POLITECNICO DI TORINO

Master of Science in Energy and Nuclear Engineering

Master's Degree Thesis

Assessment of the Energy Communities' potential for providing flexibility services.

Optimization model proposal

Supervisors:
Prof. Lanzini Andrea, Prof. Henggeler Carlos
Dr. Minuto Francesco, Prof. Lopes Marta

Candidate:
Luisia Pinto
288604

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Abstract

The whole power system is facing a deep transformation with the purpose to integrate renewable energy sources (RES) and become more sustainable, a challenge that requires huge investments and the development of new mechanisms, mainly for the distribution sector and the electricity market. In this setting, demand-side flexibility (DSF) is stated to be a crucial tool to accommodate the grid changes and its management, optimizing renewable energy use and taking advantage of the arising active role of customers.

Among the others, energy communities (EC) are playing their role in the European transition towards a less fossil fuel-dependent electricity system. Born under the Clean Energy Package to promote energy decentralization and people engagement, they are defined as voluntary organizations of people, autonomously ruled, which decide to be involved in distributed generation and related activities to provide economic, social and environmental benefits to their members rather than to be profit-driven. Their purpose encompasses promoting RES generation as well as serving the electricity system by providing flexibility services. In this sense, ECs seem to be particularly interesting for DSF because, being already an aggregation of customers, it is able to offer more valuable energy and flexibility products with respect to individual ones, also taking advantage of its internal organization. For the time being, ECs are exiting from the pilot phase, which was mainly focused on self-consumption. In the meanwhile, ECs have drawn the growing attention of entities representing power sector interests, and Member States are currently on the way to completing their legislation and regulation alignment with the European directives, extending EC activities also to flexibility products.

The forecast of ECs diffusion in future decades makes them worth being fully studied, including the possible interactions with the grid. Therefore, the purpose of this work is to explore the potential of the EC as a provider of flexibility services for the grid, in name of a virtuous integration within the system. After having analyzed the legal and regulatory framework, and reviewed the literature on both energy communities and flexibility, an optimization model is developed for an EC receiving a flexibility request from the grid and managing it to be fairly distributed among its members, according to their possibilities and assets. To do that, assets are represented by MILP load modeling, including shiftable loads, water heaters, air conditioning, and battery; electric vehicles have been included, too. An EC manager (or management system) has access to the members' expected consumption profiles and it is in charge to reorganize the load scheduling from the announcement time onward, and to calculate the amount of flexibility that should be delivered by each member, according to two different criteria: equality and equity. The tool has been tested by simulating an upward request (asking for a decrease in power) and by modeling an energy community with four characteristic profile types: simple consumers, prosumers, prosumers with a storage system, and public buildings. Different scenarios have been explored, mainly changing the size of the community and the size of the requested service, according to the evolution trend of those products - opening to residential customers, mainly decreasing in size - in order to observe how the EC can manage the provision of such services. Moreover, the two different objective functions have been compared to identify which criterion between equality and equity can fit betters members' interests.

The results highlight that, being the size of the requested service fixed and increasing the size of the energy community, the maximum flexibility provided by members decreases

both in absolute (kWh) and relative terms (%), but the two applied criteria return different flexibility distributions among members; it is observed that when the equity criterion is applied, the EC can better exploit each members' potential. In any case, choosing between them is left as a discretionary choice of the interested EC, which can evaluate by the tool the maximum amount of flexibility [kWh] or the threshold level of relative flexibility [%] asked on average to its members. For instance, the performed simulation shows that an EC of 2000 members is needed to successfully provide a flexibility service of 1 MW for 1 hour, asking each of them an absolute flexibility lower or equal to 1 kWh - corresponding to 60% of consumption on average; but 5000 end-users are needed if the relative flexibility amount wanted to be lowered to 25%.

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Acronyms

AC Air Conditioning.

AS Ancillary services.

BRP Balance responsible party.

BSP Balancing service provider.

CEC Citizen energy community.

DER Distributed energy resources.

DSF Demand-side flexibility.

DSO Distribution system operator.

EC Energy community.

ECM Energy community manager.

EMS Energy management system.

EV Electric vehicle.

EWH Electric water heater.

GHG Greenhouse gases.

HP Heat pump.

HV High voltage.

LV Low voltage.

MILP Mixed-integer linear programming.

MV Medium voltage.

REC Renewable energy community.

RES Renewable energy sources.

SS Storage system.

TSO Transmission system operator.

VPP Virtual power plant.

Introduction

1.1 Context: electrical system changing

In the global challenge to tackle climate change, the traditional way of living, producing, and consuming was put into discussion since considered not sustainable, and all sectors are facing a transition phase, in particular the ones considered GHG emission-intensive. Among the others, the transformation of the heat and power sector is a key point in this transition, since it is currently mainly driven by fossil fuels and responsible for about 45% of global emissions (figure 1.1, 2020).

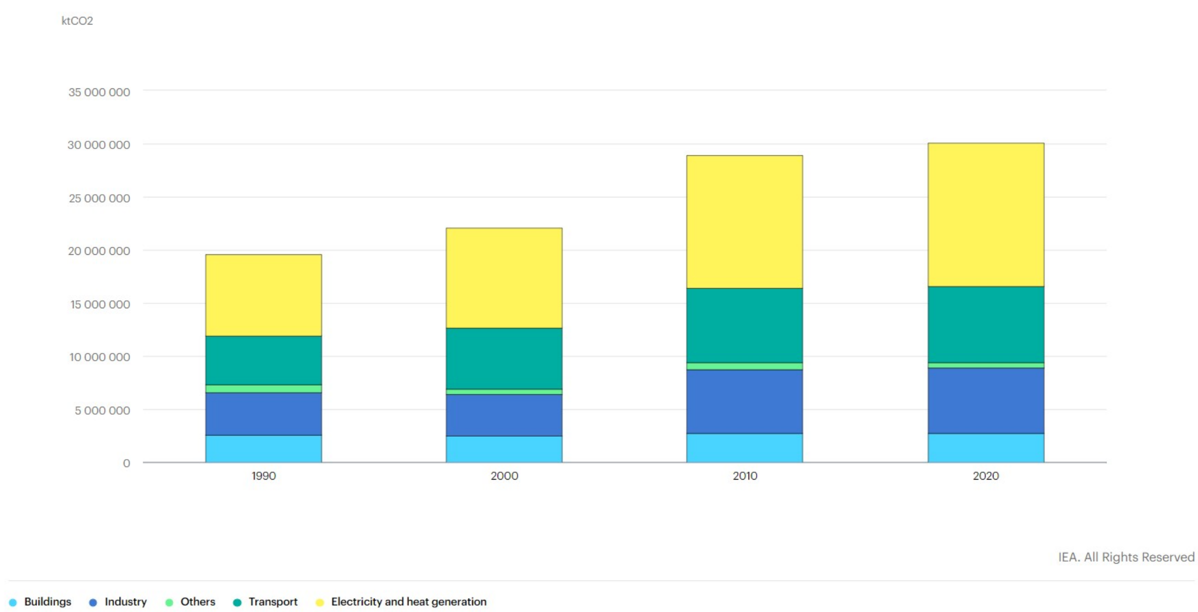

Figure 1.1: World GHG emission for sectors (source: IEA)

Regarding the power sector, the path toward a CO2-free one is anything but straightforward. As a matter of fact, it was though and designed to be highly centralized, programmable and one-directional, but the promotion of RES technologies to provide clean electricity is forcing it to become decentralized and bidirectional, and to face intermittency and scarce predictability of these sources [1, 2], figure 1.2. Such a change in its foundation paradigms makes the established working principles of the electrical system not more valid or efficient; therefore, several and clever efforts are in place to modify them, also without completely upset the roles of the actors involved and the equilibrium among them, always ensuring energy security and affordability for all [2].

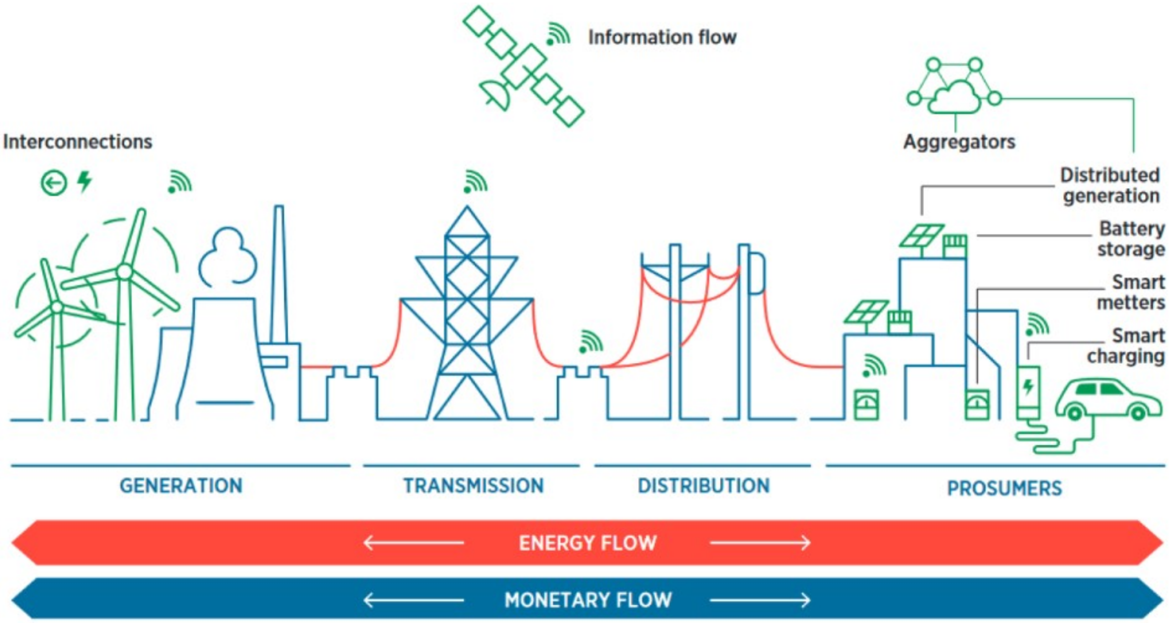

Figure 1.2: Bidirectional electricity system (source: IRENA)

1.2 The role of demand-side flexibility

To meet all these requests, in future decays the power sector would need plenty of reinforcement and modifications, which means significant investments. In alternative or in collaboration, it is possible to rely on flexibility: it is defined as the ability to «modify generation and/or consumption patterns in reaction to an external signal, such as price changes, to provide a service within the energy system» [3].

In particular, demand-side flexibility is foreseen to be one of the main tools to accommodate the changes in the network, like the increasing non-forecastable renewable energy generation, and the consequent issues in the network management. As said, it can be useful to defer or avoid additional network investment, to maintain the security of supply, to improve electricity system resilience, and to provide innovative products and services [4]. In the end, it will be crucial for the paradigm shift from a load-following supply to a supply-following demand scheme, to match RES production and optimize its use.

Talking about the modification of consumption patterns, several type of demand-side flexibility exist and can be divided into grid independence support, generally driven by on-site generation or storage, and demand response programs, which are based on the response to a system request, [5]. On the basis of the strategy adopted, demand response for consumers can be distinguished as [5]:

- implicit or price-based flexibility, when variable electricity tariffs are set to induce changes in the consumer behaviour;
- explicit or incentive-based flexibility, when a load cut or increase in consumption is explicitly asked and paid from the system operator to a contracted consumer.

Several sectors from the demand side have the potential to participate in this programs. As far as concerns residential sectors, the willingness to participate depends on several factors and behavioral variables like comfort preferences, economic welfare, and ethical orientation. Anyway, the service size required by the system is not compatible with the single customer availability, which means that it is not able to provide a flexibility amount that can be stand-alone significant for the system and for the market, like generation or industrial sectors can do [6, 7]: therefore residential customer needs to be aggregated.

1.2.1 Energy Communities as flexibility providers

Within an energy community, not only energy services, but also flexibility products can be provided to its members [8]. Energy services involve the energy produced, consumed and shared, like services to increase energy awareness, purchase and maintenance of the energy assets, supply and shared energy, or P2P supply. Flexibility services, instead, are expressed by the possibility of voluntary and time-limited change in energy profiles. By ECs, they can be provided to their members but also to the electrical system [8]: as stated in their European definition [9]. The energy community, representing already an aggregation of customers, has the potential to be an interesting provider for the system because it can offer valuable products, also benefiting of their internal organization. This potential is becoming attractive and some studies have recently approached the topic.

1.3 Objective and structure of the thesis

In light of the recent national legislation alignments with the European directives, which extend the Energy Community possible activities also to flexibility and Ancillary Services (AS), the aim of this thesis is to assess EC potential in providing this services; for the purpose, a mixed-integer linear programming (MILP) optimization model is developed. Simulating an energy community realistically, the results will highlight how an EC characteristic can manage an AS request: they represent a particular set of flexibility products, whose critical features are their size and the small response time in which the provider needs to organize. The evolution trend of these services (mainly decreasing size [10]) is opening the possibility to EC to be theoretical provider, even if it still needs a clear regulatory framework and test campaigns.

The thesis is organized as follows: an analysis of the European directives, and Italian and Portuguese national legislation, is performed in chapter **2**, in order to frame the energy community topic both in its design principles and its actuation. Subsequently, a comprehensive assessment of what flexibility is and how can it be associated to energy communities, both for its members and for grid services, is conducted. The analysis comes with a literature review, in order to catch also the research trends and directions, and to include the purpose of the present work. Therefore, in chapter **3** the methodology is introduced, followed by the presentation of a simulation framework and the corresponding results, critically examined in chapter **4**. Finally, conclusions and perspective on the future work are discussed in chapter **5**.

Literature review

2.1 European directives: RED II and EMD

The European Union is in leading position for the energy transition: in 2019 the European Union fully adopted the Clean Energy Package to move from fossil fuel-dependent system and economy towards more sustainable ones and to effectively meet the Paris Agreement objectives regarding emission reduction. It is an 8-directives energy policy framework concerning different areas of interest, such as energy performance in buildings, renewable energy, energy efficiency, electricity market, risk preparedness, governance regulation, and cooperation among regulators [11]. The Energy Community concept was born under this umbrella and is generally referred as a voluntary organization of people, autonomously ruled, which decide to be involved in distributed generation and related activities in order to provide economic, social and environmental benefits to their members rather than to be profit-driven [12, 9].

Within the Clean Energy Package, the Renewable Energy Directive represents the legal framework for the development of renewable energy in all the sectors of the European economy, and sets the target for the percentage of RES in the EU energy consumption (at least 32% by 2030). The last revision, dated 2018 and named RED II, is currently in force, but further revisions were proposed in 2021 and 2022 to increase the targets respectively up to 40% and up to 45% with the REPowerEU plan. The RED II instructions concern mainly the heating and cooling and the transport sector; also, they aim to rule a sustainable use of bio-energy and finally, to foster the active participation of citizens to the transition [11].

In this context, Renewable Energy Community (REC) is defined as a legal entity based on the open and voluntary participation of people like households, cooperatives, small-medium enterprises (SMEs), and local authorities (municipalities included), located nearby some installation of renewable energy production and that have the aim to provide economic, social and environmental benefits to their members rather than financial ones [12]. The REC is allowed to produce, consume, store, exchange within the community and sell renewable energy; it has the right to access all the suitable electricity markets as well, in a non-discriminatory manner and it should be subjected to network charges in a fair way that takes into account the overall cost sharing of the system [12]. The member states and the corresponding distribution system operators are supposed to provide a support framework to foster their development [12].

The insight is that a REC can manage both thermal energy and electricity from renewable sources, and that the proximity to the production installation is explicitly requested: the goal is to promote the production from RES.

On the other hand, the Electricity Market Directive 2019/944 (EMD), which is under continuous revision to follow technological updates, has the aim to design rules for a new and European integrated electricity market, trying to embrace the increasing integration of distributed generation and, at the same time, ensure the power grid stability, security and affordability. In effect, markets need to change to accommodate the renewable sources intermittency, but also to attract investments for new solutions, like storage, and to incentivize customers to be more aware of their energy behaviour and to give their active contribution to the system [11].

For this purpose, this EMD defines the Citizen Energy Community (CEC) mainly as the RED II does, but extending the list of allowed activities in the electrical field to aggregation, energy efficiency, electric vehicles charging, and other energy services, and underlining that the electricity can be provided by renewable energy sources as well [9]. In addition to REC, the CEC has the possibility to be open to cross-border participation and to own and manage its distribution grid. In the end, it has to be financially responsible of imbalances caused to the system [9].

From the definition it can be remarked that the CEC is been thought to be neutral from the technology point of view, but mainly devoted to electricity production and management, and enabled to participate in several related activities in order to interact with the system and eventually meet its needs.

In conclusion, some ambiguity results from the definitions given by the two directives in which the concept is addressed. The differences between the Renewable Energy Community, and the Citizen Energy Community are summed up in the table (2.1) [13, 14]: the ambiguity comes up mainly regarding the activities allowed, and therefore the role and the goal they have in future scenarios. Logically, REC could be seen as a subgroup of CEC. The definition given by the Electricity Market Directive extends the activities that an energy community can perform and embeds it in the electricity market design, resulting in a more comprehensive and network-integrated role, which is a key point, also stressed in reports regarding the future of the electricity system, to help it along its way of transformation.

Directive	**RED II 2018/2001/EU**	**EMD 2019/944/EU**
Definition	REC Art. 2 (16) Art. 22	CEC Art. 2 (11) Art.16
Geography	Proximity	No physical boundaries
Activities	Generation, trading, storage, sharing and selling of energy from RES, access to electricity markets	Generation, distribution, supply, sharing, consumption, aggregation, energy storage, electric vehicles (EV) charging, energy efficiency (EE) or other energy services, access to the market
Technologies	Renewable only - both electricity and thermal energy	Neutral - electricity only
Membership	Physical people, SMEs, local authorities, municipalities included	Physical people, small enterprises, local authorities, municipalities included
Aim	Promoting and supporting RES	Set the role of EC in the energy market framework

Table 2.1: RED II and EMD comparison

2.2 National legislation and regulation

2.2.1 Italy

By the DL 162/2019 [15], Italian first and partial transposition of RED II was aimed to start an experimental phase of the self-consumption configurations, so to be monitored and to acquire all the useful elements for the fully successive implementation of the European Directives. The definition about the membership, the rights of the member and their purposes is kept equal to the European directives. In the Art. 42bis it is stated that:

1. The REC produces electricity for its consumption with power installed smaller or equal to 200 kW, entered into operation after 01/01/2020;
2. The pre-existent grid has to be used;
3. The shared electricity is equal to the minimum, on hourly basis, of the electricity injected by the RES installations j and electricity withdrawn from all the associated members i;

$$E_{sh} = min_h \left(\sum_j E_{PV,inj,j}, \sum_i E_{Cons,i} \right) \tag{2.1}$$

4. The injection and connection points have to be located within the low voltage grid, beyond the secondary cabin (LV/MV);
5. Network charges must be paid for the withdrawn electricity, included the shared one;
6. For the shared electricity, the tariffs should be deduced by the components for the not used portion of the grid;
7. The REC can access to incentives for the installation of renewable plants which support self-consumption scheme.

The third bullet states the sharing system is designed to be a virtual one. Differently from the physical self-consumption scheme in which the installation is connected with several consumers and the grid connection is performed through only one POD (Point Of Delivery), the virtual self-consumption scheme keeps unchanged the grid configuration, so each final user has its POD (figure 2.1, [16]). In this way, the DSO is in charge of metering, and each user is free to choose its retailer.

