC	Demand Reallocation Capacity
F	Demand Function
G_{PV}	Photovoltaic generation
G_{RW}	24-h supply from renewables
ICT	Information and Communication Technologies
IoT	Internet Of Things
RCT	Ratio of the Computation Time
S_{PV}	Storage Photovoltaic system
$t_{beg,ij}$	Earliest start time appliance
$t_{end,ij}$	Latest final time appliance
$t_{sched,ij}$	Scheduled start time of appliance

patterns of multiple consumers. New technologies and applications are providing opportunities to increase energy efficiency and peak demand reduction (Silva et al., 2018). To this regard a framework for smart and sustainable development can help to reduce cost and carbon impact in residential buildings. Hence, it becomes extremely important to both intelligently control residential energy consumption, in order to reduce greenhouse gases and safeguard energy resources (Haidar et al., 2018), and to incentivise consumers to be more active and empowers them in having more control over their electricity consumption through Demand Response (DR) services. Consumers adjust their consumption by DR models, which have emerged as an instrument to relieve supply and demand imbalances of electricity (Yamaguchi et al., 2020).

1.1. Cooperative demand response

End-users demand flexibility is an important factor for implementing DR programmes. Several studies have analysed the impact of end-users participation on the success of a DR programme or proposed solutions to increase their participation (Parrish et al., 2020). For instance, Jovanovic et al. (2016) take into account the preferences of households participation, which is modelled according to their "flexibility". The results show significant savings in electricity costs. Singh and Yassine (2019) demonstrate that appliance associations are a direct reflection of consumers' energy use behaviour where an unsupervised data mining process is applied to smart metre energy consumption. However, potential consumers flexibility has been systematically ignored due to the highly different behaviours among them (Guo et al., 2018). Smart metring systems alone neither automatically recognise end-users flexibility nor drive residential customers to use energy in a more sustainable manner. To this regard, gamification-based framework was proposed by AlSkaif et al. (2018) to drive behavioural change of residential customers in relation to energy and increase their engagement.

In a smart energy-efficient buildings, consumers engagement is commonly promoted by financial incentives; customers respond to incentives programmes (e.g., increases in energy prices) by modifying energy usage behaviour as well as investing in energy-efficient technologies and practices (Shareef et al., 2018). On the other hand, in smart energy community applications, the cooperation of groups of consumers towards common goals (e.g., environmentally friendly, become green) could make a larger impact in sustainable energy management (Bauwens et al., 2022). For instance, a validation study of a cooperative DR framework was proposed in Cruz et al. (2019). To this regard, the aggregated DR optimises the time intervals of flexible smart appliances and other household devices operation preferences, maximising the consumption of those assets from available renewable energy supply without due consideration to microgeration capabilites. Other studies propose community-based local energy markets that aim to maximise self-sufficiency within a community by encouraging demand side management and local energy exchange (i.e., photovoltaics systems (PV)), which consequently minimises energy exchange with the wholesale market (Crespo-Vazquez et al., 2020). A cooperative DR management for consumers and prosumers together is a solid mechanism for future developments in this regard. The importance of understanding DR schemes will enable incorporating the behavioural factors of consumers and/or prosumers and how these impact the energy aggregation service's performance.

1.2. Prosumers

PV or any electric installations including shared batteries between neighbours are a good example of smart efficient energy communities as stated in Gallego-Castillo et al. (2021). Furthermore, the profitability of PV self-consumption installations is now positive in several countries, including Spain under the current Spanish regulation for microgeneration deployment systems (López Prol and Steininger, 2020). The benefits of self-consumption are mainly reached by sharing solar PV energy among the consumers participating in DR (Faria et al., 2019). As an example, Conchado et al. (2016) present an integrated assessment of a potential DR programme in Spanish households, including both supply and demand side considerations. Kashanizadeh et al. (2022) analyse the reliability rates and the share of battery energy storage system as a local decentralised generation assets. However, the benefits are quite low compared to the costs, and most of them come from the system generation. Most of the research works take advantage of least-cost pricing while considering prosumers flexibility behaviour and its cooperation potential.

The microgeneration acceptance can be expressed through behaviours and investments. Sauter and Watson (2007) and Souza et al. (2018) show case studies and results that will open up new opportunities for the residential electricity market. Effective deployment will partially depend on public attitudes and acceptance at both a community and household levels (Ambrosio-Albala et al., 2020). People are more likely to accept energy storage facilities in their neighbourhood establishing the aggregation or market facilitator figures (Koecklin et al., 2021). Users may weigh the expected complexity and effort against the expected DR benefits in deciding whether to enrol. In terms of management implementation, the price of the subsidy is crucial and community advertising can also enhance the electricity-saving effect (Wang et al., 2020). The aggregation is capable of exploiting the flexibility of prosumers' appliances and reducing market net costs if compared with inflexible strategies (Iria et al., 2018). Current legal framework at the EU level represents a clear opportunity for collective prosumers. Spain has already shifted from a restrictive regulation to implementing a legal framework for collectives (Inês et al., 2020).

Reputation-based policy can ensure fairness in energy allocation in decentralised energy systems and energy communities. It has been proposed for microgrids (AlSkaif et al., 2015), blockchain strategies for interoperation of DR (Liu et al., 2020) or flexible energy markets (Chukhnina et al., 2021). Reputation factor based systems also belong to the incentive-based mechanisms in cooperative games (Fiestras-Janeiro et al., 2011). Game theory has been widely used in research works that focus on developing and analysing problems related to renewable energy integration and smart grids. DR systems based on reputation are also among the common applications focused on energy management in microgrids and energy communities, where there are types of households with different energy demand profiles. For instance, clusters with higher energy generation or cooperation capacity can be rewarded appropriately (Guo and Guo, 2015). More specifically, AlSkaif et al. (2017) deploy an optimisation problem, in which a demand-side manager jointly schedules the energy consumption of appliances and the energy that each household can receive from a shared battery storage unit according to their reputation factor. Corporate social responsibility initiatives are positively associated with reputation and customer satisfaction. To this regard, Islam et al. (2021) propose a mechanism through which corporate social responsibility influences customer loyalty.