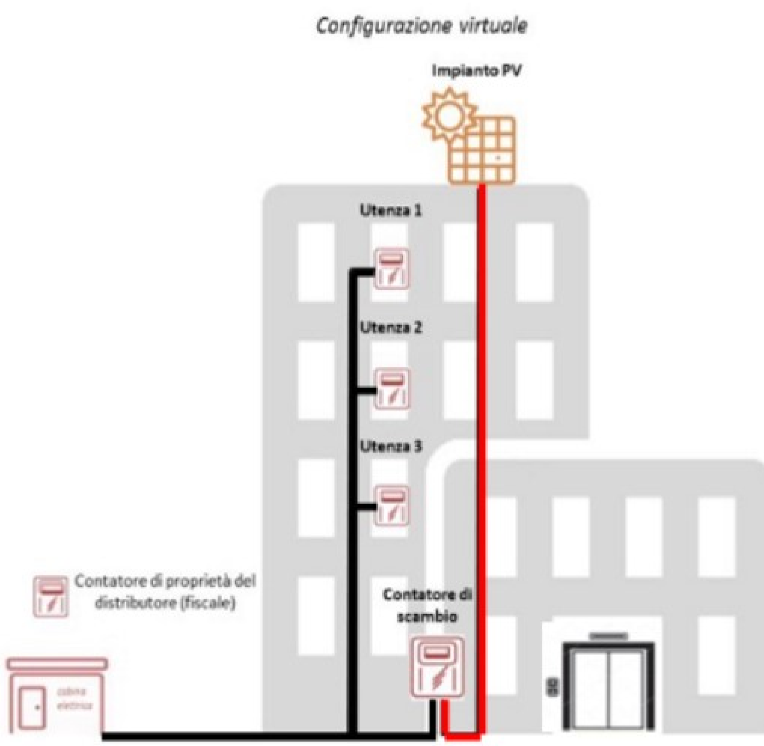

Figure 2.1: Virtual self-consumption scheme

With the Ministerial Decree of 16/09/2020 [17], Art.3, the fixed value of incentives is established, and it is supposed to be supplied for a period of 20 years.

Successively ARERA, the Italian Regulation Authority for Energy, Networks and Environment, released the deliberation 318/2020/R/eel [18] defining the tariff composition and the other technical features. This is the still in force regulation, so it is the document which states the actual and current REC working. The analysis of the current self-consumption and remuneration scheme led to the comprehension sketched in figure 2.2.

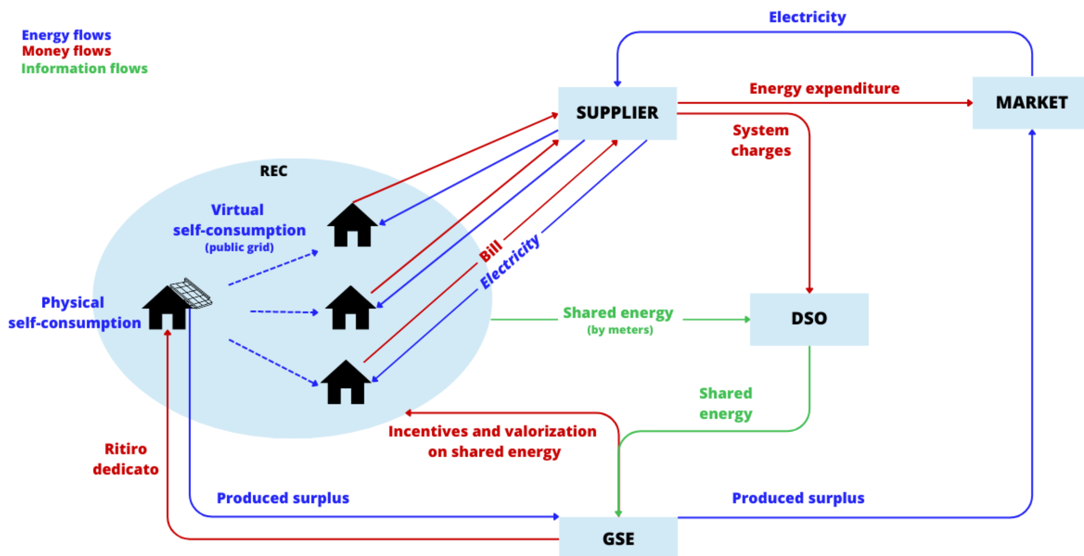

Figure 2.2: Italian REC configuration: energy, information and money flows

Generally, based on their energy flows, REC members can be divided in:

- Prosumers, that own the RES installations (or prosumagers, if they own also storage) and do the physical self-consumption, instantaneously consuming in their buildings the produced energy. The surplus is injected into the public grid, and "virtually" used to fulfil the needs of the other members. Therefore, according the definition of shared electricity given by the Italian legislation, they do not contribute to the community shared electricity;
- Consumers, without any production installation, which are traditional customer buying all the amount of needed electricity from the retailer. They are responsible for the virtually self-consumption, so for the incentivised electricity.

In the bill, the network charges are fully included in the payment, as stated from the legislation. Operating with physical self-consumption, only prosumers are able to register savings in the electricity bill. As far as concern the surplus, it can be sold on the free market, or by bilateral agreements, or its management can be entrusted to the GSE. Namely Gestore Servizi Energetici, it is the Italian public company guarantor of promoting sustainable development through renewable energy installation and energy efficiency. The DSO calculates the shared electricity thanks to smart meters, which is owned and under its control, and communicates this amount to the GSE which is in charge to remunerate the REC with [19]:

- Incentive of 110 €/MWh [17] for the shared electricity generated from RES installation with a nominal power lower than 200 kW;

- Value appreciation [18]: it is represented by the unitary fixed compensation for self-consumption (Corrispettivo Unitario Autoconsumo Forfettario), which is composed by the sum of network charges transmission component for low voltage and the maximum amount of the variable component of monthly distribution tariff for the BTAU utilities:

$$CU_{AF,m} = TRAS_E + max(BTAU_m) \qquad \left[\frac{€}{MWh}\right] \tag{2.2}$$

The value appreciation was used to be addressed as a refund or a reimbursement of the network charges, already paid in the electricity bill, for the transmission and distribution components of the shared electricity, since those parts of the network service are not used by the electricity produced and consumed within the community border. This allows the effective network charges for the REC to be cost reflective. In reality, taking into account that the REC are mainly made by households, comparing these components with the network charges they pay in the bill, it can be found that it is not exactly a refund, but it can be better explained as a monetary recognition that the system gives to the community for avoiding a congestion. In fact, BTAU is an acronym to indicate other non-households utilities connected in low voltage grid with available power lower than 16,5 kW, that are supposed to paid also $TRAS_E$, while households do not have to [20]. The incentives instead are part of the ARIM and ASOS tariffs: they are paid to the retailer and then deposited to the DSO, which transmits them to the CSEA (Cassa Servizi Energetici Ambientali). ASOS is the tariff component to support renewable and cogeneration projects. ARIM instead covers the cost for all the other projects. The incentive and the value appreciation values are going to be change to accommodate the legislative and normative updates. With a service called "Ritiro Dedicato", the community producers can also valorise the electricity injected into the grid at the Local Hourly Price PO (Prezzo Zonale Orario) which is the price formed in the electricity market, depending on the hour of injection and the market zone where the installation is.

2.2.2 Portugal

With the Decree Law 162/2019 [21], of October 25th, Portugal introduced the legal framework for self-consumption, transposing the RED II and displaying the definition of REC for the first time in Art. 19. Also in this case, the legislation marked the start of an "assessment phase", since the DGEG (Direção-Geral de Energia e Geologia) was called to identify the obstacles to REC development to propose solutions to them. The definition about the membership, the rights of the member and their purposes is kept equal to the European directive. More generally, there are not precise prescriptions for the REC, but its working makes reference to the more general collective self-consumption scheme (Art. 20), which is based on the UPAC (Unidades de Produção para Autoconsumo), an installation for energy production from renewable sources, integrated to an UI, namely a building electrical system with or without a supply contract, and devoted to satisfaction of the owner electrical needs (Art. 2). To be constituted, the Portuguese renewable energy community needs an UPAC. Always taking as a reference the self-consumption scheme, for the REC it can be stated that:

1. there is not any limit in terms of power installed, but the UPAC is subjected to a different control, registration, or license based on the size of the installation: for example, if the surplus injection into the public grid is bigger than 1 MVA, the license is subordinated to a state assessment of the grid hosting capacity (Art.3). However, the consumer is called to size it to ensure the electricity production to be as equal as possible to the UI demand (Art. 8);

2. the proximity requirement has to be evaluated for each case by the DGEG (Art. 5);

3. there is no constraint about the voltage level of the connection (Art. 5), but some practices to obtain the connection to a voltage higher than the LV can be hard to be obtained;

4. the unique remuneration is represented by the transaction of the surplus energy by means of organized or bilateral market, contacts, with the market operator, or market facilitator (Art. 4). They are responsible for the unbalances they cause to the grid;
5. the usage of the public grid, called RESP (rede elétrica de serviço público) to convey the electricity for self-consumption is a choice; also internal cables can be used (Art. 19);
6. no tariffs for grid access has to be paid for the usage of internal lines, while the ones for the usage of the RESP needs paid but they should be cost-reflective (Art. 18), which means that the tariffs regarding the network usage of voltage levels higher than the voltage level at which the UPAC is connected do not have to be paid;
7. all the allowed activities are listed in Art. 19. Particular attention is paid to highlight the vulnerable or low-income families' right to participate to the REC;
8. it does not receive incentives.

The Decree Law becomes operational with the regulation 373/2021 by ERSE (Energy Services Regulatory Authority, Portugal) [22]. This document introduces some other definitions to address the problem more practically, and clarifies the actors and the activity involved in REC management. To more precisely address technical issues, the regulation introduced other definitions beyond the UPAC, which are the Installation of Consumption IC, Installation of Storage (IA) and the Installation of Production IPr. Differently from the UPAC, the latter is a global electrical installation duly licensed and necessarily linked to RESP.

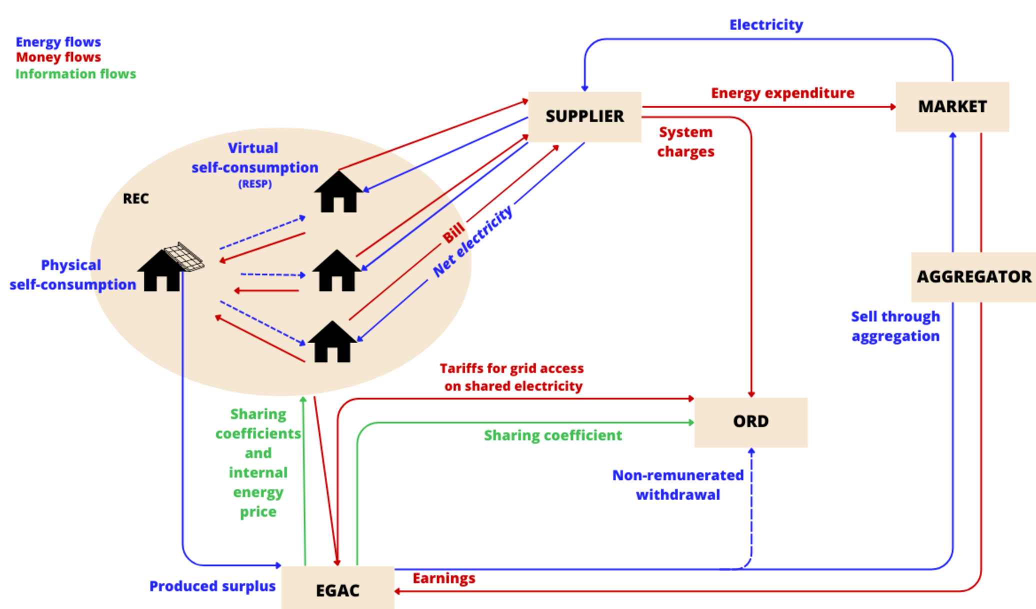

Figure 2.3: Portuguese REC configuration: energy, information and money flows

As for the Italian case, a member's distinction between prosumer and traditional consumer can be made. The prosumer can be associated to the UPAC, so he owns the installation, which is connected to his UI (or IC integrated), and uses the energy produced firstly to satisfy his demand: this is the case of a physical self-consumption. In most common cases, since it is not economically convenient to install new private cables, the surplus in injected into the RESP and used to feed the other consumers, that are IC associated to the UPAC; such a mechanism represents a virtual self-consumption.

The internal share of the electricity among the members, regulated by Art. 36, is performed by sharing coefficient that can be of two types: fixed, so established for each IC but can be variable in time, or proportional to the IC consumption measured. In both cases, coefficients must be set in a proper way and considering consumption habits. This is one of the task of the EGAC: the regulation prescribed collective self-consumption schemes to be legally represented by an "Entidade Gestora do Autoconsumo Coletivo", which is an entity that ensure the management and the commercial relationships of the configuration (Art. 9). It is responsible to define and communicate the sharing coefficient to the distribution system operator ORD (Art. 7), and for the payment to the ORD of the grid access tariff for the shared electricity (Art. 15). Being itself legally established, the REC does not need EGAC, but it still has to perform its tasks. For them, the community can entrust to an ESCo, an Energy Service Company that may also optimize the internal energy management.

Through the sharing coefficient, the electricity must be purchased within the community. On the shared electricity that uses RESP, the tariff for grid access are reduced of the usage tariffs related to the voltage level higher the one in which the plant is installed, and also by a certain percentage of the CIEG, namely the Custos de Interesse Económico Geral network charge. The CIEG discount can be partial or total depending on the Government statement. This amount is later deposited to the DSO.

$$TA_{E,shared} = TA_{general} - TU_{V>V_{installation}} - \%CIEG \qquad \left[\frac{€}{MWh}\right] \tag{2.3}$$

To fulfil the rest of their energy needs, members have to buy electricity from the retailer. Therefore, concerning money flows, it results that the REC manage two different bills: one to the EGAC for the self-consumed electricity, and another to the retailer. The surplus management can be performed in different ways (Art.19): it can be traded with a bilateral contract, or on the wholesale market by an aggregator. If not sold, the ORD can retire the surplus and use it to reduce losses.

2.2.3 Comparison: common features and substantial differences

A comparison is worth to be performed since it can provide insights on the two configurations and can build the basis to support future legal decision making, based on real examples and experience. Summing up, it is evident that, despite some differences in the money and information exchange, the two transpositions presents common features, which are the signal of an agreed first perspective and management of RECs: the community is supposed to be founded on self-consumption, meaning that the electricity production in the REC need to be devoted mainly to the satisfaction of member's electricity needs. In both cases, such a request results somehow in a financial benefit, and this can push the community to adopt intelligent management systems to optimize their behaviour and their portfolio. From the grid perspective, it is beneficial since it reduces the surplus injection that needs to be managed, avoiding local congestion. Technically speaking, sharing the electricity through the public grid is the principal conveying method: if in Italy it is stated by regulation, in Portugal it is a choice of the REC. In fact, it has the possibility to install its private lines, but in the most of the cases it is economically not convenient, so the public grid is used as well. With this configuration, the sharing turns out to be not physical but a virtual one, as shown in the figure 2.1.

As anticipated before, a clear difference is instead in the money and information flows, and in the actors that are involved in their management. The Italian configuration is based on a "refund" system accounted on the amount of shared electricity, operated by a public company because the bill for all the consumption is paid to the retailer. Differently, in Portugal part of the management occurs mainly internally and the members can buy the electricity produced at a lower price with respect to the grid, recording some savings

directly in the bill. The internal price has to be establish: this is what Energy Service Companies (ESCo) do, assuming the role of community manager and performing a local market clearing process.
The absence of an incentive scheme, and the lack of limits in REC size or voltage connection can be noticed in the Portuguese framework: in this case, the guidelines for the establishment of self-consumption schemes result less bounded to power installation size or voltage level connection constraint, but this leaves the feasibility evaluation to the DGEG depending on the cases.
Finally, another and probably the most interesting dissimilarity is represented by the issue of profit sharing. While in Portugal each person can benefit from being a REC member as much as virtuous his behaviour is, the Italian regulation approaches the REC as a whole, and the same does the GSE with the economic profits, creating a problem of not clear allocation within the community, which represents a practical concerning for the members' interest. For example, a fair profits share must take into account that, if from one side who owns production installation have to return the investment, on the other side the incentives are received for the amount of share electricity, which is enhanced mostly by the participation of traditional consumers.

2.3 New perspective from updated legislation

The 8th November 2021 Italy conformed its legislation to the European guideline publishing Decree Law 199/2021 for the actuation of the directive (UE) 2018/2001 [23]. Therefore, the definition of Renewable Energy Community is revised in Art. 31: home automation and energy efficiency actions, EV charging, possibility to play the retailer role were added to the allowed activities, but the real news concerns the explicitly stated possibility to provide ancillary and flexibility services. In the Art. 8 it also extended the access to the incentives on the energy shared among the utilities connected under the primary cabin (MV/HV) and for the installed power, for renewable production, smaller or equal to 1 MW, entered in operation after the 15/12/2021. On the same date, Decree Law 210/2021 introduced also the definition of Citizen Energy Community (Art.14) and accomplished the actuation of the EU Directive 2019/944 as well [24].

	DL 162/2019	DL 199/2021
Incentives	200 kW	1 MW
Grid connection	LV/MV (secondary cabin)	MV/HV (primary cabin)
Ancillary and flexibility services	NO	YES

Table 2.2: Italian legislation updates

In the meanwhile, primary cabins over the national area have been mapped to highlight opportunities and to facilitate design processes. The ministerial decree aimed to implement DL 199/2021 is currently under the European Commission revision [25]. The proposal, that needs to be approved, is to set an incentive tariff for the energy produced by plants of maximum 5 GW and self-consumed, which value will be composed by a fixed and a variable components, both differentiated by the installation size and its geographical location. In addition to this, it is willing to set some grant funding, for up to 40% of the investment, for municipalities smaller than 5000 citizens to establish CER with installations up to 2 GW in total by 2026. The decision for value appreciation updates is instead under the responsibility of the regulation authority ARERA; no changes have been communicated yet [25]. To state the beginning procedures for the new decree law implementation ARERA declares the intention to set a common and comprehensive regulation for all the self-consumption schemes, including also the CEC newly introduced [26]. It represents a clear effort to overcome the European ambiguity and to harmonize the definitions to the purposes. Such intentions have been reported in the ARERA deliberation Integrated Text on Distributed Self-Consumption [27]: published to better defining the different possibility of self-consumption organization, it distinguishes among CER, CEC, and different sets of self-consumers collective groups. No further specification is stated about how to promote and apply for ancillary service provision.

Few months after Italy, Portugal released the DL 15/2022 [28], with the purpose of an integrated revision of the whole National Electricity System (SEN, in Portuguese). In this document, the definition of REC and CEC are respectively in Art.189 and Art.191; as the Italian case, REC activities are extended also to the system services, directly or by means of aggregation. In addition, it establishes the new possibility to manage the shared energy also with dynamic coefficient (Art. 87).

	DL 162/2019	DL 15/2022
Storage in UPAC	NO	YES
Sharing coefficient	Only fixed or proportional	Also dynamic
Access to Ancillary and flexibility services	NO	YES

Table 2.3: Portuguese legislation updates

The updated regulation is expected for the 2023.

2.4 Interest for Energy Communities

The phenomena of people aggregation with the idea of self-managed electricity to be energetically independent was born in the 1930s, in the remote and rural areas of Germany; after the oil crisis (1973) and the Chernobyl disaster (1986), new energy cooperatives were born in North Europe, centering their activities on wind turbines, and other RES production [29]. Nevertheless, a systemic interest in energy communities has arisen in the past years, after the UE-led implementation of RECs: focused on self-consumption, which «is currently seen as the best measure to assure that there are no network issues in the long run due to expected high increase in renewables share by 2030», [30], they have helped to avoid network congestion, while attracting customers through economic benefits. By the way, their development results strongly dependent on how much clear policy and regulation are, and on the support offered for both self-consumption and flexibility [30]. For the latter, the approach of regulator authorities is still unclear [30].