1.3. Research gaps and motivation

From the literature review, the following limitations can be found in previous research. In relation to the studies carried out in the field of DR development for energy communities, it can be easily seen that: (1) there is a perceived lack of a comprehensive model to implement more effective behavioural DR programmes; (2) traditional self-consumption policies have a limited potential market for residential communities without cooperation; The possibility to save or share the self-produced energy for a future use may enhance the exploitation of renewable energy resources and the reduction of the end-users' energy procurement costs; (3) the value of aggregators and DR aggregation have been extensively studied in recent years. The importance of aggregation systems in fostering a large-scale integration of renewable energy sources is currently overlooked due to the main focus on the minimisation of peak load and electricity cost. Therefore, there is a need to provide a structure for consumers participation in the sustainability of energy communities. To fill these research gaps, the proposed analysis assumes the management of a cooperative DR programme which pools the demand of all participants and schedules it according to available renewable energy supply. In order to propose energy-saving strategies to achieve a better balance between production and consumption, we integrate the renewable energy generation at the household level. The most important contribution focuses on the categorisation of consumers according to their preferences, and its impact on the integration of microgeneration systems. Our proposal drastically transforms the distribution networks by turning them into bi-directional, both in the flow of energy and the information, and allowing new agents (e.g. aggregator or microgenerators) and energy service companies to compete in order to maximise the renewable energy consolidation. A deep analysis of consumers behaviour related to reallocation capabilities is performed. The aggregated DR scheduling algorithm enables a feasible demand reallocation in a reasonable computation time for different consumption patterns by means of a reputation system. Regarding the categorisation of consumers' preferences, we introduce a reputation factor R that mitigates the impact of user behaviour on the DR framework. R is determined for three types of behaviour according to demand preferences. Experimentation results show patterns where factors such as community demand volume, consumer flexibility and microgeneration, influence the performance of the scheduling system. Finally, we develop a case study with a benchmark that provides valuable insights into and validation of the proposed aggregated DR system.

The remainder of this paper is structured as follows. Section 2 presents the methodology, where the demand and generation profiles are constructed, the optimisation problem is introduced and the reputation factor is defined. Section 3 shows the results and discussion. Finally, Section 4 draws the conclusions and policy implications.

2. Methodology

The proposed system can be considered as a micro network where a group of consumers, connected to each other, operates with a certain degree of independence. The methodology assumes that the consumers share their electricity consumption information with the aggregator for demand reallocation. In practice, this scenario is applicable when consumers are willing to share their consumption profiles with a third party aggregation company or with their energy supplier via their smart metres. The system consists of a turn-based strategy for a group of consumers who are willing to cooperate in achieving the community's goals by sending their preferences to the aggregator. Each consumer has a set of devices i $\in \mathcal{N}$ labelled $\mathcal{A}$. As an application scenario, Fig. 1 presents a visual illustration of the system architecture. It emulates a smart residential energy community staged among different participants:

- Consumers and/or prosumers autonomously adapt their energy consumption and net generation by means of sharing nearly in real-time their electricity demand information.
- An aggregator is capable of shifting the consumers' use, and also responsible for the computation and rescheduling of the total daily load of the community.

2.1. Appliances demand profile

The consumer pre-allocates a certain amount of fixed demand and expected variable consumption for the next 24 h. A large number of appliances cannot be completely switched off without being disconnected. These appliances consume energy 24 h a day and it is referred as standby power. Cooling appliances (e.g., fridges) are usually considered as non-shiftable appliances and kettle or dishwashers, for example, are considered as dispatchable appliances. We define D_f and D_v as the fixed and variable one-hour energy demand. The total fixed and variable consumption demand for consumer i N per day is denoted by $D_{T,i}$ and given in Eq. (1).

$$D_{T,i} = \sum_{t=0}^{23} \sum_{a_{ij} \in \mathcal{A}_i} (D^t_{fi,a_{ij}} + D^t_{vi,a_{ij}}) \tag{1}$$

Each household i has a set of dispatchable appliances $\mathcal{A}_i$ whose operation can be scheduled in the next 24 h. Some appliances may be used more than once a day. Variable energy demand is characterised by its flexibility, as it takes into account the consumers' preference for an appliance to start in a given time period. For each appliance, there is a closed interval that selects a minimum start time and a maximum end time labelled by t_{beg} and t_{end}. The decision variable $t_{sched,ij}$ is defined as the operation time of the device j in household i and coincides with the start/end time range $[t_{beg,ij}, t_{end,ij}]$. The operation time is defined as the duration of the scheduled operation of the device on the next day. Hence, the demand must be activated for a time between two predefined times: $\forall_{ij} \in$ A, $t_{sched,ij} \geq t_{beg,ij}$. The demand schedule must also finish before the end time, as: $\forall_{ij} \in$ A, $t_{sched,ij} \leq t_{end,ij}$. Consumer i will set the following operation data for each device j (i.e., appliance) $a_{ij} \in \mathcal{A}$. Table 1 shows the most common devices used for different types of behaviour defined in Cruz et al. (2021), average consumption, operation time, preferred time and flexibility (Cruz et al., 2019; Torriti, 2017; Powells et al., 2014; Lo Piano and Smith, 2022).

2.2. Renewable power profile

Certain number of households have an on-site solar PV system and generate an amount of renewable energy. The degree of microgeneration has been selected and sized based on the daily demand profile for PV production in household (IEA, 2022). The microgeneration capacity is denoted by $G^t_{PV} = [0, \ldots, 23]$. G_{PV} is an optional variable for energy demand reallocation at prosumers. The supplier provides information on the reliable renewable energy sources and the fossil energy scheduled for the next 24 h using a variable denoted by $G^t_{RW} = [0, \ldots, 23]$. G_{RW} is essential in optimising a fair renewable energy allocation between consumers' fixed and variable energy demands. It is available to satisfy the energy resources at the current time slot t and a participant decides whether to participate in the cooperation for the energy provision of the next 24 h. A prosumer has the ability to

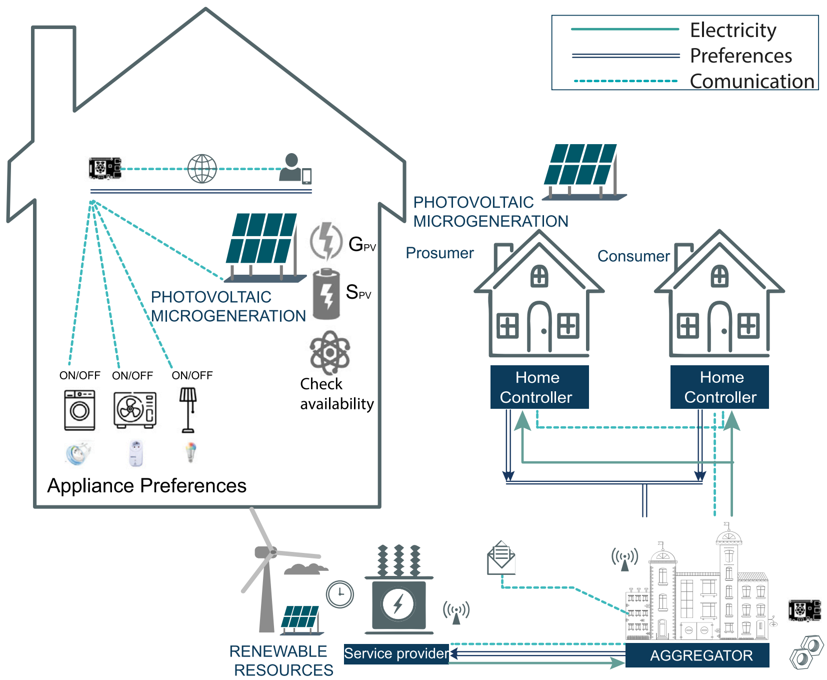


Fig. 1. System design setup of prosumers, an aggregator and energy service providers.

Table 1
List of appliances and their operation data for the different operation scenarios.

Target	Level/ temporal flexibility	Appliance	Peak likelihood	Prefered time per day (in hour)			Operation time (No. hour)	Average consumption (kWh)		Proportion of dwellings with appliance (%)
				Scenario I	Scenario II	Scenario III		Operative	Standby	
		Electric oven	High	16	10	3	3	2.13 – 5	0.005	61.6
Lighting cooking appliances	Medium/ Sub-hour	Microwave	High	14	12	4	4	1.25 – 3	0.01	85.9
		Refrigerator	High	18	10	10	10	1.77 – 4	0.01	96
		Kettle	High	20	14	6	6	2 – 5	0.005	97.5
		Hob	High	18	12	2	2	1 – 3	0.01	46.3
Electrical-based heating, cooling appliance, integrated-battery devices	Low/ Sub-hour	Tumble dryer	Middle	18	12	2	2	2.60 – 3	0.005	41.6
		Iron	Middle	18	12	2	2	1 – 3	0.01	90
		Dishwasher	Middle	20	14	3	3	1.13 – 2	0.015	33.5
		Washing machine	Middle	18	12	2	2	0.40 – 4	0.01	78.1
		Washer dryer	Middle	18	12	2	2	0.8 – 4	0.01	15.3
		Vacuum	Middle	18	12	3	3	2 – 4	0.01	93.7
		Electric shower	Low	18	12	4	4	9 – 12	0.01	67
Entertainment devices	None	Console	Middle	24	18	12	12	0.12 – 1	0.005	70.2
		Television	High	24	18	12	12	0.12 – 1	0.005	99
		Computer	High	18	12	4	4	0.14 – 1	0.005	70.8
Electric vehicles, thermal loadings	High/ Hour	Electric battery	Middle	24	18	12	12	0.12 – 6	0.005	22
		Central heating	Middle	18	12	3	3	0.40 – 3	0.01	53
		Electrical panel	Middle	18	12	4	4	0.50 – 4	0.01	60

send its own PV generation to the aggregator, which is responsible for both, demand reallocation of PV energy provided by prosumers (G_{PV}) and delivery of energy from the energy service provider (G_{RW}).

The consumers are classified according to their renewable energy generation (i.e., called prosumers), the possible storage and the required demand. While certain prosumers (C_1) have an "on-site" renewable energy generation unit without any storage device, others (C_2) have both renewable energy generation and storage facilities.

Initially, prosumers C_1 check their available on-site renewable energy thanks to the capabilities of the home controller (see Fig. 1). In case of enough renewable provision for the entire time slot, consumers can self-supply. If the micro-generated renewable energy is limited to meet the whole demand in the entire time horizon, the consumer will participate in the aggregated DR programme by aggregating its preferences for the next day's energy supply, with the possibility to send the "on-site" generated renewable energy to the aggregator.

$$G^t_{RW,C1} = \sum_{t=0}^{23}(G^t_{PV,C1} - D^t_{C1})$$
$$G^t_{RW,C2} = \sum_{t=0}^{23}(G^t_{PV,C2} + S^t_{PV,C2} - D^t_{C2}) \tag{2}$$

$S^t_{PV,C2}$ is the energy supply available by the storage system of prosumers C_2 that is charged by the surplus PV energy of those prosumers. When the total energy demand at time t exceeds the microgeneration capability ($D^t_T > G^t_{PV}$), the user will participate in the DR programme

Table 2
Occupancy patterns for different aggregation scenarios.

Class	Occupancy pattern	Assumptions
Scenario I	6:00–11:00 am	Members with a part-time job in the evenings or single pensioners and flexible preferences.
Scenario II	6:00–12 am and 17:00–23:00	Adults with full-time jobs and non pensioner, with energy consumption spread throughout the day and three consumption peaks. Their preferences are not flexible.
Scenario III	6:00–12 am and 17:00–23:00	Working people and multiple pensioners with flexible and fixed demand preferences. Daily energy consumption is distributed in two main periods.

The timeslots follow the occupancy patterns obtained from Dunbabin et al. (2015). The timeslot interval of 6:00–11:00 am (Scenario I) has been selected to test the reallocation capacity in a context of a high flexibility demand pattern.

and the aggregator will schedule its energy demand for the next 24 h. The daily energy exchange with the aggregator for each group of consumers is calculated in Eq. (2).

2.3. Demand reallocation problem formulation

The aggregator verifies on a daily basis that the total energy demanded by all appliances of all consumers in the system meets the daily energy provided by both the service provider and the consumers. The data collector is responsible for a reallocation of the total community demand that is fair to all consumers and at the same time targets the available renewable supply for each time slot.