In spite of not being one of the main interests of European DSOs at the moment [31], energy communities are mentioned to be among the topics, introduced by the EMD, that will considerably touch upon DSO's activities [31]: since promoting the engagement of active customers, they are considered beneficial but, provided that the most of them will remain connected to the grid, the DSO is supposed to collaborate with them and to give them access to the grid in a non-discriminatory manner, also by setting a fair tariff structure for grid connection. These issues can lead to wonder about what could be the technical implication of ECs uptake, and if they will imply further burden to DSO tasks [31]. On a DSO's perspective, they should also be "grid supportive" [13]. In effect, if correctly enabled, they represent an opportunity for the DSO's mission and can play their role in improving local balancing and providing flexibility, so to increase grid resilience and to optimize DSO's investment plans [13]. In order to do that, precise technical coordination on large scale performed by the DSO is needed, and without that, the flexibility potential benefits from ECs can lead instead to a lack of data security, problems with energy supply, system stability and balancing [32], accelerating network management complications at local level [33].

In addition, some other key aspects are still to be clarified, like the EC role in the energy market and their relationship with the other market stakeholders. For a successful implementation, flexibility must be adequately remunerated by proper schemes, and not by lower network tariffs [34], and new EC business models including also flexibility services are recommended [35, 5].

2.5 Demand-side flexibility

Flexibility is generally defined as the ability to «modify generation and/or consumption patterns in reaction to an external signal, such as a change in price, to provide a service within the energy system» [36] and is becoming increasingly important when talking about the changes that power system is facing since the past decades. With the aim to reduce GHG emissions, the switch to renewable or low-carbon energy resources led to a distributed, non-forecastable and intermittent generation that the current network is not prepared to handle, since it was designed to work with a stable and vertically controlled generation, and predictable users' behaviour; its established management results to be no more economically efficient if it has to match with distributed energy resources [33]. In addition, the growing electricity demand, led both by the adoption of more electricity-based technologies, like EVs, and increasing number of users, is becoming demanding to the grid, generating problems in terms of grid capacity and congestion [37]; capacity is linked to the maximum power generation that the grid can host, while congestion arises when the transmission lines are not sufficient to transfer power according to market desires.

The simple expansion of the grid can be considered one of the solution, but it is a long-term and expensive option, so generally undesirable [38]. An alternative can be to explore the potential of smart grids, including storage systems and coordination systems, organized to boost self-sufficency from the grid and to provide flexibility. In effect, flexibility is recognised as one of the main tools to accommodate the changes in the network and the consequent management issues: if well organized, it can allow a suitable integration of distributed renewable energy resources and electric vehicles, so to ensure the security of supply and to improve electricity system resilience, to defer and/or avoid additional network reinforcements and investments [39], with the In the end, it will be crucial to realize the final goal of a paradigm shift, from a load-following supply to a supply-following demand scheme, to match RES production and optimize its use. Flexibility was traditionally provided by generation side, but with intermittent and uncontrollable RES generation, it become a scarce resource; therefore, demand-side flexibility is becoming progressively more relevant, leading to a design of innovative and tailored product and services.

Flexibility from demand-side can derive for different sectors, as classified in figure 2.4, and each one has a different potential depending on the type of load and technologies owned. The industrial sector has a grate potential, both in terms of size and of type of loads [7], which can be divided in interruptible, like cements crushes and mills, or adjustable ones, like smelting furnaces. For the commercial sector, the availability of flexibility highly depends on the business activity [7]: supermarkets and touristic accommodation facilities, for instance, have different loads and different interests to comply with, so some marginal amount of flexibility may be evaluated by cases. With the penetration of EVs, also the designation of public parking lots can be advantageous. The agricultural sector can make available the flexibility of water pumps for irrigation, water tank towers and the potentially shiftable consumption pattern of farms [7]. Residential consumers are characterized by a set of different appliances, that in literature are distinguished in uncontrollable, so non-flexible, Thermostatically Controlled (TCA) and Non-Thermostatically Controlled Applicances (NTCA); TCA, which included electric water heaters, heat pump and heating, ventilation, air conditioning devices, and can provide bigger amount of flexibility with respect to NTCA [7]. The flexibility potential is in general unlocked by Energy Management Systems (EMS).

Regardless their potential, consumers participation in energy and flexibility markets is though a complex matter: even if their action can be predicted to an extent by psychology and behavioural economics, they cannot be considered agents with a perfect rationality,

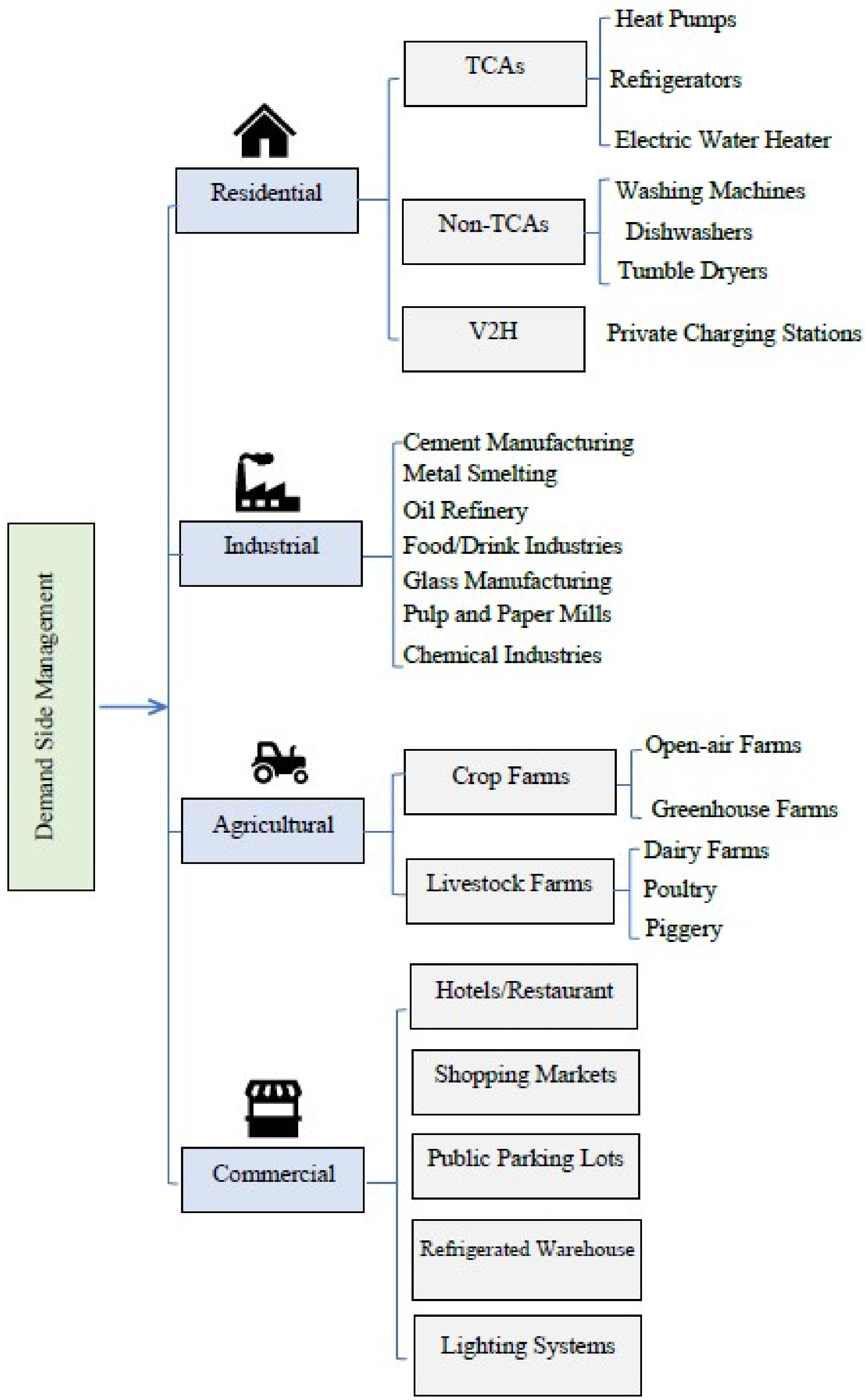

Figure 2.4: Demand-side flexibility sectors classification (source: [7])

therefore their response for flexibility provision is affected by uncertainty [40]

Demand side management to provide flexibility can be divided into two main categories of strategies: grid independence support and demand response programs, as detailed in figure 2.5. The first is enabled by some on-site generation installation combined with a certain degree of control on consumption: the demand-side users capability of self-consumption reduces their dependence on the electricity network, and can avoid local congestion. On the other hand, demand-response is more complex and includes a range of different programs. On the basis of the strategy adopted, they can be distinguished as [1]:

- implicit or price-based flexibility, when variable electricity tariffs are set to induce changes in the consumer behaviour;
- explicit or incentive-based flexibility, when a load cut or increase in consumption is explicitly asked from the DSO to a contracted consumer.

Priced-based flexibility is adopted generally in a one-day period, and depending on the type of program it requires a slow or fast response. For Time-of-Use (ToU) pricing, energy prices are differentiate for time intervals, typically longer than an hour, and known in advance, so that consumers can easily decide how to react; Critical Peak Pricing (CPP) works similarly but with much higher tariffs in the peak periods. With Real Time Pricing (RTP), instead, prices can be settled in few hours or less than an hour in advance, so a fast response is needed. All of this measures are available to regulate both load increase or reduction. In incentive-based flexibility, customers receive incentives for their actual participation in the market, that can be voluntary or mandatory: this kind of programs are generally contracted, and some penalties may be considered in case of a not-satisfied request. More typically, with the exception of some ancillary services, these measures operate to force load reduction: demand bidding, emergency programs, direct load control and interruptible/curtailable programs are the main strategies.

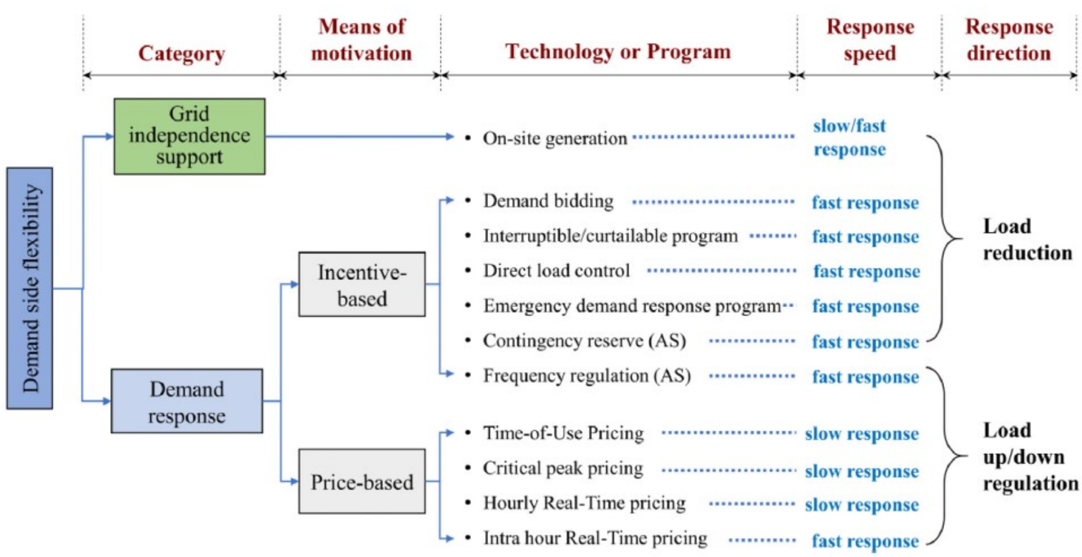

Figure 2.5: Demand-side flexibility overview (source: [5])

To exchange demand-side flexibility in a market based mechanism, different actors are involved [41], as shown in figure 2.6. For implicit flexibility, end-users sign contracts directly with their retailers. Differently, explicit demand-response, needs to interact with an aggregator to have access to the marketplace, where flexibility bids can be matched with the service requests. The aggregator, or Balancing Service Provider (BSP) has the role to collect the bids of different small customers, which otherwise cannot offer relevant products on the market, and its task are the procurement of balancing services, the settlement of imbalances, the calculation and allocation of energy costs and profits [42].

Balance Responsible Party (BRP) is a private legal entity that overlooks the balance of one or multiple access points to the transmission grid, and it is financially responsible for the imbalances in the electricity market. It manages demand-side flexibility by adjusting its production and consumption [43]. DSO and TSO are the distribution and transmission grid operator that ask for and benefit of flexibility services. TSO is responsible for managing the transmission grid, which carries electricity from power plants to the distribution grid, and for guaranteeing a constant frequency. It manages demand-side flexibility by ensuring the transmission grid is stable and can handle fluctuations in energy demand and supply. It also coordinates with BRPs and DSOs to ensure the grid remains balanced and reliable. [44] DSO is responsible for the distribution grid management, which carries electricity from the transmission grid to consumers. It manages demand-side flexibility by encouraging energy users to participate in demand response programs, which involve reducing energy consumption during critical periods, such as peak hours. To fully unlock this potential, regulatory frameworks still need to be clarified [31], data access and security is needed [4], and a better coordination between DSO and TSO is required [1].

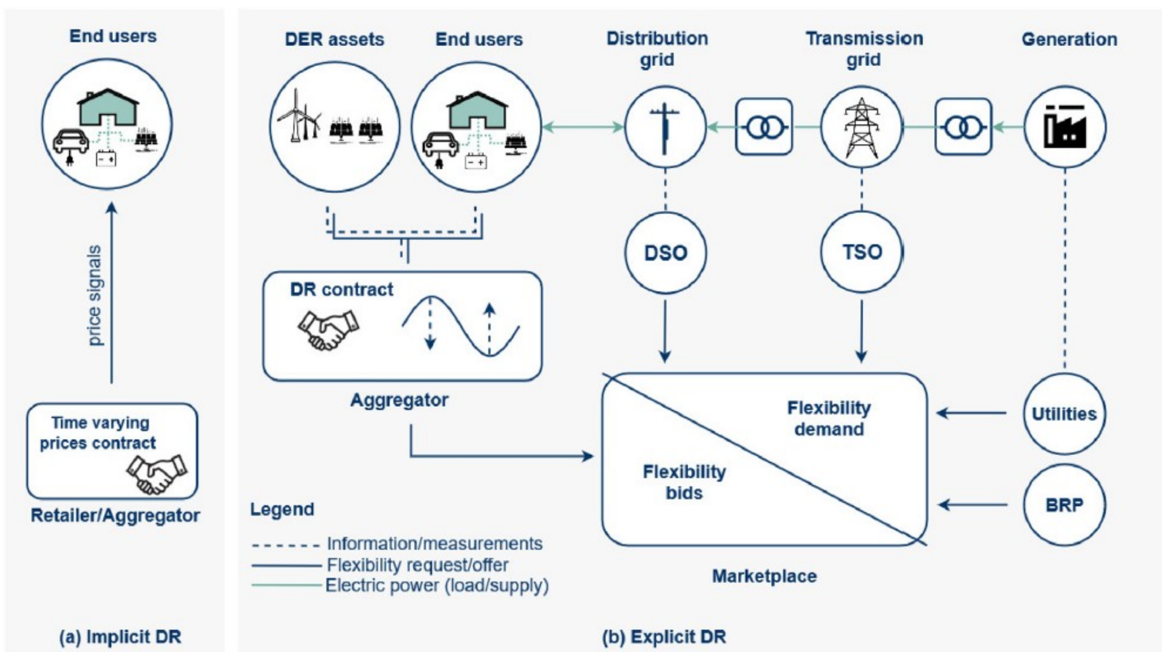

Figure 2.6: Demand-response actors and processes (source: [41])

2.6 Ancillary services

The power system need to be balanced all the time in both energy (kWh) and capacity (kW), so these two products are traded in markets from the day ahead. Anyway, they are not sufficient to let the system operate in a reliable mode, that means to ensure and maintain the instantaneous and continuous match of consumption and demand, to manage flows on transmission lines and to implement control schemes. Therefore, additional services, called balancing or ancillary (AS), are needed by the system operators [45] both in normal conditions and when contingencies occur to solve congestion, providing frequency reserves and ensuring the balancing of the system; when the TSO is not able to maintain the latter, they are involved also in the restarting of the power system [5, 46]. Because of the particular characteristics of the services, like the little notice and the fast response, typically they were provided by generators, but the above-mentioned changes of the electrical system are paving the way to some modifications and to new products [5]. When AS are provided from the demand side, they are categorized as demand-response flexibility services and are remunerated by incentives (figure 2.5). In Europe they are organized in hierarchical levels [47]:

- primary frequency control, based on primary reserves like synchronous generators, it is in general automatic and a mandatory for all the relevant units, so it is not traded. It is used to keep the frequency close to the 50 Hz, which is the nominal one, after some variances;
- secondary frequency control: it is called automatic Frequency Restoration Reserve (aFRR), it is activated within 180s and it is used to restore the frequency to the rated value;
- tertiary frequency control is called to restore the frequency or to face uncertainties or unexpected event. It is divided into two types of reserves: the manual Frequency Restoration Reserve (mFRR) delivered within 15 min, and the Replacement Reserve, delivered within 120 min and necessary to restore the tertiary reserves for probable demand shift, RES injection or long faults.

2.6.1 Evolving flexibility services market

In the scenario of paradigm changing for the electricity network, as it was already said demand-side flexibility is becoming largely important. To be compliant with the European objectives proposed by the Climate and Energy Package, also the market for flexibility services provision which was historically committed to conventional large-scale power plants (e.g. heat, hydro), should be accessible to distributed energy resources, characterized by low or medium voltage connection and small size. This can be done by a whole system redesign, service reform or product evolution. Changes are actually being implemented since the past decade in Europe, with some differences depending on nation, but general trends for the regulatory evolution of the market and the service request features arise as compromise between the System Operator and the Balancing Responsible Party interests [10]:

- to be able to satisfy the minimum bid size, distributed energy resources are generally aggregated. The **pooling of different assets categories**, including not only production units (e.g. from RES), but also storage and load demand response is an advantageous choice for the BRP to precisely satisfy the system request. It may need a new assessment of the pre-qualification tests by the TSO;
- with the intention to open the market access to DER and residential customer, the European trend is to decrease the **minimum bid size** from 10 MVA up to 1 MW or a few hundreds of kW: Italy, for example, is trying to decrease it up to 0.2 MW [10], [48]. Nevertheless, too small bids can increase the number of transactions and may reveal to be not economically convenient, so trade-off solutions need to be explored;
- about **duration** the proposal is to decrease the maximum delivery time since it enhances both the certainty of provision and a larger integration of DERs and RES in the electricity dispatch. Also this solution can increase the number of transaction needed per day;
- decreasing the **delivery time**, or equivalently increasing the ramp rate is widely appreciated because, differently from conventional plants, DERs are able to respond to fast signals, and it allows to decrease the uncertainty linked to RES, too;
- generally, units committed to the ancillary services provision are symmetric reserve: this means they are requested to be capable of supply the same amount of downward and upward capacity (e.g., in MW). This clearly excludes several categories of DERs and new units, like renewables energy sources , that are usually only capable of providing a downward reserve". Therefore, future regulation is foreseen to create new **asymmetric products**;

2.6.2 Italy: the UVAM project

In Italy, ancillary services are managed by the TSO TERNA in the MSD market (Mercato del Servizio di Dispacciamento), which is composed of two stage: a planning stage called Ex-Ante MSD, and a second one called MB (Mercato del Bilanciamento), devoted to real-time balancing. The participation to the market is mandatory for units qualified for providing the services. Non–relevant units, that have a capacity lower than 10 MVA, like demand units or units powered by RES, are enabled to participate, and some studies are on the table mainly to include them in MSD by aggregation [47]. In effect, since 2017, Italy decided to promote pilot projects to assess the technical and economical feasibility of distributed energy resources (DERs) and non-programmable RES (NP-RES) organized as virtual power plants (VPP) to provide ancillary services [49]. They are called Virtual Enabled Units (Unità Virtuali Abilitate or UVA, in Italian) and can have different structures depending on the type of units aggregated:

- UVAC, namely aggregates of consumption units only (Unità Virtuali Abilitate di Consumo);
- UVAP, aggregates of production units only (Unità Virtuali Abilitate di Produzione);
- UVAM, aggregates of mixed demand and production units (Unità Virtuali Abilitate Miste).