The proposed solution concept to this reallocation problem is given according to Eq. (3). Function F handles the optimal reallocation for the variable demand according to the time interval for which the device is scheduled. The demand reallocation follows a meta-heuristic method based on the particle swarm optimisation technique, which provides low computational cost in terms of required time and number of iterations needed to find the optimal solution (Kennedy and Eberhart, 1995). Therefore, the solutions must satisfy the $t_{sched,ij}$ of each device in each household and avoid overconsumption in specific time periods.

$$D^t_{fi} + min\{\mathcal{F}(D^t_{vi})\} \le G^t_{RW} + G^t_{RW,C1} + G^t_{RW,C2} \tag{3}$$

The 24-hour output vector of scheduled community consumption is given by considering G_{RW} and G_{PV} taking into consideration the demand preferences provided by the participants. Function F searches the optimal time interval for the activation of each device j in household i given its activation time, its preference interval and the available supply of renewable energy. In particular, taking into account the variables $\mathcal{A}$, $t_{sched,ij}$, $t_{beg,ij}$ and $t_{end,ij}$, the reallocation will determine whether a setting is appropriate by minimising the total overconsumption (in hours) of the community's appliances versus the available renewable supply in a given time interval.

2.4. Reputation factor

We define the reputation factor R in which the aggregator will be able to reliably allocate the available renewable energy. The idea is to identify coalitions in terms of their behaviour as they have patterns in favour of cooperation. The behaviour has been determined on three scenarios, which have been previously defined in Cruz et al. (2021). The reputation factor R also helps to distinguish and validate consumers' behavioural patterns. For the proposed framework, the aggregator maintains a reputation value for each individual household based on the amount of renewable energy previously shared. The reputation of consumer i represents the ratio between the total amount of G_{PV} or S_{PV} shared by prosumers, and the available energy demand after the scheduling process G^t_{RW} - D_T (Eq. (4)). The reputation factor $\mathcal{R}$ helps to validate consumers' behaviour. It provides a positive value between 0 and 1 that are dynamic according to each household cooperative and energy consumption behaviour. The more renewable energy a household shares, the higher its reputation factor will be. This could motivate actors to modify their energy consumption behaviour and/or share more renewable energy.

$$\mathcal{R}_i = \frac{\overline{G^t_{PV,i}}\Big|_0^{24} + \overline{S^t_{PV,i}}\Big|_0^{24}}{\overline{G^t_{PV,i}}\Big|_0^{24} + \overline{G^t_{PV,i}}\Big|_0^{24} + \overline{[G^t_{RW} - D^t_T]}\Big|_0^{24}} \tag{4}$$

3. Results

The simulation results are illustrated by conducting experiments on several scenarios to evaluate and analyse the proposed system reaction, even in critical cases (i.e. the case of energy outage or higher peak hours consumption). The reallocated demand mainly affect the computation time and the reallocation capacity, which depends of different demand preferences and conditions (i.e., integration of the prosumers into the scheduling process). Section 3.1 highlights the reallocation capability also for the case when the microgeneration is included at household level. In addition, Section 3.2 presents the results on the reallocation based on the reputation factor. Finally, Section 3.3 highlights the regulation and acceptance analysis of aggregated DR in Spain.

3.1. Aggregated demand reallocation analysis including microgeneration

In this section, the algorithm behaviour is analysed depending on the consumers' preferences. Those parameters (i.e., t_{beg}, t_{end}, and the operation time) generate a demand profile with a symmetric demand trend over 24 h or a larger fluctuation trend in small time slots. Table 2 summarises the occupancy patterns and assumptions under three possible scenarios, which are devised to show the effects on the aggregator energy management process. The reallocation is performed centrally by the aggregator, which manages to balance the load uniformly along the day. The scenarios are identified as follows:

Scenario I conforms to a flexible community, where consumers' time preferences are relaxed; scenario II follows a rigid community, where participants have more constrained time flexibility to shift their demand. This scenario is exemplified for a set of consumers with particular socio-economic or work situations. Finally, Scenario III is focused for a diverse community, where demands display more heterogeneous dynamism.

The aggregated DR capabilities are analysed when including prosumers in the reallocation process. It also specifies how the reallocated demand is influenced under controlled scenarios. The analysis is focused on the satisfied demand capacity and the needed fossil resources for three types of situations: (1) consumers send their preferences to the aggregator under enough G_{RW}; (2) the aggregator owns limited G_{RW} to supply the whole community; and (3) the microgeneration is included in different contexts of demand preferences and G_{RW} resources.

Fig. 2 shows the demand to be reallocated (blue) that is scheduled by a group of consumers in the community, the renewable availability provided by the energy provider (green) and the reallocated demand achieved by the aggregator (red) under flexible preferences (scenario I). The prosumer integration is also evaluated into the scheduling process (black). Next, Fig. 3 illustrates the reallocated demand achieved under

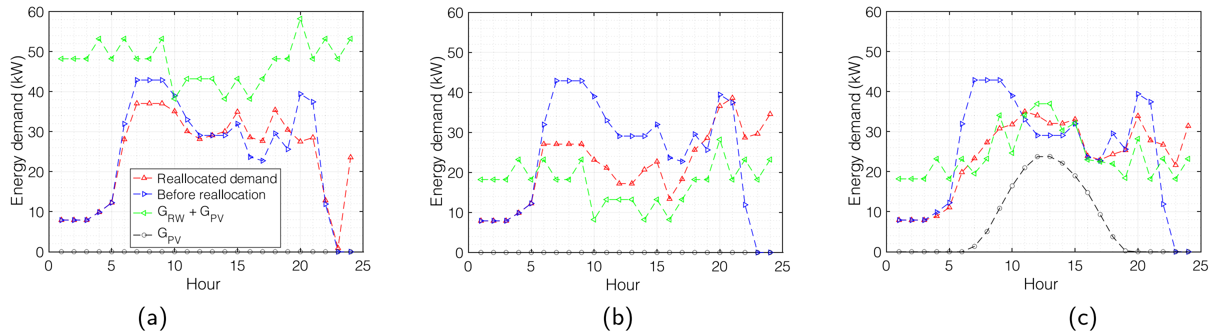


Fig. 2. Total reallocated demand in scenario I for enough G_{RW} (a); limited G_{RW} supply (b), prosumers integration (c). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

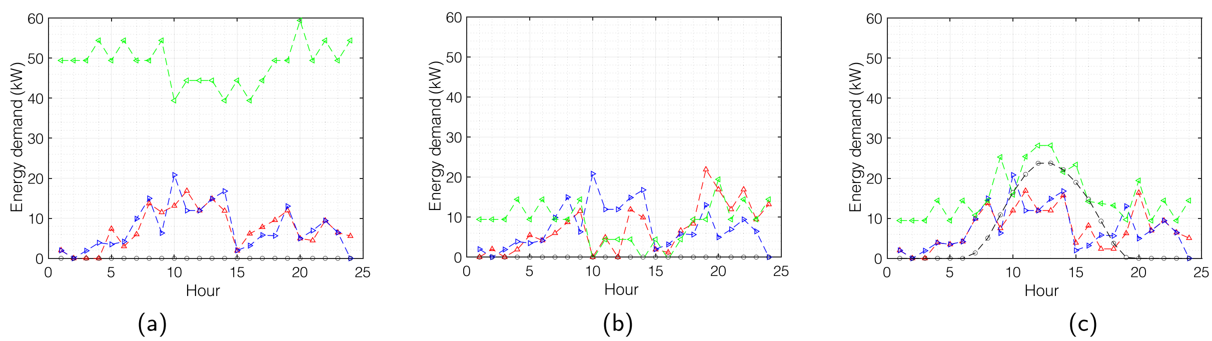


Fig. 3. Total reallocated demand in scenario II for enough G_{RW} (a); limited G_{RW} supply (b), prosumers integration (c). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

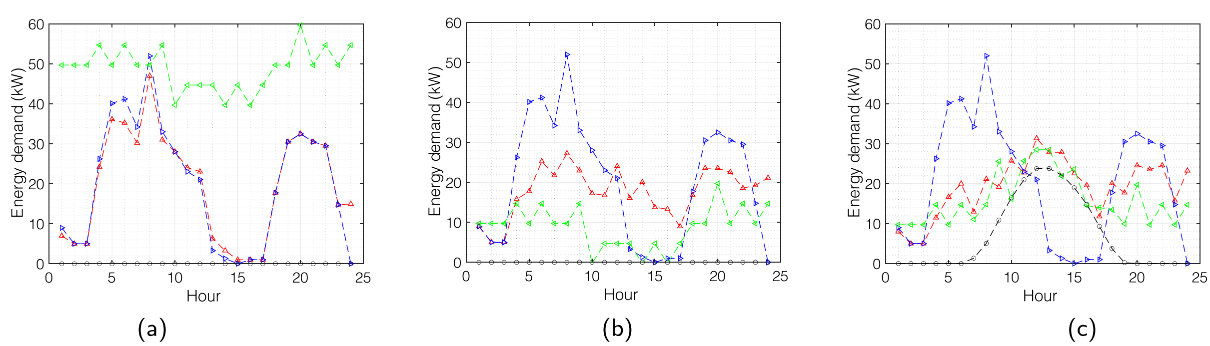


Fig. 4. Total reallocated demand in scenario III for enough G_{RW} (a); limited G_{RW} supply (b) prosumers integration (c). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

rigid preferences (scenario II). Finally, Fig. 4 illustrates the reallocation achieved by heterogeneous preferences (i.e. users defined by flexible and fixed preferences), which is exemplified by the scenario III. It is worth noting that the amount and type of G_{RW} and G_{PV} supply (green) in these scenarios and cases are determined by the service provider and the capacity of microgeneration is provided by prosumers. The main results are summarised as follow:

The first assumption is stated under enough G_{RW} supply (green) over the entire time slot (see Figs. 2a, 3a, 4a). From those figures, it is shown that the aggregation is able to supply the required demand of the community (blue) without a need for fossil energy resources. The demand is reallocated according to consumer preferences by reducing peak consumption (red in Fig. 2a). Under enough G_{RW}, the PV supply does not have a significant effect on the reallocated demand. For instance, a 3% of the reallocated demand is exceeded for scenario II if 10 or more additional prosumers participate in the process. This trend is also shown for the scenario III (1%) (see Fig. 5). The second assumption is exemplified in the case of limited G_{RW} energy supply (see Figs. 2b, 3b, 4b). The aggregation DR system tries to maximise the use of available G_{RW}, which is evaluated using the parameter Demand Reallocation Capacity (DRC). DRC is defined as the ratio of average load scheduling to the maximum standard deviation per slot obtained after reallocation and it is expressed in percentage format. For instance, DRC is increased up to 35% in scenario I, but nonetheless, limited fossil energy is still needed to supply the entire community (23%). The results also show a reduction in peak demand up to 70% in some scenarios (see Fig. 2b, scenario I). This situation also arises in scenario III (heterogeneous preferences), as the community cannot be supplied

Table 3
DRC and reputation factor R obtained for three scenarios with different G_{RW} conditions.

	Scenario I		Scenario II		Scenario III	
	Reputation factor R	DRC (%)	Reputation factor R	DRC (%)	Reputation factor R	DRC (%)
Limited G_{RW}	0.68 ± 0.13	59 ± 12	0.50 ± 0.15	23.6 ± 2.2	0.50 ± 0.1	39.4 ± 5
Enough G_{RW}	0.65 ± 0.15	41.5 ± 9	0.72 ± 0.04	9.3 ± 4.6	0.44 ± 0.12	11.7 ± 0.9

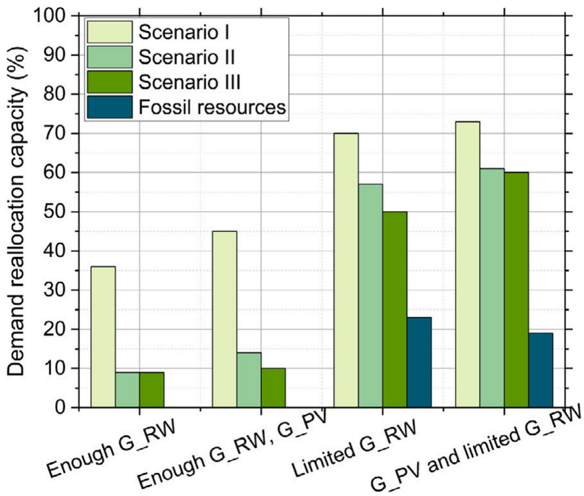


Fig. 5. DRC and fossil resources needed for different scenarios and cases.

with only G_{RW} and a 19% percentage of fossil resources is required. In this scenario, the two main consumption peaks are reduced due to the increase of reassigned capabilities up to 50% (see Fig. 4b). The last assumption is exemplified for a PV supply that is included in the aggregated DR system: Figs. 2c, 3c, 4c show the reallocated demand achieved when a group of prosumers send their generated PV to the DR aggregator. The reallocated demand in this case is properly scheduled to match the PV renewable supply, specially for the scenario I (see Fig. 2c).