The latter project starts from 2018, as result of UVAC and UVAP merging: they can include small scale power plants and larger production units, stationary energy storage systems, electric vehicles and loads. They have no restriction in terms of grid voltage level connection, but they should be compliant with the aggregation perimeter, defined by the italian TSO and currently referred to Italian provinces, which cannot exceed the market zone.
Initially the minimum size threshold to participate in markets was set to 10 and 5 MW, but to enlarge the audience to small customers, it was lowered to 1 MW for UVAM.
For the time being, italian UVAM projects have been enables to provide only particular AS, summarized in the table 2.4 with the respective technical requirements, both in upward and downward requests, remunerated with a pay-as-bid mechanism [50].

Service	**Minimum bid size**	**Response time**	**Delivery Duration**
Congestion Management	1 MW	within 15 min	at least 120 min
Tertiary spinning reserve	1 MW	within 15 min	at least 120 min
Tertiary replacement reserve	1 MW	within 120 min	at least 480 min
Balancing	1 MW	within 15 min	at least 120 min

Table 2.4: AS services open to UVAM project and technical requirements (source:)

In order to be able to participate to AS market, UVAM has to be flanked by a Balancing Service Provider or aggregator, and the Balance Responsible Party. The first is in charge to trade and supply services on the market, the second is responsible for the unit exchanges with the grid and the correlated imbalances. The BSP has to communicate to the TSO the UVAM baseline curve, one day ahead of the delivery day, with a time resolution of fifteen minutes, which is corrected by the TSO with real-time exchanges, and also the units of the UVAM involved in the provision of the service [50].
With affinity reasoning, since composed of both demand and production units as definition, energy communities can be related to UVAMs, or better, an UVAM could be formally an EC, so they are taken as example for the case study.
In any case, the efforts made to study DERs participation to AS market are dovetailing with the national legislation alignment with the European directive (introduction of AS

possible provision), paving the way also for EC to contribute to system stability and operation.

2.6.3 Portugal

Ancillary services framework in Portugal seems to remain tailored to the characteristics of generators, making difficult the access to demand-side flexibility resources [51]. Reserva de Regulação Primária, analogous to FCR, is mandatory for conventional generators and non-remunerated. The aFRR, called Reserva de Regulação Secundária, is mandatory for selected generator considered able to provide the service, but no renewable production units are currently included; it is remunerated through a balancing market mechanism only for capacity and it is not symmetrical. Replacement Reserve, or Reserva de Regulação Terciária, is procured through a market scheme where bids are mandatory for selected generators but no renewable as wind or PV installations can participate; it is remunerated both for energy and capacity, and it is not symmetrical [51]. Recently, the market was open to consumers with some pilot projects that have been tested to assess the possibility for consumers to participate to RR market. Constraint for participants are a capacity bigger or equal to 1 MW, the connection to medium or high voltage level and the licence to demonstrate the technical capability to provide the service. Therefore, the program is limited to industrial customers, and aggregation of smaller consumption sites was excluded for this campaign [52]. The aggregator framework was introduced in national legislation in 2022 [51].

2.7 Flexibility products deliverable by an EC

Within an energy community, not only energy services, but also flexibility services can be provided to its members. Energy services involve the energy produced, consumed and shared, like services to increase energy awareness, purchase and maintenance of the energy assets, supply and shared energy, or P2P supply. Flexibility services, instead, are expressed by the possibility of voluntary and time-limited change in energy profiles. In the context of energy communities, CECs in particular, also an internal and external flexibility [8] can be defined. It can be explained by the fact that variable tariffs (implicit flexibility) lead the community to exploit its resources to perform a local energy optimization, that generally has to be managed by an ESCo. On the other hand, the flexibility directly asked by DSO or TSO and rewarded (explicit) has instead an effect on these external actors and needs an aggregator to interact with them. To sum up, the Universal Smart Energy Framework (USEF) [8] proposes the following schemes:

Therefore, is possible to list the flexibility services deliverable by ECs. Among the internal flexibility services, can be distinguished:

- community self-balancing - subjected to variable energy supply cost, a CEC can decide to organize its self-balancing to generate some profits, like in countries where net-metering of the shared assets is allowed. Profit generation depends on the net-metering time, and in general it is observed that it is economically valuable when it is small. For CEC operating as a closed distribution grid with a single connection point with the DSO, which is a possibility prescribed by the IMD, also network charges are paid once;

- kWmax control of the community load, which consists in performing an optimization to reduce the maximum total load of the community. It seems to be financially viable only if the CEC operates as a independent microgrid, one-point connected with the main grid. A useful consideration for the future can be to consider the CEC as a virtual single connection to the grid;

- ToU optimization - variable price tariffs can lead the CEC members to shape their energy use, so to reduce their energy bill. Since communities have a better negotiation

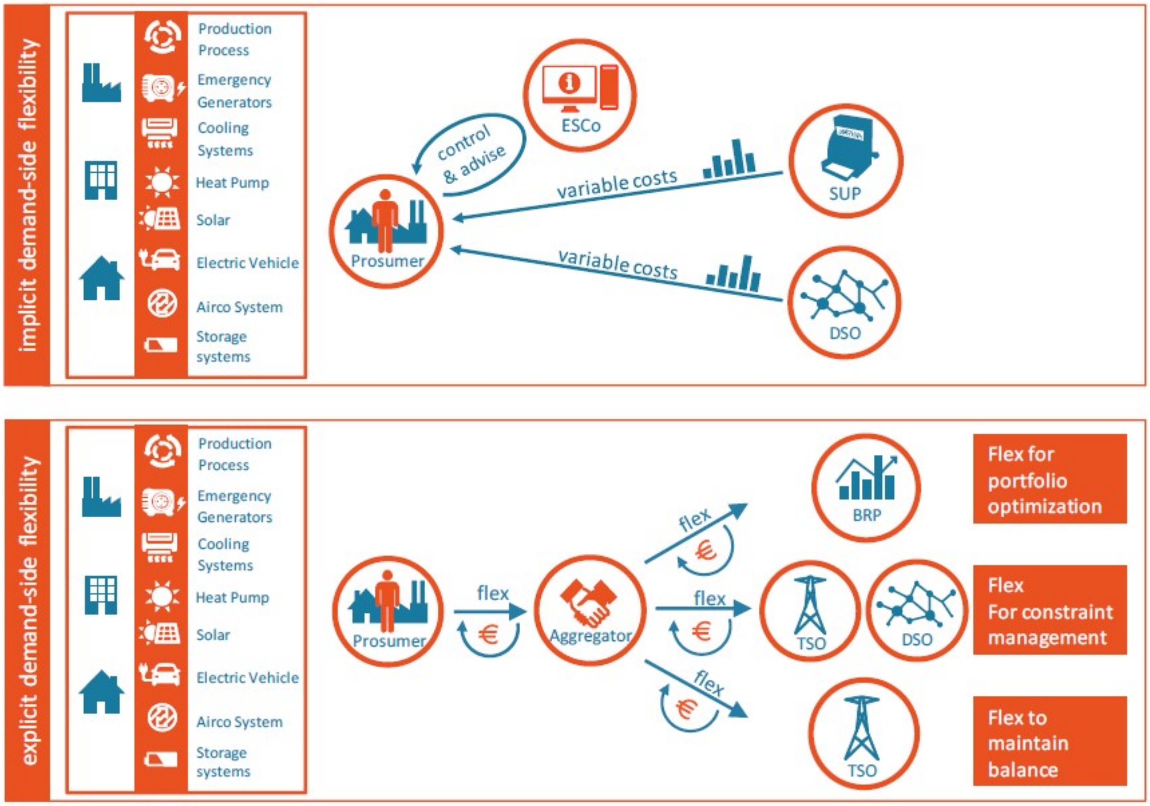

Figure 2.7: Implicit and explicit demand flexibility for energy communities (source: [8])

position, they can ask the supplier for tailored tariffs for the community profile. ToU can be economically interesting only with changing-in-time tariffs;

- emergency power supply - the CEC can decide to install a battery as backup to reduce the aggregate VoLL (volume of Lost Load) during grid outage.

As far as regard external flexibility services, they are generally pooled and addressed with the name of

- explicit DSF services: thanks to an aggregator, or assuming itself the role of an aggregator, if expertise is present, the CEC can participate to their markets.

This type of services can be offered to DSO for constraint management, like congestion management or voltage support, or to the TSO in the form of balancing services. They can also be offered and traded to the BRP for its portfolio optimization [45].

In literature, studies have largely been performed mainly regarding price-based flexibility, typically with the aim to assess how different members can exploit the potential of internal assets for flexibility [53], to optimize EC's self-consumption and profits [54], or to maintain members well-being during fault occurrences [55]. Recently, some studies also focused on the possibility of flexibility or ancillary services provision operated by energy communities. In [56] an heuristic method is proposed for the topic: it considers an energy community made of residential photovoltaic-battery system members with the aim to calculate its provision capacity for upward flexibility services. It is designed to satisfy urgent requests from the grid, so it operates in few minutes exploiting the PV over-generation and the batteries state of charge. With the purpose to allow the service capacity to remain constant over time, a centralized and successive-steps approach is considered: once the time-variable service capacities of the members are calculated, they are flatten and joined to calculate the overall capacity of the EC, which is communicated to the system operator. The accurate approach of the tool in terms of constant capacity provision is the key value of the work; nevertheless, the assumption of considering an EC only made by prosumers with battery systems is improbable, and the role of the EC is limited to capacities aggregation, with no further advantages of being a member.

In [57], a local EC equipped with a shared storage installation (community energy storage, CES) is studied and a hierarchical energy management framework is built. A two-stage strategy has been implemented, considering firstly members autonomous cost-optimal decisions and then the corresponding coordination by the CES to maximize the EC self-consumption and self-sufficiency. Therefore, a methodology for flexibility quantification is added and the EC is further considered to provide ancillary services to grid, through the management of load flexibility and community storage capacity sharing. The work presents the EC's flexibility service provision with a multi-level assessment, considering the preferences of the members, a shared storage system and addressing the demand-side perspective with economic and sustainability objectives.

In the study proposed in [58], the EC is located in the distribution network and participates to mFRR or RR services: it is composed of a number of residential consumers, who share as a community a PV system installation and a static battery. Also EV are taking into account to contribute to increasing its flexibility. A two-step scheduling of the community, performed by an energy community management center (ECMC) is contemplated: one performed in day-ahead, to assess the available flexibility capacities, and the second in real-time, to maximize the EC profits. The model provides a realistic simulation of an EC providing flexibility for ancillary services, but leaning to an external aggregator for the collection of the whole capacity reserve to satisfy the grid request.

2.8 Goals and novelties of the work

Following the evolution trend of the European ancillary service market and its opening to the demand side, energy communities may be considered providers that, differently from other customers, can also benefit from an internal organizational structure. Therefore, it may be interesting to assess the EC potential in providing flexibility services, taking into consideration the potential advantages of a coordinated action. Being ECs in their first development phase, the interest in their potential for this kind of services may be seemed untimely; up to now research has been mainly focused on the EC internal organization to optimize self-consumption [54], contributing to energy poverty [59], performing peer-to-peer exchanges [60], and assessing price-based flexibility [61], mainly to optimize EC profits. on the other side, since demand side flexibility is becoming an urgent matter, the market of ancillary services is evolving and different demonstrative project are going on, as seen for the Italian UVAM one. Recently, models to provide flexibility services by EC have also been proposed [58, 56, 57].

The objective of this research is to assess EC's potential as providers of flexibility services to the grid as stand-alone entities, by developing a mixed-integer linear programming (MILP) model to fairly organize the community's flexibility response. In this setting, the main contributions with respect to previous works are:

- considering an EC manager in the role of the aggregator, receiving and self-organizing the EC for the grid request to provide the flexibility needed;
- including in the EC model different end users characterization, in addition to residential consumers and prosumers, like public buildings;
- fairly distributing costs and benefits among EC members while responding to the grid requests.

Methods and models

The aim of the work is to assess the energy communities potential in providing non-traditional flexibility services to respond to particular needs of the grid (e.g. Ancillary Services). To model the EC, three different levels have been taking into account: the community one, ruled by the EC manager (ECM) and object of optimization, the single members consumption behaviour and preferences, which have been considered including detailed MILP devices' models.
The model can be run with different input data, and different time discretization and time frame. It has been developed in the IBM ILOG CPLEX Optimization Studio environment.

3.1 Overview

The model wants to mimic energy communities as composed of a set of end-users ($i = 1, \ldots, N$) having an electricity supply contract and a set of energy assets like loads, local generation, storage system, possibility of bidirectional exchanges with the grid. More in detail, thermostatic loads (EWH, HP), shiftable loads (e.g., dishwasher, washing machine, cloth dryer), storage system, PV generation and electric vehicles (EV) have been modeled. The EC as an entity has a contract with the System Operator for the provision of flexibility services. The flexibility request is characterized by its magnitude (MW), the announcement time t_a and the duration of the service $[t_s, t_e]$; the difference between t_a and t_s defines the response speed. As flexibility services are not scheduled but called when needed with little notice, the model is built to respect this condition and is bounded to re-arrange consumption profiles from the subsequent instant of the request communication. Therefore, being t_a, t_s and t_e known as input, the time frame is subdivided into the intervals $Time_1$, $Time_2$ and $Duration$ as follows:

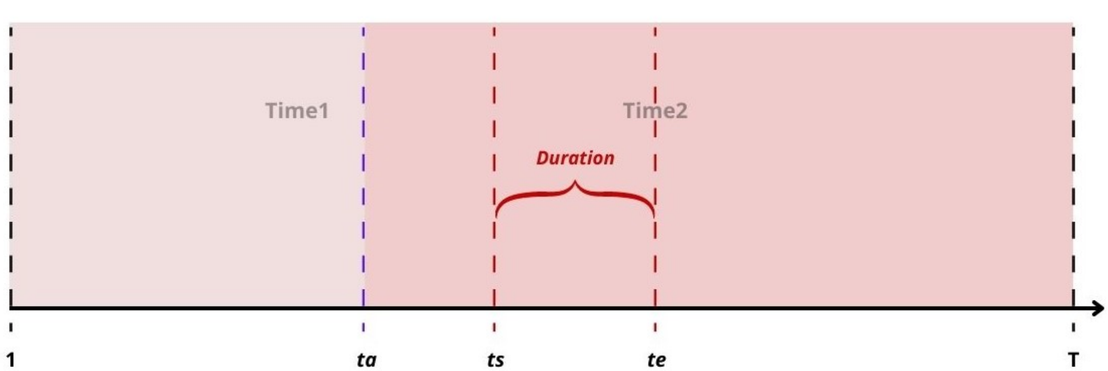

Figure 3.1: Time subdivision - before and after the request; service duration.

An EC manager role is foreseen to fairly split the flexibility requested among the members, rescheduling loads operation from the announcement time onward ($Time_2$, 3.1): for the purpose, it has access to the members' expected disaggregated consumption profiles $P_{i,t}^{G2H,e}$ (grid to home power, expected before the service request - for each member i and each time t of the time frame) and to their devices specifications and comfort preferences. For each member, load scheduling is managed by an EMS. On account of this, a MILP load model based on the one proposed by the authors in [62, 63] was developed. Control strategies allow load rescheduling, in order to calculate the decision variable $\Delta P_{i,t}$ as the variation of power requested to members i during time t of the service duration to satisfy the request. It is defined by the difference of the expected load profile, which is an input of the model, and the one rescheduled in face of the service request, obtained as power balance by optimization. The amount of flexibility that should be delivered by each member $flex_i$ is then evaluated as integral of the power variation over the duration of the service.

3.2 MILP load models

For the purpose of the tool, detailed and modular models of the appliances type that are relevant for flexibility represent the core blocks of the work. The models used are the results of previous works [62, 63], and they have been adapted to the purpose of the study. Modelled flexible loads are divided into four categories:

- shiftable load, namely that can be shifted along the day, like washing machine (WM), clothes dryer (CD), dish washer (DW);
- stoppable loads, that work with an on/off status, like the electric water heater (EWH);
- reducible loads, which power can be reduced or adjusted. In this case, thermostatic loads like air conditioner or heat pump (AC, HP) have been modeled;
- storage devices, considering both electric static battery or storage systems (SS) and electric veichle (EV).

In the following sections the inputs needed, the decision variables and the constraints for each of them are presented: the subscription t refers to the time steps over the time frame, while i refers to EC members.

3.2.1 Shiftable loads

To model the work of this kind of loads, the following needs to be known as input:

- the duration $d_{j,i}$ and the power $f_{t,i,j}$ (kW) requested for operation cycle of the load j of the end user i, which is discretized by the Δt;
- the time for the operation, which is set in the range after the request $[T1, T2] = [t_a + 1, T] = Time_2$;
- the expected operation schedule, in time and power $p_{t,i,j}^{sh,e}$.

Assuming perfect information, once the service is announced and extracting the information from the expected operation schedule, a boolean variable $k_{i,j}$ is calculated to state if the load has to be shifted or not: in particular, if at the time of announcement t_a has already worked or is working, k is set equal to 0, and in the last case the load is let to finish. Otherwise, it can be shifted in $Time_2$, in a range that will depend on the constraints. The decisions variables that are stated are: $p_{t,i,j}^{sh}$, which is the power needed by the load j during $Time_2$, and $w_{t,i,j}$, a boolean variable equal to one when the load starts. The shiftable loads rescheduling is subjected by the following constraints, so to allow them to be operated in $Time_2$:

$$p_{t,i,j} = k_{i,j} \cdot \sum_{r=1}^{min(d_j,t,(t+1-T1))} f_{r,i,j} * w(t-r+1), i, j \quad t = T1, ..., T2, \quad i = 1, ..., N, \quad j = 1, ..., J \tag{3.1}$$

$$\sum_{t=T1}^{T2-d_j+1} w_{t,j,i} = 1 \qquad i = 1, ..., N, \quad j = 1, ..., J \tag{3.2}$$

$$w_{t,i,j} = 0 \qquad t = (T2 - dj + 2), ..., T2, \quad i = 1, ..., N, \quad j = 1, ..., J \tag{3.3}$$

Depending on the other conditions, the constraint 3.1 sets non-zero values of the power matrix for the shiftable operation; equations 3.2 and 3.3 state when the variable $w_{t,i,j}$ is set to 1, so when the load rescheduling starts.

3.2.2 Electric water heater loads

For EWH model, the following are needed as input:

- the power of the resistive heating element Q_i (kW);
- the expected consumption of the EWH along the day $q_{t,i}^{EWH,e}$ and power losses $Pt, i^{loss,e}$;
- the estimated water tank temperature along the day $\tau_{t,i}^e$; expected water withdrawals for consumption in time $m_{t,i}$ (L) for all the time frame;
- minimum and maximum comfort water temperature $[\tau_{min,i}, \tau_{max,i}]$ (°C);
- the hot water tank capacity M_i (kg);
- inlet water temperature $\tau_{net,i}(\circ C)$;
- features of the device and parameters for the energy equation: the area of the tank envelope A_i (m2), the heat transfer coefficient of the tank U_i (W/m2.°C), the specific heat of the water c_p (kJ/kg.C), the ambient temperature around the EWH in $\tau_{amb,t,i}$ (°C);
- a specified temperature τ_{req} to be kept, higher or equal, for a minimun time of t_{req} to eliminate the bacteria like legionella.