Fig. 5 shows the DRC achieved in the different scenarios. Each situation is evaluated based on G_{RW} and G_{PV} availability. Under limited G_{RW}, DRC presents the highest capacity. However, the aggregator needs extra fossil resources to reallocate all the scheduled demand. Enough G_{RW} provisions always achieves a positive effect on the reallocation process, increasing DRC by 35% or 10% for flexible or mixed preferences, respectively. The worst situation is denoted in scenarios II and III under limited G_{RW} supply. The reallocation is achieved to mitigate peak consumption taking into account G_{RW} and G_{PV} supply. However, the presence of fossil resources appears to a greater extent for a sufficient community supply (up to 19%). In addition, PV provision improves reallocation capacity in cases of limited G_{RW} supply. For example, the most satisfactory situation is obtained in scenario I, which increases demand reassignment by 28% to mitigate G_{RW} scarcity through prosumers integration. In this case, additional fossil energy is hardly needed for certain time slots.

The increase of prosumers under enough G_{RW} does not optimise the reallocated demand due to the impossibility to achieve the provisions to a dis-par time slot. This is a limitation of stand alone PV systems, which are considered as non dispatchable renewable energy supply sources and hence are not able to reallocate the demand generation to other time slots. This can be solved using other complementary technologies, such as energy storage systems. However, Celik et al. (2020) and Terlouw et al. (2019) demonstrate that PV generation negatively affects the aggregator's profit, as the investment in a storage unit is currently not cost-effective when the lifetime of the battery and its degradation are being considered. In addition, consumers without on-site energy technologies benefit more than owners of PV storage systems (Zakeri et al., 2021). Pilot experiences focused on the prosumers' participation at the household level will facilitate the diffusion of self-production and the viability of these systems. There are examples to modify this trend, such as the study proposed by Mir-Artigues and del Río (2021), which promotes strict self-supply due to the fact that the price of exported kWh is lower than its generation cost.

3.2. Reputation analysis

Traditionally, a load aggregator maintains cooperative relationships with participants. They only registers with the aggregator and participate in the activities. For instance, it is assumed 0.5 kWh as the required demand to be reallocated by 0.2 kWh available G_{RW}. The energy demand is provided without any priority for the consumers and/or prosumers. In this scenario, consumers who do not participate in electricity generation could obtain <<green>> energy while prosumers would receive fossil energy resources. Therefore, the aggregated systems should recognise consumer behaviour to reallocate energy efficiently, in order to encourage the coalition for the installation of renewable generation and, in turn, to participate optimally in the aggregation process. In literature, consumption-shift scenarios based on reputation factors are established to achieve cost savings, where prosumers share their surplus renewable energy (AlSkaif et al., 2017). To this end, the degree of energy sharing can be determined by assigning a reputation factor.

Here, experiments have been conducted on prosumers with certain reputation value participating in the aggregation turn-process. Table 3 summarises the R factor obtained for three scenarios and G_{RW} conditions, and Fig. 6 illustrates the DRC achieved and the R factor obtained along different days. R value is high for prosumers with flexible preferences (scenario I) ($R > 0.5$). The result obtained for the scenario I leads to a better management of renewable resources. R value is reduced for prosumers who require a demand that cannot be easily reasigned ($R = 0.5$) regardless of the G_{RW} conditions (scenarios II and III). Finally, a one-week analysis is performed to determine the reputation factor evolution. The scenario II (rigid preferences) offers a worse reputation mainly in the early days (see Fig. 6b). However, there is a slight trend throughout the week concerning R improving its value a few days later ($\Delta R = 0.3$ for scenario I,II; and $\Delta R = 0.5$ for scenario III).

3.3. Reallocation time analysis in the DR aggregation process

The global behaviour is analysed taking into account different cases in the community as follows: type of energy demand (a), trends in demand preferences (b), G_{RW} provision (c) and type of behaviour pattern consumption (d). The Ratio of the Computation Time (RCT) is the ratio between the mean required time and the maximum time required for each case, and it is expressed in percentage. It is noticed that the differences in the required time for the reallocated demand in cases of high/low demand are negligible For instance, the algorithm requires additional resources in a high demand and fluctuations context (RCT = 53,66% - 52.48%). A slight trend is noticed when the aggregator receives a non-uniform[1] energy profile from the service provider G_{RW} (RCT = 50.34%).

[1] The amount of renewable energy in each of the 24 slots is different.

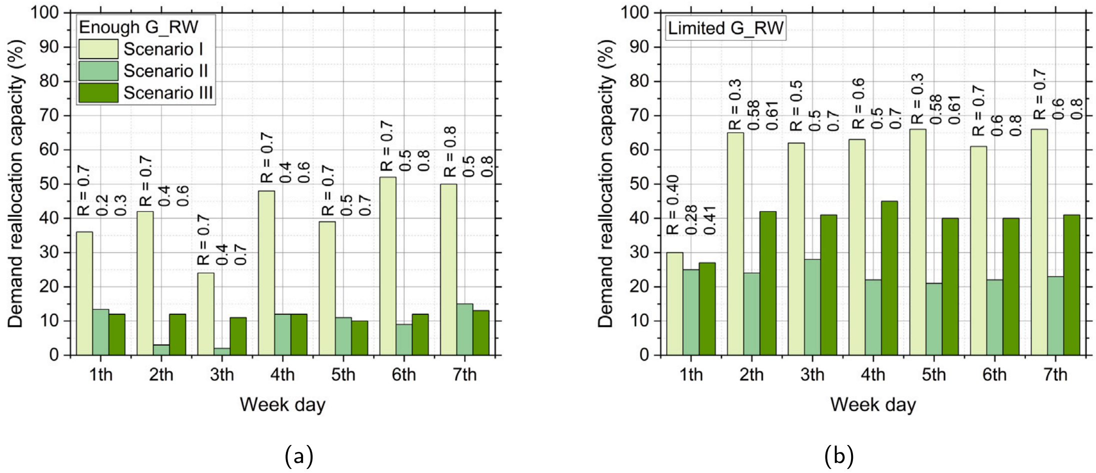


Fig. 6. DRC and R obtained along the week for three scenarios with enough G_{RW} (a); limited G_{RW} (b).