The decision variables, defined in $Time_2$, are the rescheduled power consumption of the device $q_{t,i}^{EWH}$, temperature of the water in the tank $\tau_{t,i}$, power losses through the envelope Pt, i^{loss}, and the binary variables $v_{t,i}$ to define the on/off state of the device and $n_{t,i}$ to count when the temperature starts to be equal or higher than τ_{req}.
It is subjected to the constraints:

$$q_{t,i}^{EWH} = v_t \cdot Q_i \qquad t = (t_a + 1), ..., T, \quad i = 1, ..., N \tag{3.4}$$

$$P_{t,i}^{loss} = A \cdot U \cdot (\tau_{t,i} - \tau_{amb,i}) \qquad t = (t_a + 1), ..., T, \quad i = 1, ..., N \tag{3.5}$$

$$P_{t,i}^{loss} \geq 0 \qquad t = (t_a + 1), ..., T, \quad i = 1, ..., N \tag{3.6}$$

$$\tau_{t+1,i} = \frac{M_i - m_{t,i}}{M_i} \cdot \tau_{t,i} + \frac{m_{t,i}}{M_i} \cdot \tau_{net} + \frac{q_{t,i}^{EWH} - P_{t,i}^{loss}}{M_i \cdot c_p} \cdot \Delta t \qquad t = t_a, ..., T, \quad i = 1, ..., N \tag{3.7}$$

$$\tau_{t,i} \geq 0 \qquad t = (t_a + 1), ..., T, \quad i = 1, ..., N \tag{3.8}$$

$$\tau_{i,t} \geq \tau_{min,i} - BM \cdot v_t \qquad t = (t_a + 1), ..., T, \quad i = 1, ..., N \tag{3.9}$$

$$\tau_{i,t} \leq \tau_{max,i} + BM \cdot (1 - v_t) \qquad t = (t_a + 1), ..., T, \quad i = 1, ..., N \tag{3.10}$$

$$\tau_{t,i} \geq \sum_{t'=1}^{min(t_{req},t)} \tau_{req} \cdot n_{t-t'+1,i} \qquad t = 1, ..., T, \quad i = 1, ..., N \tag{3.11}$$

$$\sum_{t=1}^{T-t_{req}+1} n_{t,i} = 0 \qquad t = 1, ..., T, \quad i = 1, ..., N \tag{3.12}$$

BM (in eq. 3.9, 3.10) is just a big positive number that allows the constraints on the temperature range to be mutual respected. Some initial conditions need to be set as constraints for $\tau_{t,i}$ and Pt, i^{loss}: they are taken from the input expected values at t_a, $\tau^e_{t_a,i}$ and $Pt_a, i^{loss,e}$. Constraint 3.4 sets the power requested from the EWH, as the product of the resistive element power and the variable that states its on/off status; equation 3.5 calculates the power losses of the tank with the environment, ensuring they are positive (3.6). Constraints from 3.7 to 3.10 govern the water temperature evolution in the tank, taking into account the inlet water, the losses, and the hot water withdrawals, ensuring that it will remain in the expressed range of acceptability $[\tau_{min,i}, \tau_{max,i}]$; finally, constraints 3.11 and 3.12 ensure that the temperature lays above the temperature requested to kill bacteria for the time requested.

3.2.3 Air conditioning loads

The air conditioning has been modeled as a reducible devices (inverter technology). As input it needs:

- the nominal power of the AC appliance $P_{nom,i}$ (kW);
- the expected consumption of the AC along the day $P_{t,i}^{AC,e}$;
- the estimated indoor temperature of the AC along the day $\theta^e_{t,i}$;
- the levels of power at which it can work L_i [e.g. $L = 4$: 25%, 50%, 75%, 100%];
- the outdoor temperature $\theta_{ext,t}$ (○C);
- minimum and maximum indoor temperature comfort range $[\theta_{min,i}, \theta_{max,i}]$ (○C)
- the coefficient of the energy balance on the building, computed in the thermal model as in [25]: β_i, α_i, γ_i. U is the (weighted average) overall heat transfer coefficient of the building unit envelope (kW/(m2○C)), A is the surface area of the envelope [m2], so UA is the overall thermal conductance of the unit envelope (kW/○C), and C is the

overall thermal capacity (kJ/∘C). COP is the coefficient of performance of the AC appliance:

$$\beta_i = \frac{U_i \cdot A_{b,i}}{C_i} \cdot \Delta t \tag{3.13}$$

$$\alpha_i = 1 - \beta_i \tag{3.14}$$

$$\gamma_i = \frac{COP_i}{C_i} \cdot \Delta t \tag{3.15}$$

The indoor temperature oh the building $\theta^{in}_{t,i}$ and the power of the AC working after the service request $P^{AC}_{t,i}$ are defined as decision variables, together with the auxiliary binary variable $\delta^{l}_{t,i}$ to define at which level the device is working.

It is subjected to the constraints:

$$\begin{gathered}\theta^{in}_{t,i} = \alpha_i \cdot \theta^{in}_{t-1,i} + \beta_i \cdot \theta^{ext}_{t-1,i} + \gamma_i \cdot P^{AC}_{t,i} \\ t = (t_a + 1), ..., T, \quad i = 1, ..., N\end{gathered} \tag{3.16}$$

$$\theta_{i,t} \geq \theta_{min,i} \qquad t = (t_a + 1), ..., T, \quad i = 1, ..., N \tag{3.17}$$

$$\theta_{i,t} \leq \theta_{max,i} \qquad t = (t_a + 1), ..., T, \quad i = 1, ..., N \tag{3.18}$$

$$\begin{gathered}P^{AC}_{t,i} = (0.25 \cdot \delta^1_{t,i} + 0.50 \cdot \delta^2_{t,i} + 0.75 \cdot \delta^3_{t,i} + \delta^4_{t,i}) \cdot P_{nom,i} \\ t = (t_a + 1), ..., T, \quad i = 1, ..., N\end{gathered} \tag{3.19}$$

$$\sum_{l=1}^{L} \delta^l_{t,i} \leq 1 \qquad t = (t_a + 1), ..., T, \quad i = 1, ..., N \tag{3.20}$$

It also needs an initial condition for the indoor temperature $\theta_{t,i}$ at t_a, which is taken from the estimated one, $\theta^e_{t_a,i}$. Constraints from 3.16 to 3.18 govern the indoor temperature evolution, considering the inertia of the apartment, the exchanges with outdoor environment and the gains from the heat pump (in heating mode) and neglecting internal gains, ensuring that the temperature will remain in the comfort range. Constraints 3.19 and 3.20 define at which level mode the air condition has to work.

3.2.4 Storage devices

Storage devices model gathers the static storage system (SS) and electric vehicle battery (EV). Their models are substantially but for this tool they have been differentiated because for SS bidirectional power exchange is possible, while for EV only charging process is considered: this means the EV is assumed only as a load. Further implementation can include vehicle-to-grid exchange (V2G).

The storage system model needs as input:

- charging and discharging efficiency of the battery $\eta^{B,ch}_i$, $\eta^{B,dch}_i$;
- minimum and maximum allowed battery charge $B^{min}_{charge,i}$, $B^{max}_{charge,i}$ (kWh), or state of charge SOC (%);
- maximum charge and maximum discharge power allowed for the battery $P^{max}_{B,ch,i}$, $P^{max}_{B,dch,i}$ (kW);

- the expected battery charge for all the time frame $B^{e}_{charge,t,i}$;
- battery charge, if requested, at the end of the planning period $B_{req,i}$.

The decision variables that needs to be defined in $Time_2$ are the battery charge after the request $B_{charge,t,i}$, and the power exchanged with the house $P^{B2H}_{t,i}$ and $P^{H2B}_{t,i}$; these two are ruled by binary variables $s^{B2H}_{t,i}$, $s^{H2B}_{t,i}$.
The problem is subjected to the following constraints:

$$B_{charge,t,i} = B_{charge,t-1,i} + \eta_i^{B,ch} \cdot P^{H2B}_{t,i} \cdot \Delta t - \frac{P^{B2H}_{t,i}}{\eta_i^{B,dch}} \cdot \Delta t \qquad t = (t_a+1),...,T, \quad i = 1,...,N \tag{3.21}$$

$$B_{charge,t,i} \geq B^{min}_{charge,i} \qquad t = (t_a+1),...,T, \quad i = 1,...,N \tag{3.22}$$

$$B_{charge,t,i} \leq B^{max}_{charge,i} \qquad t = (t_a+1),...,T, \quad i = 1,...,N \tag{3.23}$$

$$P^{H2B}_{t,i} \geq 0 \qquad t = (t_a+1),...,T, \quad i = 1,...,N \tag{3.24}$$

$$P^{H2B}_{t,i} \leq P^{max}_{B,ch,i} \cdot s^{H2B}_{t,i} \qquad t = (t_a+1),...,T, \quad i = 1,...,N \tag{3.25}$$

$$P^{B2H}_{t,i} \geq 0 \qquad t = (t_a+1),...,T, \quad i = 1,...,N \tag{3.26}$$

$$P^{B2H}_{t,i} \leq P^{max}_{B,dch,i} \cdot s^{B2H}_{t,i} \qquad t = (t_a+1),...,T, \quad i = 1,...,N \tag{3.27}$$

$$s^{B2H}_{t,i} + s^{H2B}_{t,i} \leq 1 \qquad t = (t_a+1),...,T, \quad i = 1,...,N \tag{3.28}$$

The initial condition for the battery charge at t_a is taken from the expected state of charge $B^{e}_{charge,t_a,i}$. Constraints from 3.21 to 3.23 govern the evolution of the battery charge ensuring that the charging and discharging processes will not take the battery out of the minimum and maximum suggested levels. Constraints from 3.24 to 3.27 instead are forcing the variables stating the power exchanges to be positive and to respect the upper limits of power for the charging and discharging processes. Finally, constraint 3.28 is ensuring these two processes to not be simultaneous.

For what concerns the electric vehicle model, instead, it needs as input:

- the charging efficiency of the vehicle battery $\eta_i^{V,ch}$;
- minimum and maximum allowed battery charge $V^{min}_{charge,i}$, $V^{max}_{charge,i}$ (kWh), or state of charge SOC (%);
- maximum charge power allowed for the EV battery $P^{max}_{V,ch,i}$ (kW);
- the expected EV battery charge for all the time frame $V^{e}_{charge,t,i}$;
- the estimated time of departure from and arrival at home of the vehicle t_d, t_b, and therefore the time intervals in which the EV is at home $[1,..t_d]$, $[t_b,...,T]$;
- EV charge requested at departure time t_d, $V_{req,i}$.

The decision variables that needs to be defined in $Time_2$ are the vehicle charge after the request $V_{charge,t,i}$, and the power exchanged during the charging process $P^{H2C}_{t,i}$, which is ruled by binary variable $s^{H2V}_{t,i}$. Only the charging process is modelled since it is the one for which power exchanges between EV and the grid are expected.
Depending on the time at which the service is requested, the intervals in which the previous

constraints are valid changes: the most general case is defined by the set $Time_{2,EV} = ([1,..t_d] \cup [(t_b+1),...,T]) \cap Time_2$.The model is subjected to the following constraints:

$$V_{charge,t,i} = V_{charge,t-1,i} + \eta_i^{V,ch} \cdot P_{t,i}^{H2V} \cdot \Delta t \qquad t \in Time_{2,EV}, \quad i = 1,...,N \tag{3.29}$$

$$V_{charge,t,i} \geq V_{charge,i}^{min} \qquad t \in Time_{2,EV}, \quad i = 1,...,N \tag{3.30}$$

$$V_{charge,t,i} \leq V_{charge,i}^{max} \qquad t \in Time_{2,EV}, \quad i = 1,...,N \tag{3.31}$$

$$P_{t,i}^{H2V} \geq 0 \qquad t \in Time_{2,EV}, \quad i = 1,...,N \tag{3.32}$$

$$P_{t,i}^{H2V} \leq P_{V,ch,i}^{max} \cdot s_{t,i}^{H2V} \qquad t \in Time_{2,EV}, \quad i = 1,...,N \tag{3.33}$$

$$V_{charge,t_d,i} \geq V_{req,i} \qquad t = t_d, \quad i = 1,...,N \tag{3.34}$$

Always depending on the case, the initial condition for the EV state of charge at the time of announcement t_a may be needed,as well as the condition at the time of arrival t_b; the information are taken from the expected state of charge $V_{charge,t_a,i}^e$, $V_{charge,t_b,i}^e$. Constraints from 3.29 to 3.31 govern the state of the EV charge ensuring that the charging process will not take the EV battery out of the minimum and maximum suggested levels. Constraints 3.32 and 3.33 instead are forcing the variables stating the power exchanges to be positive and to respect the upper power limit for the charging process. Constraint 3.34 force the EV charge to be compliant with the owner preferences.

3.2.5 End user complete model

In addition to flexible loads, that are owned differently from members, also non-flexible load, composed of devices like lights, fridge and electronic devices, is needed to realistically simulate members consumption patterns. It is given as an input data $P_{t,i}^{base}$, as well as the photovoltaic generation $P_{t,i}^{PV}$. In addition, the also the contracted power P_i^C for each member is given as input, defining the maximum power that is possible to exchange with the grid. As anticipated, is essential to know as input the expected consumption profile of the members $P_{t,i}^{G2H,e}$ like the sum of all the disaggregated load profiles, and, if any, also the expected power injection $P_{t,i}^{H2G,e}$.
Therefore, some other decision variable have to be defined to globally characterize the building and its interaction with the grid after the request: $P_{t,i}^{G2H}$ for the withdrawals and $P_{t,i}^{H2G}$ for the injections, ruled by the binary variables $s_{t,i}^{G2H}$ and $s_{t,i}^{H2G}$. The latter are subjected to the constraints:

$$P_{t,i}^{G2H} \geq 0 \qquad t = (t_a+1),...,T, \quad i = 1,...,N \tag{3.35}$$

$$P_{t,i}^{G2H} \leq P_i^C \cdot s_{t,i}^{G2H} \qquad t = (t_a+1),...,T, \quad i = 1,...,N \tag{3.36}$$

$$P_{t,i}^{H2G} \geq 0 \qquad t = (t_a+1),...,T, \quad i = 1,...,N \tag{3.37}$$

$$P_{t,i}^{H2G} \leq P_i^C \cdot s_{t,i}^{H2G} \qquad t = (t_a+1),...,T, \quad i = 1,...,N \tag{3.38}$$

$$s_{t,i}^{G2H} + s_{t,i}^{H2G} \leq 1 \qquad t = (t_a+1),...,T, \quad i = 1,...,N \tag{3.39}$$

$$P_{t,i}^{G2H} - P_{t,i}^{H2G} + P_{t,i}^{PV} = P_{t,i}^{base} + P_{t,i}^{AC} + \sum_j p_{t,i,j} + q_{t,i}^{EWH} + P_{t,i}^{H2V} + (P_{t,i}^{H2B} - P_{t,i}^{B2H}) \qquad t = (t_a+1),...,T, \quad i = 1,...,N \tag{3.40}$$

Constraints from 3.35 to 3.38 define the variables stating the power exchanges with the grid as positive and limiting them to be compliant with the contracted power; constraint 3.39 ensures that the exchanges cannot happen simultaneously, but one at a time. The constraint 3.40 is basically the power balance of the building, that can be better illustrated in figure 3.2.

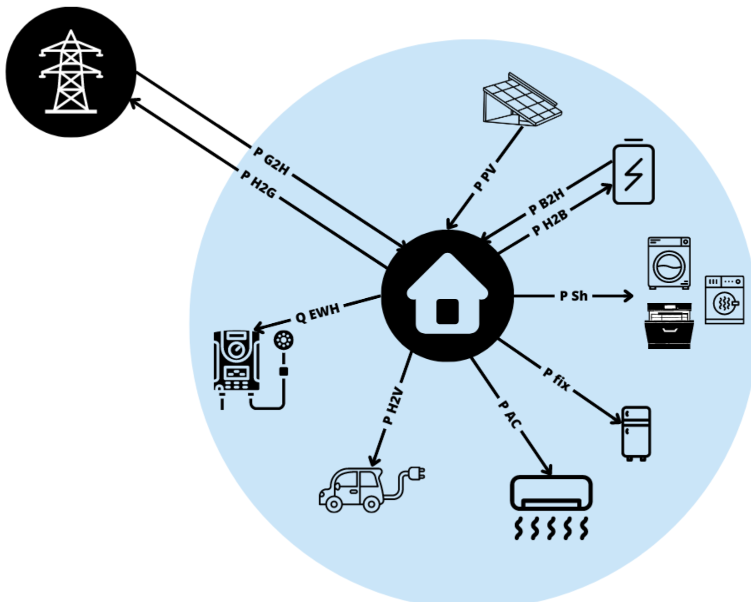

Figure 3.2: Power balance on the members building

	Input Data	**Decision variables**
Shiftable	$p^{sh,e}_{t,i,j}$, $d_{j,i}$, $f_{t,i,j}$, $[T1, T2]$, $k_{i,j,k}$	$p^{sh}_{t,i,j}$, $w_{t,i,j}$
EWH	$q^{EWH,e}_{t,i}$, Q_i, $Pt,i^{loss,e}$, $\tau^{e}_{t,i}$, $m_{t,i}$, $[\tau_{min,i}, \tau_{max,i}]$, M_i, $\tau_{net,i}$ A_i, U_i, c_p,$\tau_{amb,t,i}$, τ_{req}, t_{req}	$q^{EWH}_{t,i}$, k $\tau_{t,i}$, Pt,i^{loss}, $v_{t,i}$, $n_{t,i}$
AC	$P^{AC,e}_{t,i}$, $P_{nom,i}$, $\theta^{e}_{t,i}$, L_i, $\theta_{ext,t}$, $[\theta_{min,i}, \theta_{max,i}]$, U_i, $A_{b,i}$, COP_i, C_i	$\theta^{in}_{t,i}$, $P^{AC}_{t,i}$, $\delta^{l}_{t,i}$
Storage	$\eta^{B,ch}_i$, $\eta^{B,dch}_i$, $B^{min}_{charge,i}$, $B^{max}_{charge,i}$, $P^{max}_{B,ch,i}$, $P^{,max}_{B,dch,i}$, $B^{e}_{charge,t,i}$, $B_{req,i}$	$B_{charge,t,i}$, $P^{B2H}_{t,i}$, $P^{H2B}_{t,i}$, $s^{B2H}_{t,i}$, $s^{H2B}_{t,i}$
EV	$\eta^{V,ch}_i$, $V^{min}_{charge,i}$, $V^{max}_{charge,i}$, $P^{max}_{V,ch,i}$, $V^{e}_{charge,t,i}$, t_d, t_b, V_{req,i,t_d}	$V_{charge,t,i}$, $P^{H2C}_{t,i}$, $s^{H2V}_{t,i}$
Power balance	$P^{base}_{t,i}$, $P^{PV}_{t,i}$, $P^{C}_{t,i}$, $P^{G2H,e}_{t,i}$, $P^{H2G,e}_{t,i}$	$P^{G2H}_{t,i}$, $P^{H2G}_{t,i}$, $s^{G2H}_{t,i}$, $s^{H2G}_{t,i}$

Table 3.1: Input and decison varibles of the model

3.3 Management of the AS request

In a first attempt, the model has been developed for the provision of flexibility that requires a decreasing in power withdrawals; anyway, it can be further extended to all the request types with the adoption of sign rules. The management of the request is imputed to the EC manager. With all the input data provided for each customer, is it possible to aggregate the profiles to see the global EC expected consumption profile, simply obtained by the sum of all the customers ones:

$$P_{EC,t}^{G2H,e} = \sum_{i=1}^{N} P_{t,i}^{G2H,e} \qquad t = 1, ..., T \tag{3.41}$$

Additional decision variables are considered in the model, which are:

- the variation of power consumption requested to each member for all the duration of the service. It is obtain as difference of the expected power profile, known as input, and adjusted consumption for the flexibility purpose, which is a decision variable obtained as power balance of the owned assets rescheduled (eq. 3.42). In the case of power decreasing, this variable is constraint to be greater than zero (eq. 3.43)

$$\Delta P_{t,i} = P_{t,i}^{G2H,e} - P_{t,i}^{G2H} \qquad t = t_s, ..., t_e, \quad i = 1, ..., N \tag{3.42}$$

$$\Delta P_{t,i} \geq 0 \qquad t = t_s, ..., t_e, \quad i = 1, ..., N \tag{3.43}$$

- consequently, the overall flexibility evaluated for each member during the service period can be calculated as decision expression in eq. 3.44; with the inequality 3.43, it results a quantity grater than zero:

$$flex_i = \sum_{t=t_s}^{t_e} \Delta P_{t,i} \cdot \Delta t \qquad i = 1, ..., N \tag{3.44}$$

Taking advantage of the internal organization of the community, the optimization goal is to fairly distribute the flexibility requested by the service. It can be done implementing two different objective functions:

1. minimizing the maximum amount of flexibility [kWh] requested to members, according to the criterion of equality;

$$min[max(flex_i)] \tag{3.45}$$

2. minimizing the maximum relative flexibility [%], with respect to their consumption pattern or available flexible load during that period, following the criterion of equity.

$$min \left[max \left(\frac{flex_i}{Consumption_i} \right) \right] \tag{3.46}$$

In both cases, the problem is subjected to the following constraints:

- operational constraints coming from the devices models, so that for each customer is possible to obtain the new power scheduling observing the devices working principles and users comfort options (constraints from 3.1 to 3.40);
- the constraint on power difference (constraint 3.43);
- the overall EC flexibility, namely the sum of all the customer contribution,s must satisfy the flexibility request during the whole duration of the service:

$$\sum_{i=1}^{N} \Delta P_i \geq SIZE_{MW} \qquad t = t_a, ..., t_e \tag{3.47}$$

Results

4.1 Simulations

In order to test the tool and to provide some critical assessment on its usefulness, several simulations has been performed with a simplified example of an energy community. Some assumptions have been made for it to be realistic: it is modeled with a number N of customers which extend mainly over residential customers, typically family units living in apartments, to reproduce the current trends of existent ECs [64]. They are differentiated in simple consumers, prosumers with PV installation and prosumers with also a storage system. To look forward, public buildings like education buildings, services or offices have been included, too [64]. The EC composition has been assumed as follows:

EC size	**Consumers**	**Prosumers**	**Prosumers with storage**	**Public buildings**
Variable	50%	20%	10%	20%

Table 4.1: Simulation - Community features

The model can be run with different time discretization and time frame; anyway, to align the test with the experience of the UVAM project, they have been performed with a time discretization $\Delta t = 15min$ and along one-day time frame ($24h$).

The simulation is performed in Turin during a winter day (9/01/2020): the weather input data is taken from the database [65], and the photovoltaic generation is extracted from PV-GIS tool. The characterization of the users is instead provided by LoadProfile-Generator (LPG), a modeling tool for synthetic residential electricity consumption that performs a full behavior simulation of the people in a household and uses that to generate load curves, based on German households' preferences. A presentation of the different members characterization follows in paragraphs **4.1.2**, **4.1.3**, **4.1.4**, **4.1.5**.

4.1.1 Tests

The tool is flexible and various input data can be changed to explore the different possible scenarios, for instance also about the time and the duration of the service, the response speed. With this example, tests have been performed fixing the starting time of the service and the announcement time, but changing the size of the request and the size of the energy community, as stated in the tables 4.1, 4.2; in addition, two different objective functions have been evaluated within the same framework, to explore how the flexibility is better spread among member. Two criteria have been analysed: equality (o.f. 3.45), minimizing the maximum flexibility amount [kWh] requested, and equity (o.f. 3.46), minimizing the maximum relative flexibility [%] with respect to the consumption patter or the flexible load.

Service size	Notification time	Starting time	Duration
Variable	1 h before	4 pm	1 h

Table 4.2: Simulation - Requested service features

4.1.2 Consumer

The consumer type is modeled as a family of two adults working from home that owns a dishwasher, a washing machine and a clothes dryer, an electric water heater and an heat pump; his contracted power is $P_C = 3.5kW$.

Load	Device specification	Comfort preferences
HP	$P_N = 1.4kW, COP = 3$	19°C - 21°C
EWH	$P_N = 1.5kW$	50°C - 75°C
DW	$P_N = 1.7kW$	12 pm - 7 am
WM	$P_N = 1.8kW$	12 am - 5 pm
CD	$P_N = 1.7kW$	8 pm - 12 pm

Table 4.3: Simulation - Consumer characterization

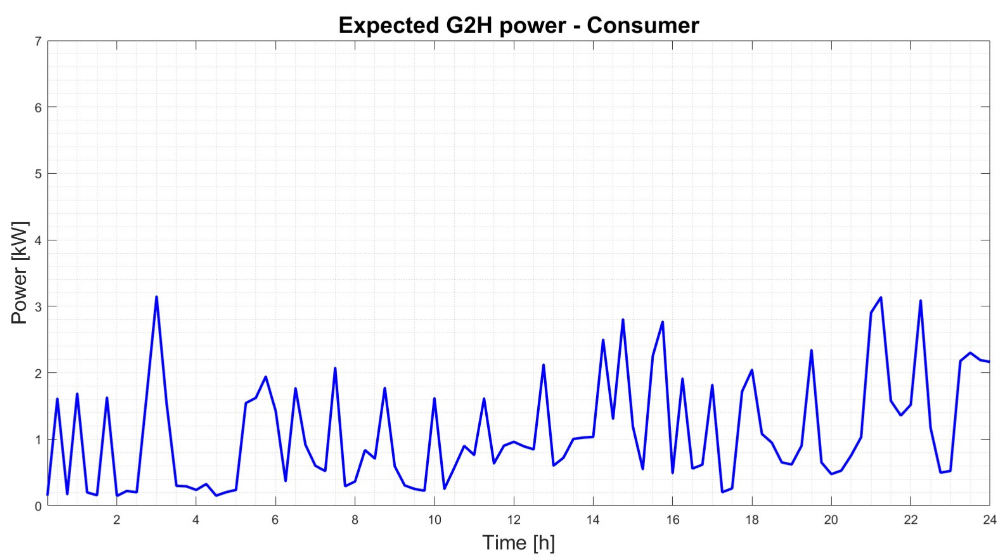

Figure 4.1: Consumer expected consumption profile

4.1.3 Prosumer

The prosumer type is modeled as a family of two working adults and two children. They own a dishwasher, a washing machine and a clothes dryer, an electric water heater and an heat pump; his contracted power is $P_C = 3.5kW$ and he has a PV installation of $P_{PV} = 2kW$ used for self-consumption.

Load	Device specification	Comfort preferences
HP	$\mathrm{P}_N = 1.6kW, COP = 3$	19°C - 21°C
EWH	$\mathrm{P}_N = 1.5kW$	50°C - 85°C
DW	$\mathrm{P}_N = 1.7kW$	3 am - 6 am
WM	$\mathrm{P}_N = 1.8kW$	10 am - 2 pm
CD	$\mathrm{P}_N = 1.7kW$	8 pm - 11 pm

Table 4.4: Simulation - Prosumer characterization

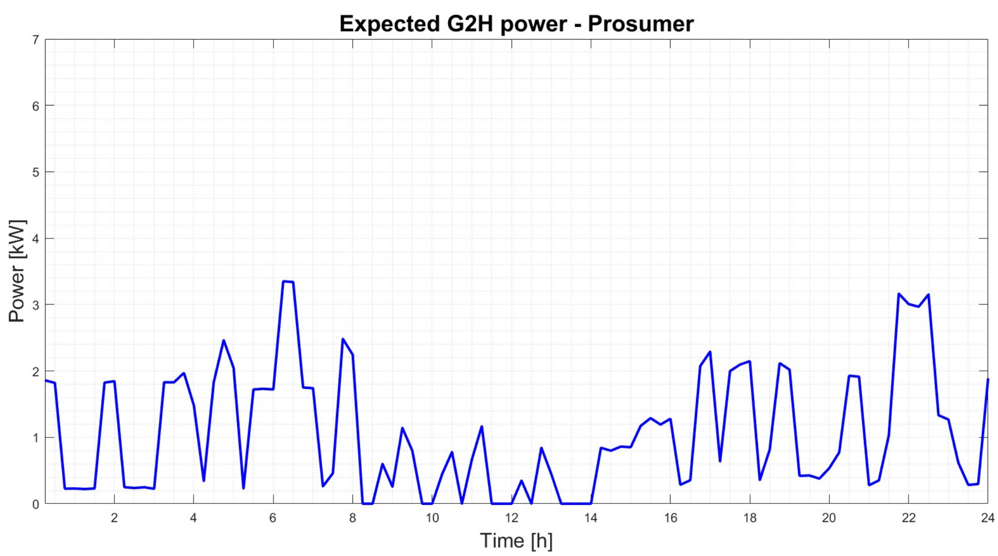

Figure 4.2: Prosumer expected consumption profile

4.1.4 Prosumer with storage

The prosumer type is modeled as a family of four, including two working adults. They owns a dishwasher, a washing machine and a clothes dryer, an electric water heater, an heat pump and an electric vehicle; its contracted power is $P_C = 4.5kW$, he has a PV installation of $P_{PV} = 3kW$ used for self-consumption and a storage system (SS).

Load	Device specification	Comfort preferences
HP	$P_N = 1.4kW, COP = 3.5$	19°C - 21°C
EWH	$P_N = 1.5kW$	50°C - 75°C
DW	$P_N = 1.7kW$	12 pm - 5 am
WM	$P_N = 1.8kW$	5 am - 8 pm
CD	$P_N = 1.7kW$	9 pm - 12 pm
SS	4.5 kWh	Charging with PV generation surplus
EV	30 kWh	$SOC_{req} = 80\% at8:30am$

Table 4.5: Simulation - Prosumer with storage characterization

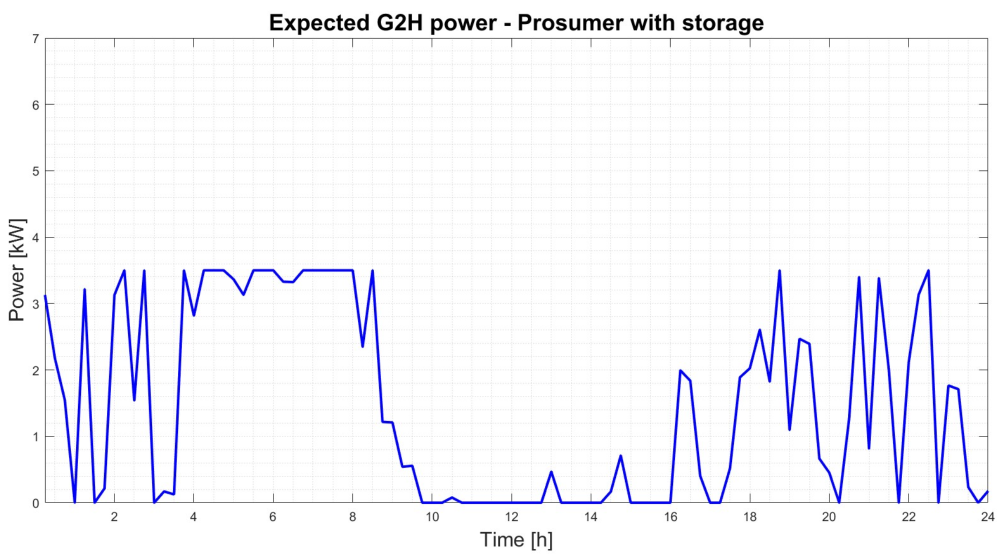

Figure 4.3: Prosumer with storage expected consumption profile

4.1.5 Public buildings

The public building type is modeled as a office building of two floors with an heat pump, and the not-flexible load takes into account lights and a set of work stations equipped with computers. His contracted power is $P_C = 6.9kW$.

Load	Device specification	Comfort preferences
HP	$P_N = 4kW, COP = 4$	18°C - 22°C

Table 4.6: Simulation - Public building characterization

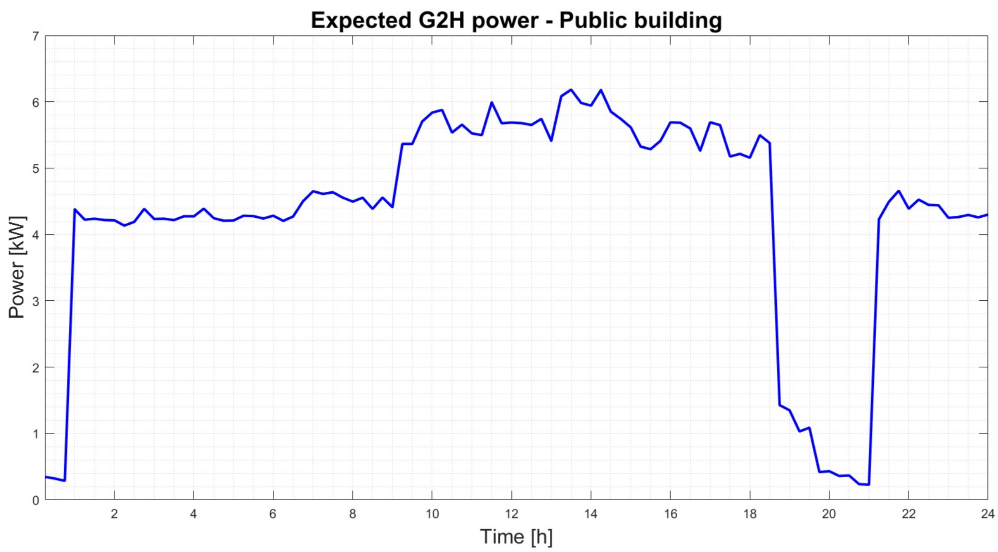

Figure 4.4: Public building expected consumption profile

4.2 How the tool works

In this section some evidences on how the tool works are collected: the simulation of 0.2 MW of upward flexibility requested to an EC of 200 members is taken as example. In the figure 4.5 it is shown the power withdrawn by the EC from the grid, adjusted with respect to the expected one, starting from the announcement time up to the end of the service: from 4 pm to 5 pm, as detailed in figure 4.6, the difference between the two curves is grater or equal to the size of the service requested, maintained for all the duration. It can be seen that the rescheduling has effects also on the power expected after the service.

Each of the members takes part to the service modifying its consumption pattern depending on the available flexible loads: some of the end-user cases follows to better illustrate how the load types that have been modeled behave, but the analysis is not exhaustive of the whole flexibility provided by each one. In case of the consumer, it can be seen in figure 4.7 that the washing machine was programmed to start working after 3pm, but after having receive the service announcement, the load is rescheduled, and supposed to be shifted after 10 pm. About the electric water heater, the prosumer case is analysed: the service request forced the EWH to be switched off during the delivery time, when it was programmed to be on, and up to the end of the service, even if this provide flexibility only in the first quarter-of-hour of the service. It affects the water temperature in the boiler, which evolution is depicted in figure 4.9

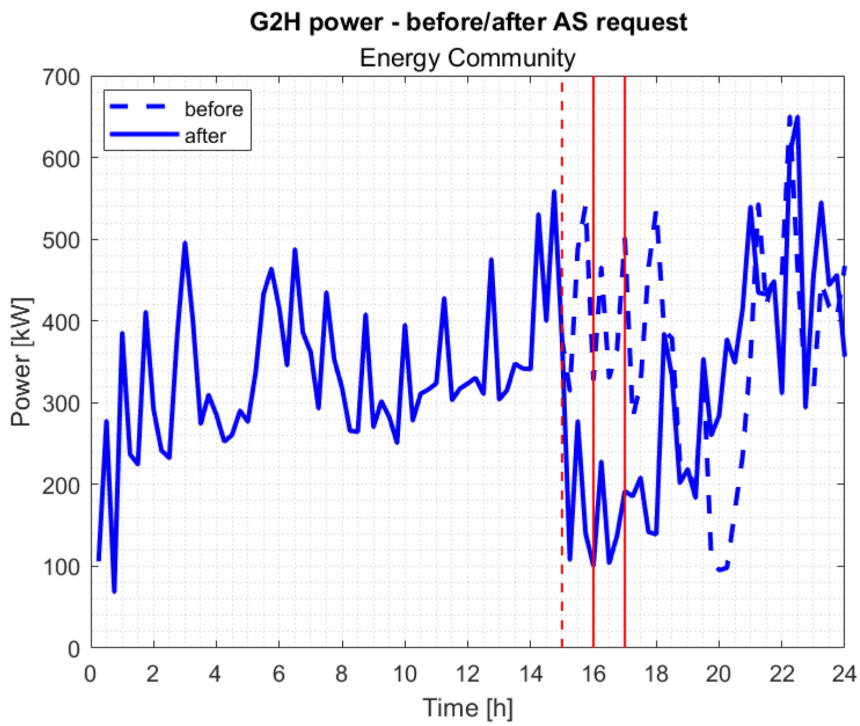

Figure 4.5: Energy Community P_{G2H} before and after the request

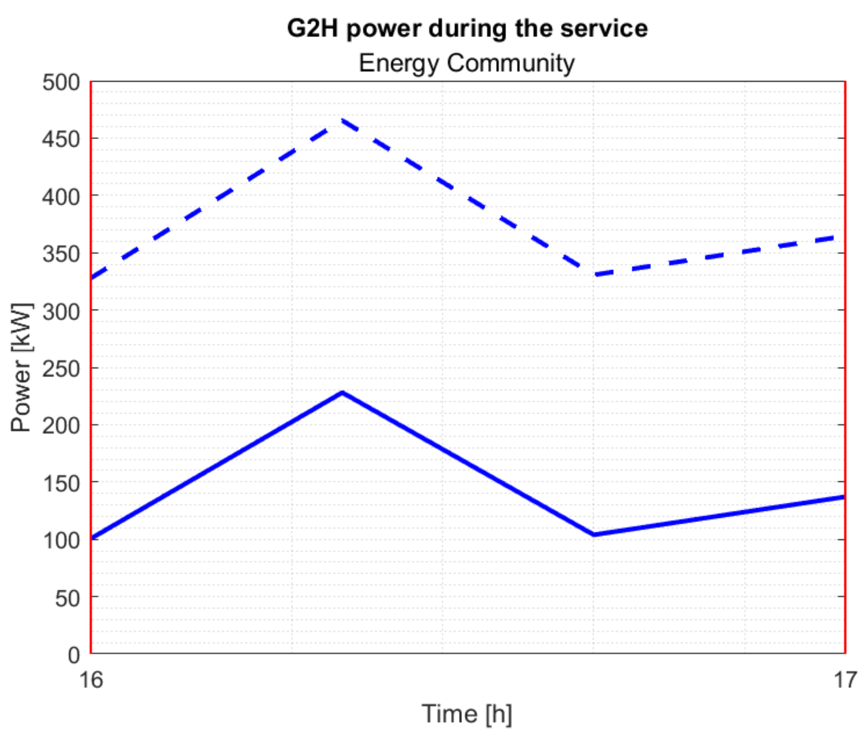

Figure 4.6: Energy Community P_{G2H} durign the service

As expected, in case the battery has available charge, it is highly involved in the provision of flexibility: it is the case of the prosumer with storage reported in figure 4.10. The battery, which is recharging with the PV generation surplus, intervenes to power the prosumer building to allow it reducing its electricity demand from the grid: what results is a