3.4. Regulation and acceptance analysis of aggregated DR in Spain

Despite the existence of some projects based on smart communities, explicit regulation has not yet started and demand aggregation is not implemented in the Spanish electricity system. The aggregated schemes are centred for the uninterruptible demand programmes, which are deployed by large industrial electricity consumers, such as construction industries or factories connected to the high voltage grid. The structure of the Spanish electricity sector is regulated and the government is responsible for establishing grid remuneration methods.

The Spanish regulations and rules approved, Royal Decree-Law (RDL) 900/2015 introduced a slow transition towards a distributed generation model considering small-scale systems. Furthermore, RDL 15/2018 removed the so-called solar tax to give certainty to energy prosumers. The regulation defines different types of self-consumption: collective and individual. In addition, consumers, individually or through an aggregator, can provide all energy needs at any time of the day to the service provider.[2] This regulatory framework aims to create a more efficient and dynamic market as a whole, in which the consumer becomes an active element in the market and establishes measures to promote energy efficiency. Measures to deploy the participation of small consumers were considered in the electricity RDL 24/2013 and RDL 216/2014. In turn, the BOE-A-2021-8362 legislation resolved on May 6th 2021 already approved the operating rules for the daily and intra-daily electricity markets. More specifically, the 11.a rule emphasises the review of procedures' needs for the storage and the aggregator incorporation. These actors will not be linked to the electricity sale.

On other hand, the integrated national energy and climate plan 2021–2030 presented by Institute for energy diversification and saving (Idae, 2020) highlights the need for renewable resources integration into the electricity system. At the same time, RDL 23/2020 is focused on measures for the promotion of renewable energies. It anticipates accessibility regulation and connection issues including action mechanisms based on the "pay-as-bid" system. In order to achieve the climate objectives assumed by Spain, a whole regulatory development is still pending.[3]

The technical developments and pilot implementation can be seen as a proof of concept and a starting point for establishing regulations for cooperative DR programmes. This will require involvement of other staekholders in the energy sector and careful development of legal frameworks for end-users participation in such programmes based on environmental, economic or social benefits. The Spanish energy market is aiming for a reduction in consumption peaks and a promotion of flexibility measures at the consumer level to achieve reduction in greenhouse gas emission neutrality by 2050 (Spain, 2020). The development of energy storage systems and other ICT developments for the optimisation of energy consumption and production, which, together with the use of other sectors (e.g. electric mobility and electric heating) put the consumer at the centre of the energy transition. With the introduction of the proposed rules, aggregated DR systems could be a reality in Spain from 2022, year to carry out qualification tests and market participation. We are undoubtedly at a crucial moment for the development of new energy management systems.

An initial analysis of aggregated DR acceptance is carried out in Cruz (2022), which was distributed telematically via web. Conceived as a preliminary study, it aims to measure the impact and acceptance for both, efficiency platforms and microgeneration capabilities on aggregated DR systems for residential consumers. The survey is detailed in Surv (2022), and the main results are summarised below:

1. The majority of the participants (97%) show interest in the knowledge and/or use of energy efficiency tools. However, most of them are not familiar with concepts such as smart energy communities, aggregation or DR (17%), and IoT-based user applications (30%). In terms of renewable resources, a low percentage of interviewees are not familiar with the generation and management of resources at home (23%). This result may be due to a lack of familiarity with ICT - IoT capabilities applied in the residential sector. Specifically, a limited number or participants would be interested in the use of renewable energy resources (37%) and to a lesser extent, users would be willing to use microgeneration resources (20%).
2. In general, consumers understand peak generation (72%) and demand and/or price could reduce consumption in the future. However, only a 60% of participants are interested in appliances automatisation and a lower percentage (37%) would be willing to plan and/or estimate their energy demand for the next day. This low acceptance is mainly due to a lack of awareness of the benefits for a shared energy resource system through the use of ICTs. One of the causes may be due to concerns about the security of communications and the real benefit of using aggregated DR in their daily lives (40%).
3. Consumers would be fully involved in preferences modification in order to organise the consume (54%). On the contrary, only 11% of participants would demand consumption time preferences with no scope for demand reallocation. In general, users

[2] Markets publication and competition regulation was performed by the national commission (18423/2019).

[3] The regulation should define the relationship model between the service provider and the aggregator.

are in favour of applications to schedule their preferences (95%) and would have no problem installing a controller in their home to control their appliances (90%), activating/deactivating appliances according to the reprogrammed demand.

In literature, the studied surveys suggest security and privacy as essential factors to implement a smart DR infrastructure (Vardakas et al., 2015). It is also recommended to explore money-saving opportunities as reasons for changing electricity consumption patterns. However, there is evidence that households will revert to their old consumption habits if they cannot see the impact of their behavioural changes on their daily lives (Annala et al., 2014). Therefore, it is important to provide consumers with meaningful information about demand reallocation processes in order to encourage sustainable energy consumption (Ellabban and Abu-Rub, 2016). Social influence, social and personal awareness to changes needed in the society, habit formation, individual self, will help stimulate sustainable consumer behaviour changes (White et al., 2019).