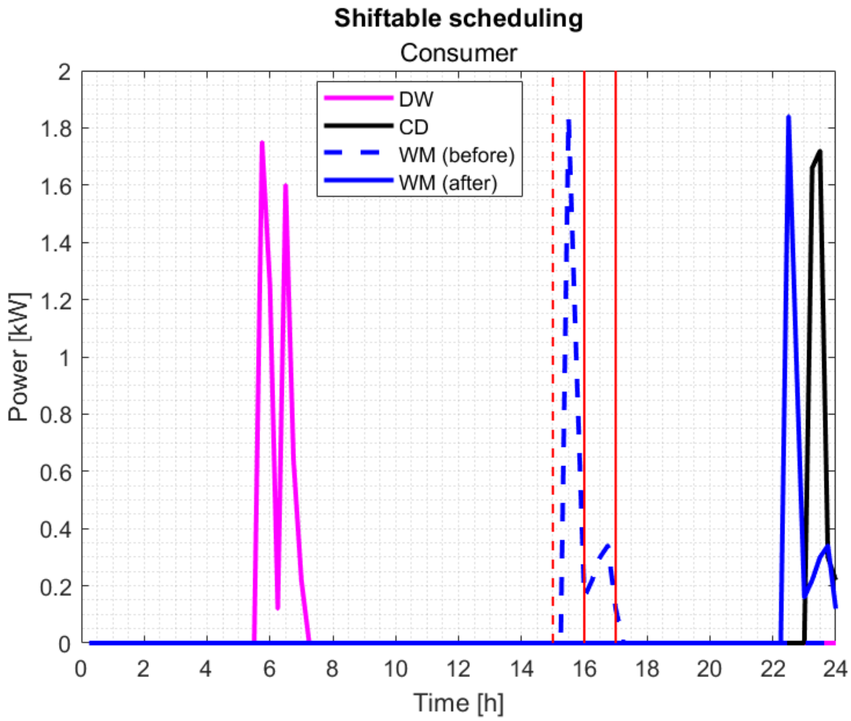

Figure 4.7: Shiftable rescheduling - Consumer

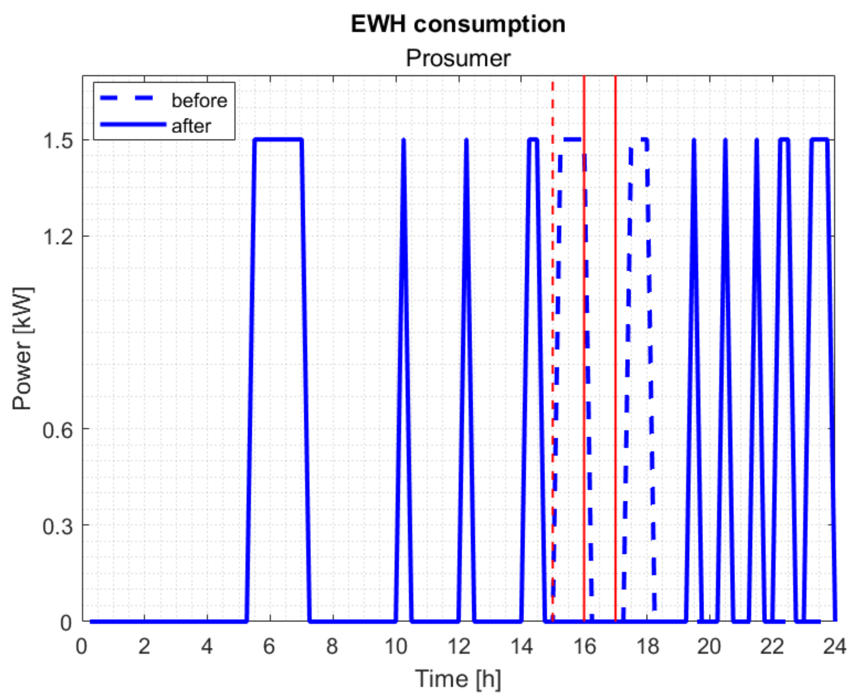

Figure 4.8: Electric water heater scheduling - Prosumer

difference on its charge level with respect to the expected one. Finally, the Air conditioner unit is analysed in the case of the public building: as it can be seen from figure 4.11 it was expected to work at full power up to 6 pm (end of office work), but because of the request, it is turned off. This has effect on the indoor temperature, which slowly decreases in time, but remains in the range of acceptability (figure 4.12). The EV is not shown since it is

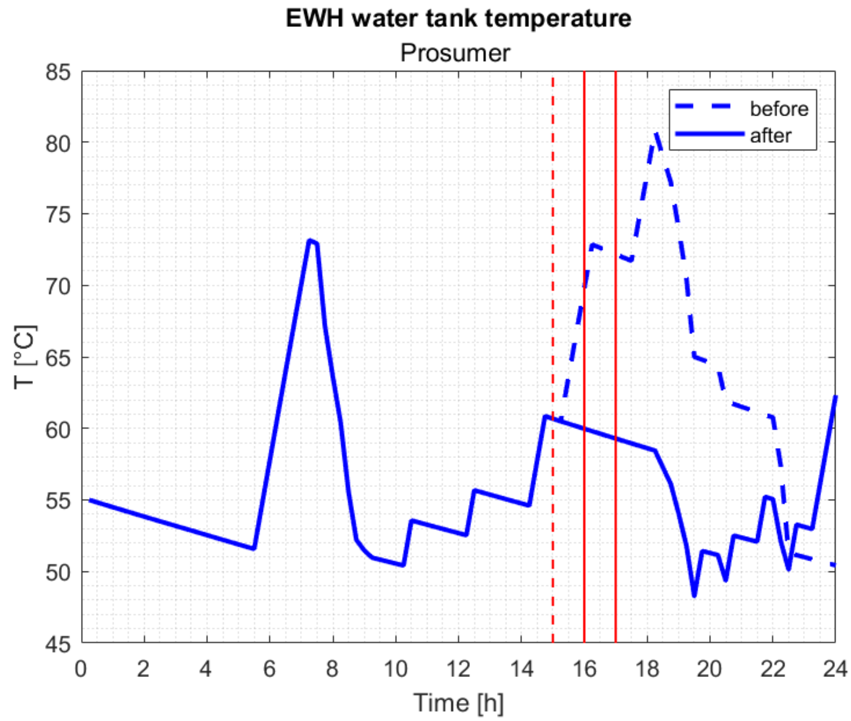

Figure 4.9: EWH water tank temperature - Prosumer

not at home at the time of the request, but, if present and charging during the service, it can simply provide flexibility reducing the rate at which he withdraws power from the grid.

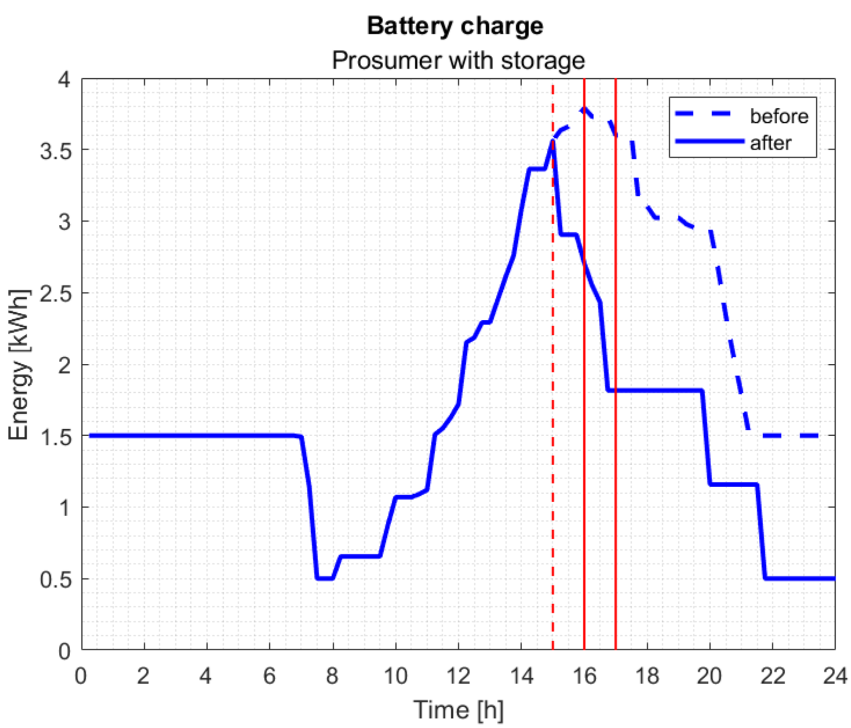

Figure 4.10: Battery charge expected vs actual - Prosumer with storage

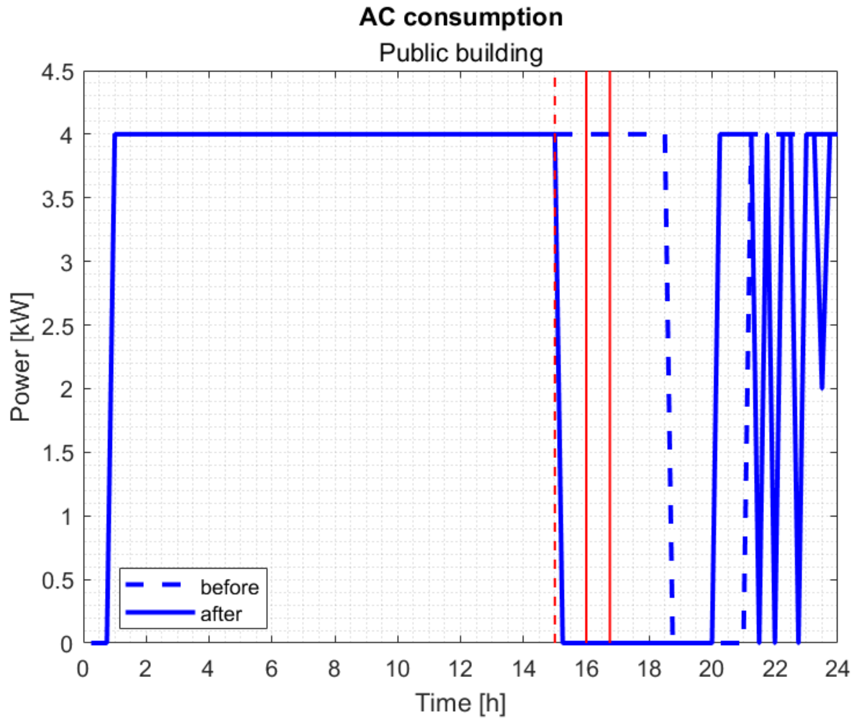

Figure 4.11: Air conditioning - Public building

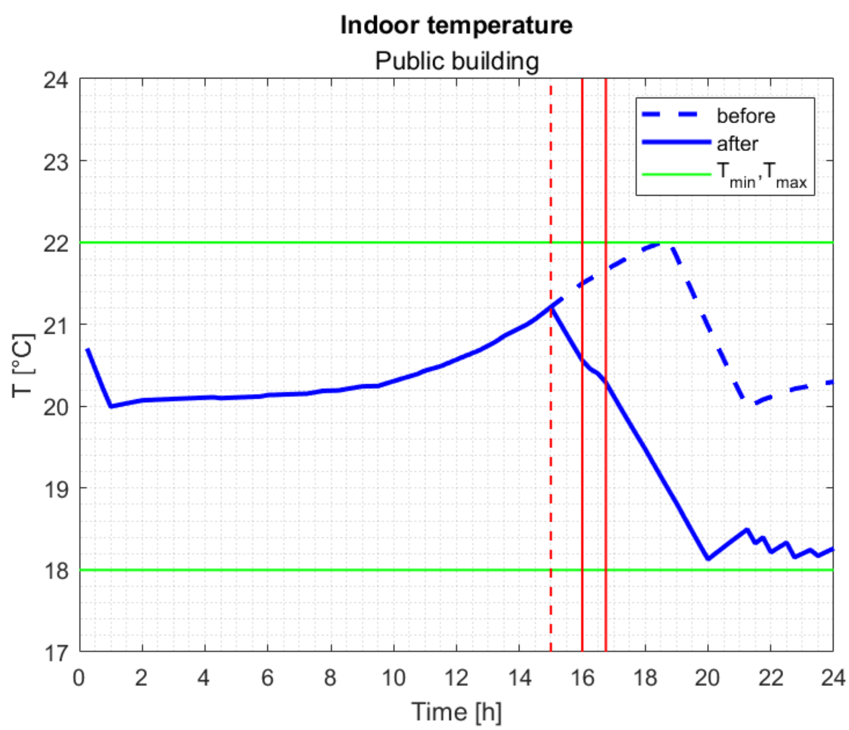

Figure 4.12: Indoor temperature - Public building

4.3 Results from simulations

In this section the results from the overall simulation campaign are summarized. Taking into account the randomness of hypothesis made for the simulation, the final aim is therefore to show the qualitative effect of the objective functions used, to critically analysed which one the members can more benefit from, and to depict the potential of the tool for the assessment of specific and real cases.

As a first step, the results obtained using the equality objective function (o.f. 3.45) are analysed. The test campaign has been performed varying the energy community size from 200 to 15000 members, and the service request size to 0.2 MW to 10 MW, to follow the trend described in [10]. The collection of the results are shown in the following figure, that reports the maximum amount of flexibility requested [kWh] among the members, for each pair of EC size and requested service.

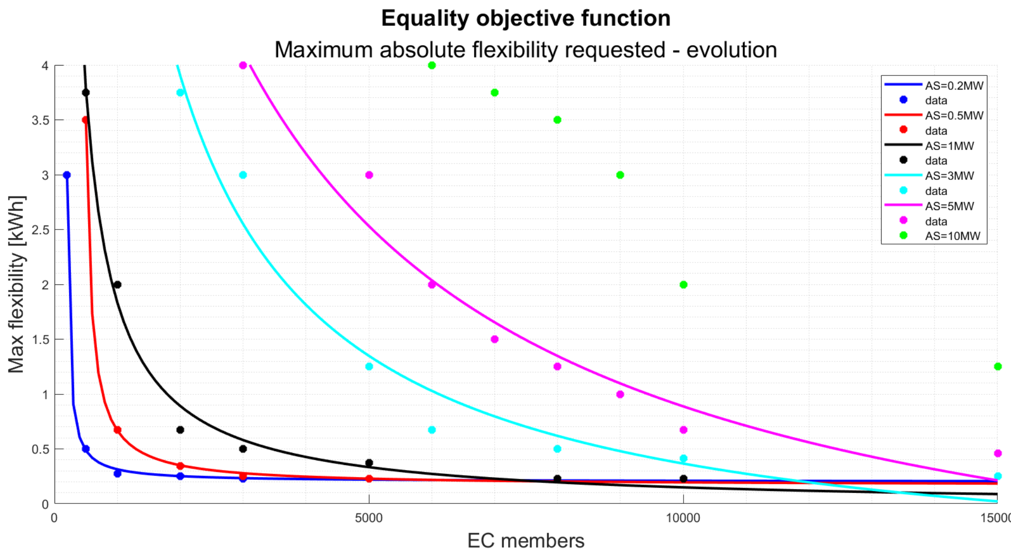

Figure 4.13: Maximum absolute flexibility requested - evolution map [kWh] - OF: eq(3.45)

With a fixed service size, the maximum amount flexibility requested to a member progressively decreases with the number of EC members, with a trend that it is possible to be interpolated by an hyperbola: as expected, it is inversely proportional to the number of members that are supporting the service. For bigger requests, the hyperbolas shift towards the center of the first quadrant and its eccentricity, which is the span between its branches, gradually increased. This means that the maximum flexibility still decreases with EC members, but with a rate that progressively reduces moving from small to big requests: namely, it requires big flexibility amount even for big EC, so it becomes more challenging to provide the service. A consequence is that the minimum EC size that can satisfy the whole request, even with all members providing the maximum flexibility, increases for bigger requests.
Along with the maximum amount, it is important to observe flexibility distribution among the community. Taking the 1 MW request as example, the statistical distribution is clearly visualize with a boxplot in figure 4.14: it returns the difference between the 75^{th} and 25^{th} percentile as the width of the box, that is called interquartile range (IQR), and the median value as horizontal line in it. The maximum flexibility requested corresponds to the upper edge of each ranges, and it is highlighted by a black line plot.

It is evident that, already for 2000 EC members, the maximum amount of flexibility requested (in kWh) can be considered quite low and it is really close to the average and minimum flexibility. This is a desirable condition in which all members are providing more or less the same amount. For bigger number of members, the IQR narrows even more, and some members are also considered to provide no flexibility. A smaller EC instead, in order to satisfy the service request, experiences a not-well spread flexibility distribution among members, that can vary form 0.6 kWh to 3.75 kWh; it is also relevant that the members responsible of providing the maximum amount are out of the 75^{th} percentile, that means

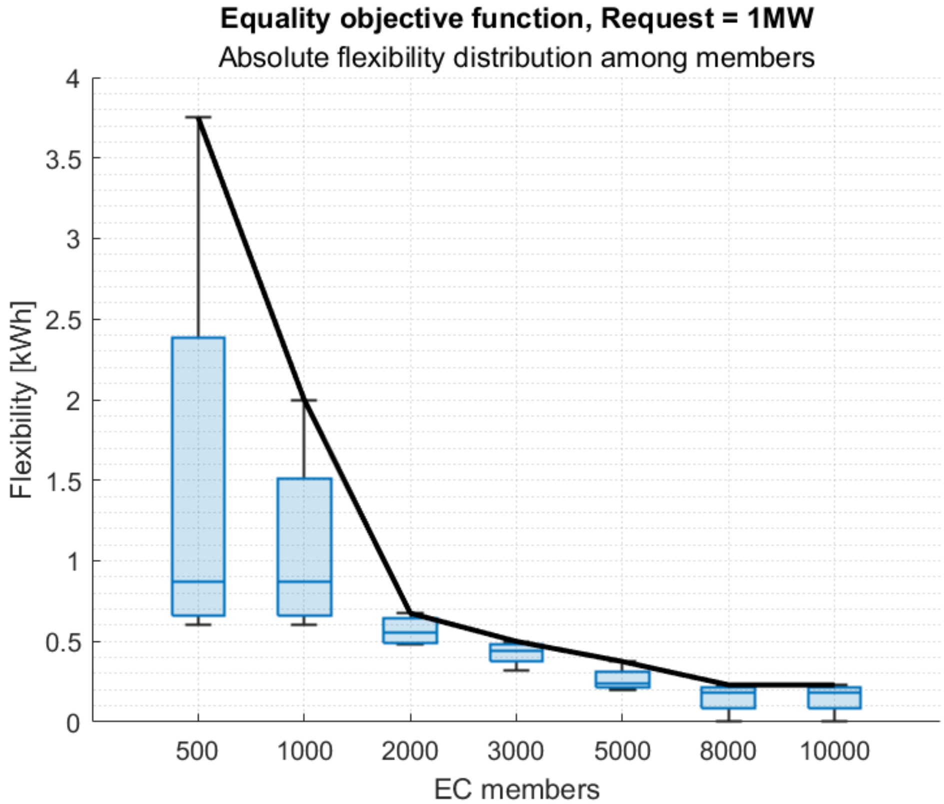

Figure 4.14: Absolute flexibility distribution among members [kWh] - OF: eq(3.45)

that the service provision is mainly supported by few members.

To better contextualize data, it is useful to compare the amount of maximum flexibility requested to a member with his consumption profile, or his available flexible load. Still for the 1 MW request example, the maximum flexibility is given in relative terms in figure 4.15. Furthermore, the latter needs to associate to an overall member contribution map (fig. 4.16), in order to understand which kind of user is providing the maximum flexibility, and to quantify how much he is renouncing to, also in comparison with the other community members.