4. Conclusions and policy implications

4.1. Conclusions

The development of efficient mechanisms for energy management in smart communities is still an open challenge. Residential communities tend to play an important role to the success of DR programmes. The consumption measurement and energy use, as well as instilling energy-efficient behaviours in consumers, are as necessary as promoting advances on energy use. We envision the aggregated DR framework to evolve towards achieving a balanced method between green energy consumption and provision. Proposed as an optimal demand reallocation scheme for a smart residential community, the role of aggregation for enabling distributed energy resources is to provide electricity services at scale. The research is focused on the analysis of the consumers' behaviour by analysing the performance in terms of demand reallocation capacity and computation time not only for consumers, but also for proactive consumers that voluntarily participate in the aggregated process. To this regard, the inclusion of microgeneration technologies based on renewable energy plays an important role when limited renewable energy is supplied by the service provider, as each consumer can assign individually its demand, or by the aggregator. However, the unlimited increase of prosumers participation does not necessarily optimise the reallocation resources (the DRC value obtained remains constant). Furthermore, the reputation factor helps us to analyse three types of consumer behaviour, specially for households that are equipped with PV systems and flexible preferences.

The results of a preliminary analysis to uptake aggregated DR systems are also presented. It is concluded that consumers would be willing to participate in a collaborative DR system, but they would be concerned about its security and functionality operation. This research work can be enhanced by analysing the main services that an aggregation process can offer to end-users in order to stimulate a more responsible energy use. One of the main limitations is the difficulty of extracting consumer flexibility information from the data set used for validation of the proposed system. Furthermore, pilots deployment in living labs are needed to validate the results of our analysis. We have defined an aggregation model that can be adapted to the Spanish electricity market. However, there is a need for determining the roles, rights and responsibilities of independent aggregators and end-users. This can be accelerated by conducting pilot projects in a controlled environment. The development of a coordination system between aggregators, market operators and customers should be considered in order to avoid distortions and undesired consequences on the current system. A future study of how the prosumers could be compensated for their participation will be performed. An even greater challenge to be performed is the real-time power generation application and demand estimation methods that may also be employed to adjust upcoming operation and properly schedule consumer demands.

4.2. Policy implications

Firstly, the residential sector is very sensitive to energy price signals. Therefore, the economic implications could focus on proposals for replacing price signal structures and, where appropriate, introduce additional incentives or policy mechanisms to support energy carriers of greater efficiency. One of the main weaknesses in policy implications of DR systems is the unstable effectiveness of policy instruments and the commitment. It is due to the low quality or under-implementation of instruments, the poor enforcement, or the ineffective instrument design.

Secondly, tackling climate change requires a change in patterns and methods of consumption. Policies, as well as new legal and regulatory frameworks should be put in place to create incentives for new return energy demand structures. Relevant concepts, such as storage, aggregation and renewable communities, were recently introduced by the Spanish RDL 23/2020, which adopted measures in the field of energy and other areas of economic recovery from COVID-19. However, Spain has not considered energy efficiency and flexibility policies (RDL 6/2022) and even it has not developed directives concepts that were defined in RDL 23/2020.

Thirdly, a very close coordination in the planning and actions execution between the public institutions and end demand consumers would be essential in order to be able companies and participants make decisions in a rational and efficient manner. This action requires the introduction of specific rules (i.e. options on how consumers can participate in the energy market). To this regard, RDL 244/2019 put in place clearer definitions of prosumers, simplified compensation schemes, and streamlined technical and administrative requirements. It is expected to reduce previous barriers to entry for self-consumption, as energy service providers can offer the optimal technical solutions.

Finally, if the electrical grid is decarbonised, the residential housing sector can meet the 28% emission reduction target for 2025 under the Paris Agreement (Pan et al., 2017). The large-scale use of renewable energies requires the mobilisation of significant investments in generation or pilot DR infrastructures, among others. A CO_2 tax or a floor price would provide a clear price signal for the reduction of CO_2 emissions by new funds to contribute to new technologies (e.g. aggregated DR, home storage implementation and renewables production).

Spain has shown important leadership on clean energy transitions regulations. When all Spanish plans and strategies are implemented, a completely different energy sector will emerge, where fossil fuels are no longer dominant. In conclusion, there are good reasons for governments to strive to give subsidies to smart solution platforms and hardware needed to realise cooperative DR systems. It is also important to take a comprehensive approach for market measures and system designs, weighing the different challenges and striving to find a balance that speed up the transition to a more sustainable and smart residential energy sector.

CRediT authorship contribution statement

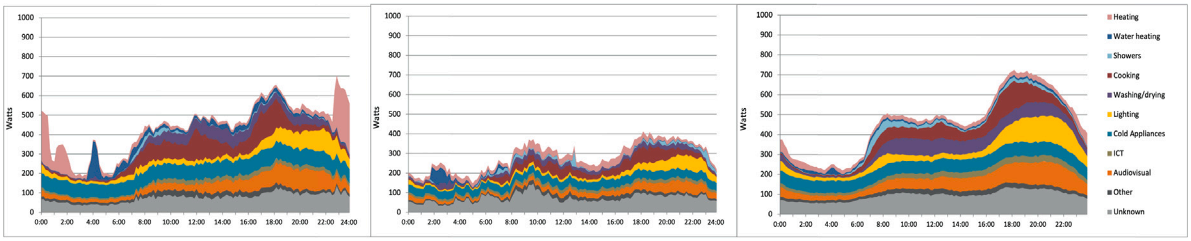
Carlos Cruz: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing. **Tarek Alskaif:** Investigation, Writing – review & editing. **Esther Palomar:** Investigation, Funding acquisition, Writing – review & editing. **Ignacio Bravo:** Investigation, Funding acquisition, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.



(a) (b) (c)

Fig. 7. Average energy demand of 29 matching households profiles with no children and multiple pensioners members in scenario I (a); single and non pensioner members' matching 35 households in scenario II (b); and average energy demand of 259 matching heterogeneous households profiles in scenario III (c). The mean of behavioural profiles was designed by Architectural Research as part of DECC and DEFRA's analysis of the Household Electricity Study (Dunbabin et al., 2015).

Acknowledgements

This paper is a result of the ENEFF-PILOT project, funded by Comunidad de Madrid, Spain (Spain) under the Talent Attraction Grant 2017, with reference 2017-T1/TIC- 5184.

Appendix

We include as an Appendix a more detailed simulation assumptions of the scheduling process. Fig. 7 shows the mean occupancy patterns and type of energy demand for three possible scenarios.

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