What can be extracted is that for small EC, who is giving more flexibility in terms of kWh is the public building (about 70% from figure 4.15), but in percentage it is not the bigger effort: consumer and prosumer are giving approximately the same relative flexibility, which is the 100% of their flexible loads (fig. 4.17) and the prosumer owning storage system is providing a flexibility that is the 100% of its consumption pattern. This is possible because, if the battery is charged and available as happens in this case, all consumption, including non-flexible load, turns to be powered by the battery, bringing to zero the withdrawals from the grid. As the number of members increases, what happens is that public buildings are still providing the greater amount [kWh], but lower relative flexibility. Their contribution progressively decreases, up to become null and to leave the major stress to residential end-users. Considering the flexibility potential that public buildings have in this simulation, since modeled with a single, big, reducible thermostatic load (HP), other strategies may be explored.

A new boxplot is therefore useful to summarize the results, plotting the relative flexibility distribution over the EC (fig. 4.18): boxes are showing a large range of relative flexibility among members, in which the median is shifted towards high percentage that, as stated before, is allocated to residential participant even if they have not the bigger

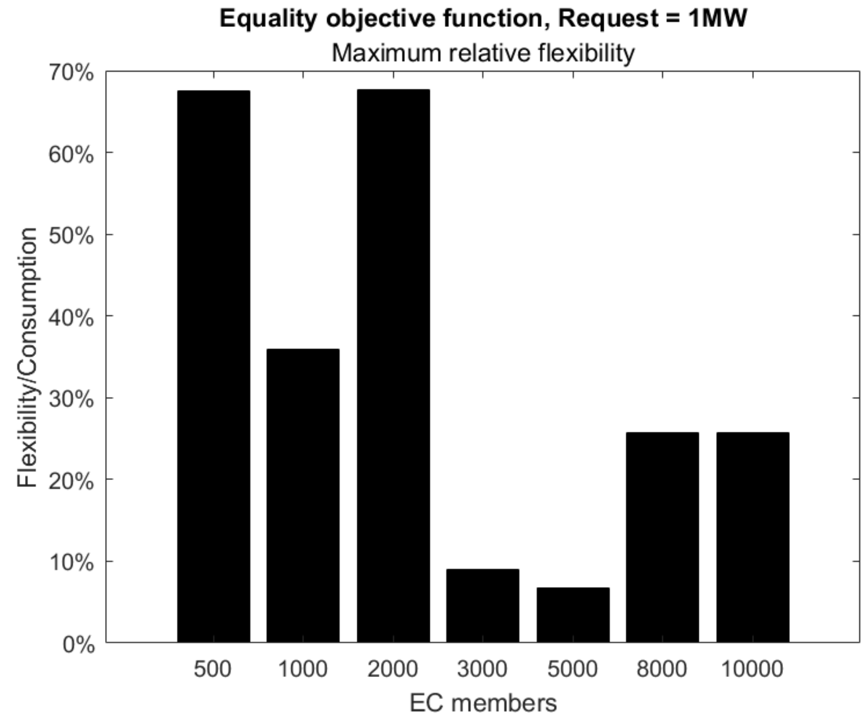

Figure 4.15: Maximum relative flexibility [% of consumption] - OF: eq(3.45)

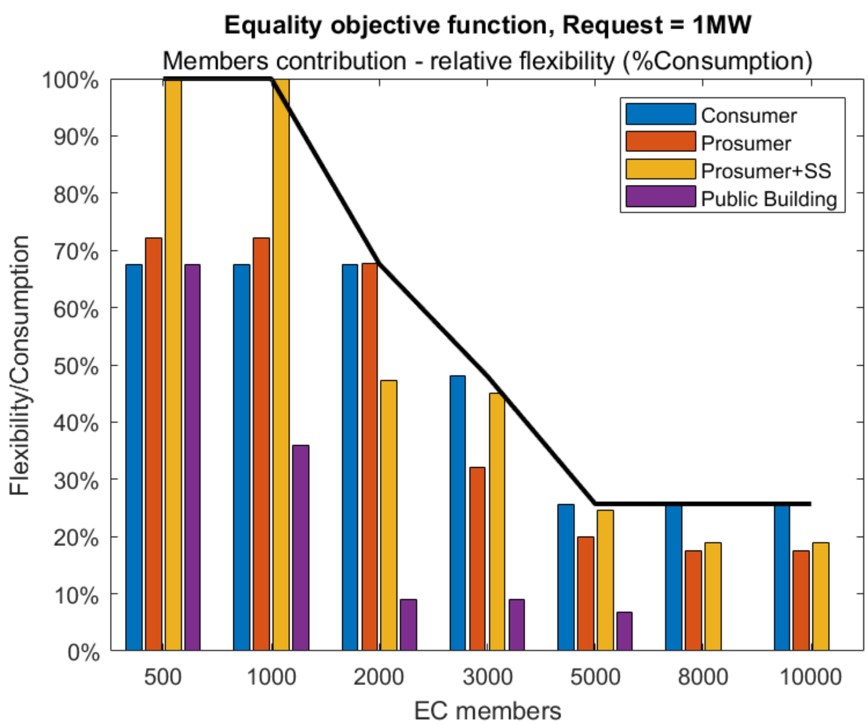

Figure 4.16: Relative flexibility contribution of members [% of consumption] - OF: eq(3.45)

flexibility potential.

Analogue plots and results, with service request size of 0.2 MW, 0.5 MW, 3 MW, 5 MW and 10 MW are discussed in the Appendix.

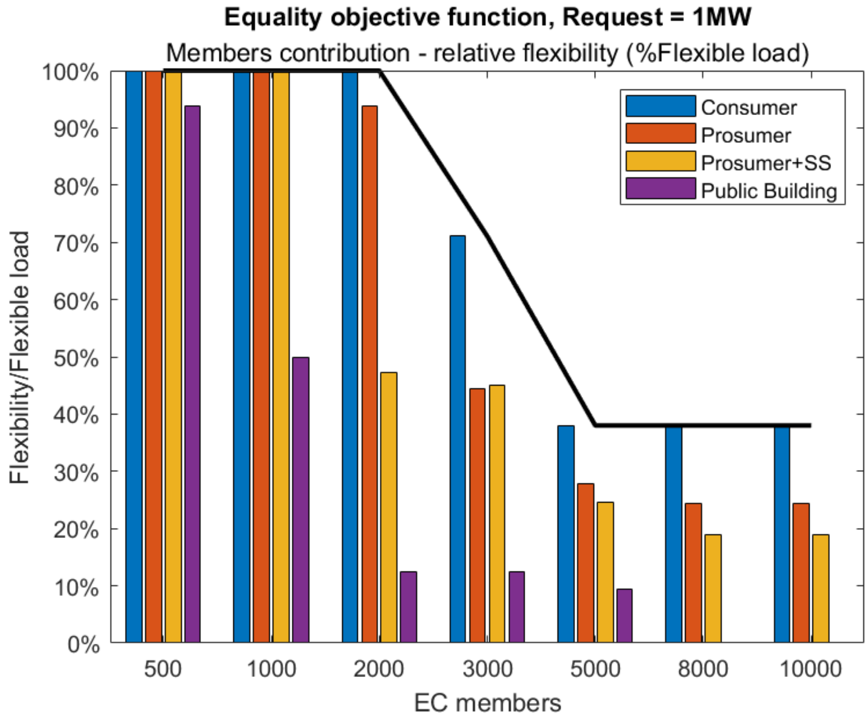

Figure 4.17: Relative flexibility contribution of members [% of flexible load] - OF: eq(3.45)

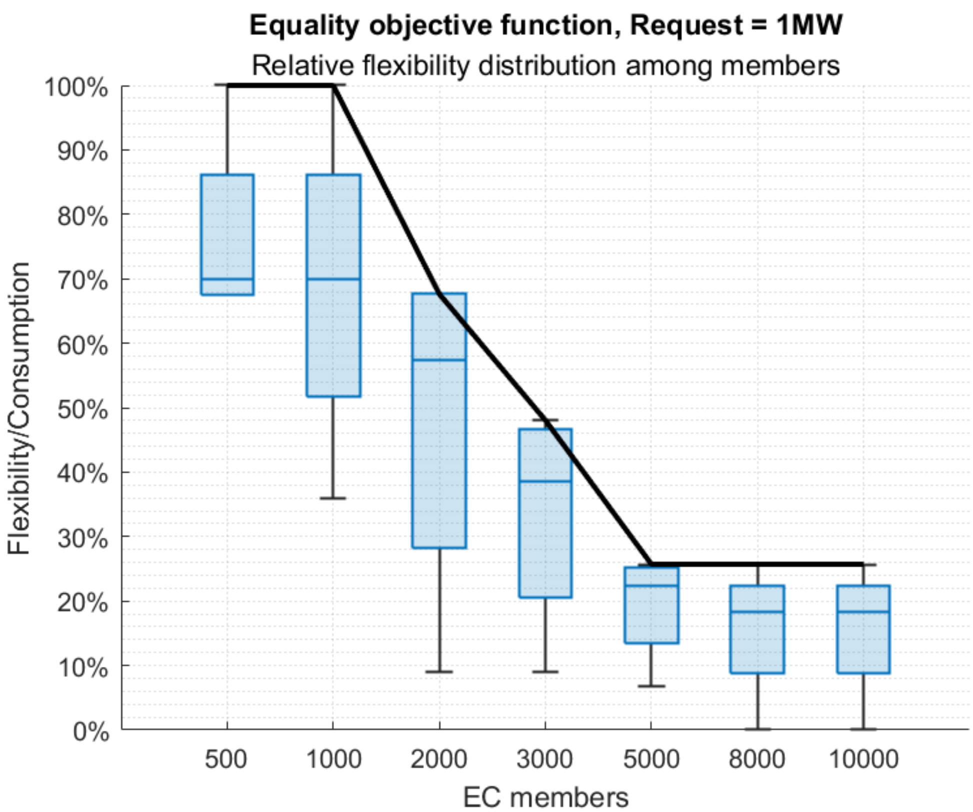

Figure 4.18: Relative flexibility distribution among members [%] - OF: eq(3.45)

Another scenario is therefore explored setting the equity criterion (objective function 3.46), so to split the request in fair relative amounts, according to end users possibilities and assets: differently from the correspondent figure obtained for the previous objective function, the flexibility distribution in terms of kWh covers a wider range (figure 4.19), while in relative terms it is fairly splitted, as the narrowed box width suggests, as well as a more centered median line (figure 4.21). It is confirmed also in figure 4.20, in which it is possible to appreciate the better exploited potential of public buildings.

For an EC size higher than 5000 members, prosumers are requested to provide 0 kWh of flexibility: it can be interpreted as a matter of chance for the particular circumstances of this simulation, like the hour and the available flexibility of the other members. In fact, it has to be considered that the consumer provision remains constant for EC sizes from 2000 to 10000 members: this is the evidence that he cannot further reduce his flexibility since it is linked to a shiftable loads rescheduling, which acts like a flexibility block that cannot be reduced or interrupted. Therefore, being the tool not able to minimize the maximum relative flexibility, another one is taken to zero, since it is not necessary to be compliant with the requests.

Particular attention has to be paid to prosumer with storage profiles: as already said, it can be noted in figures 4.16, 4.17 and 4.20 that for small ECs he is the member providing 100% of his available flexibility, which corresponds to consumption in presence of a storage with available charge, as it is the case. This leads to another qualitative consideration: for end-users not owning a storage or not taking advantage of that (in case of shared assets), the flexibility provided to the system corresponds, to some extent, to a discomfort: shifting, switching off or reducing loads means to give up some particular habits or comfort status. On the contrary, if a certain battery charge is available, all the electric loads are just shifted to be powered by the storage rather then by the grid, so it does not results as an actual discomfort of the end-user. Nevertheless, a discomfort measure for storage owners can be the one associated to the difference between the expected battery SOC, and the actual SOC after the service provision, clearly shown in figure 4.10.

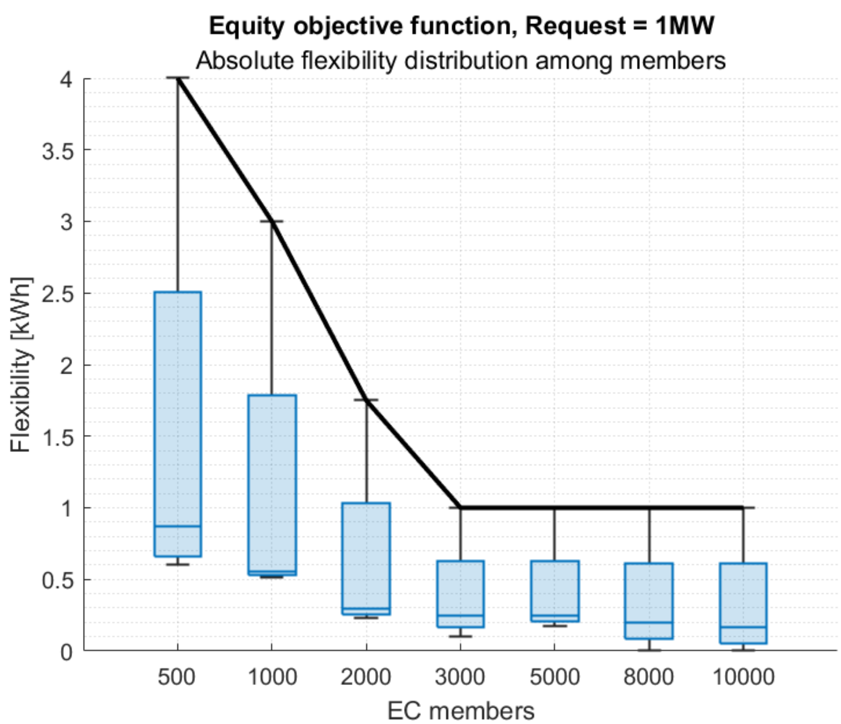

Figure 4.19: Absolute flexibility distribution among members [kWh] - OF: eq(3.46)

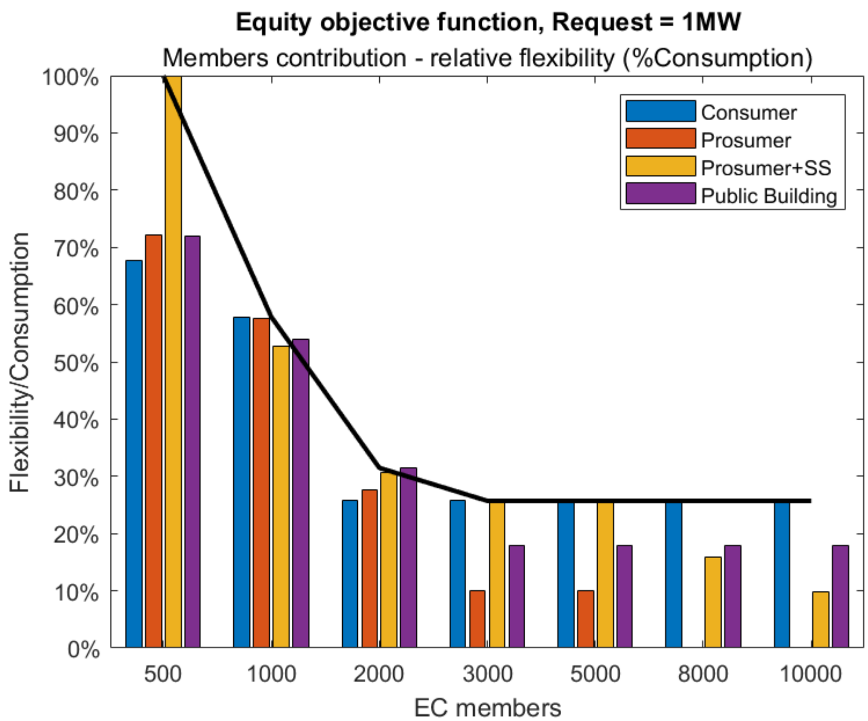

Figure 4.20: Relative flexibility contribution of members [% of consumption] - OF: eq(3.46)

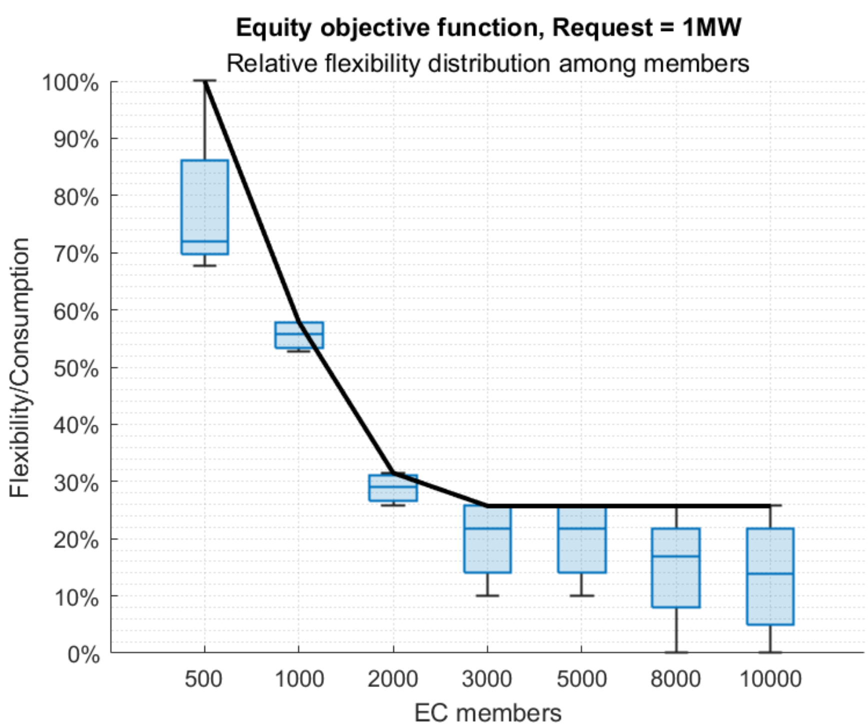

Figure 4.21: Relative flexibility distribution among members [%] - OF: eq(3.46)

To conclude, the results analysed underline that the two objective function reflects the equality (o.f. 3.45) and the equity (o.f. 3.46) principles. Which one can better suit the case of an energy community is an open discussion and can also be discretionary choice of the EC management. It has to be noticed that, in both cases, the relative flexibility requested to members arranges to be around to 30% of their consumption patterns beyond a certain EC size: the difference is that this condition is reached before in case of equity optimization (objective function 3.46, 2000 EC members) rather than the fair splitting of flexibility under the equality principle (o.f. 3.45). This means that, for the analysed composition and for a certain EC size, splitting the request following the equity criterion not only is better from the single member point of view, but can reach an advantageous condition for the whole community, namely to provide flexibility under a certain threshold.

For a feasibility assessment of an EC (already existent - known number of members) willing to participate in flexibility services, the tool can be useful to analyze which can be the maximum amount of flexibility requested for a given service size, and to decide if it is acceptable or not. Reversely, during the design of an EC that will include flexibility services provision, it is possible to set a flexibility acceptance threshold (e.g. 1 kWh per member) and to figure out what can be the minimum number of members able to satisfy both comfort and service provision conditions (example in figure 4.22, result from equality objective function). For example, it can be stated that, to be able to provide 1 MW of upward service for a 1 hour duration, asking members a flexibility equal or lower than 1 kWh each, an EC of 2000 members is required. At this point, it is also possible to make some economic consideration: taking the UVAM as reference and assuming a remuneration of 200 €/MWh for service [66], and hypothesising 70% of accepted services over a year of requests, a remuneration of 25€/member per year can be estimated. Finally, associating figure 4.22 to figure 4.18, it is evident that, for the stated conditions, 1 kWh of flexibility corresponds to 60% of members consumption on average; if this contribution is wanted to be decreased down to 25%, an EC of 5000 end-users is needed.

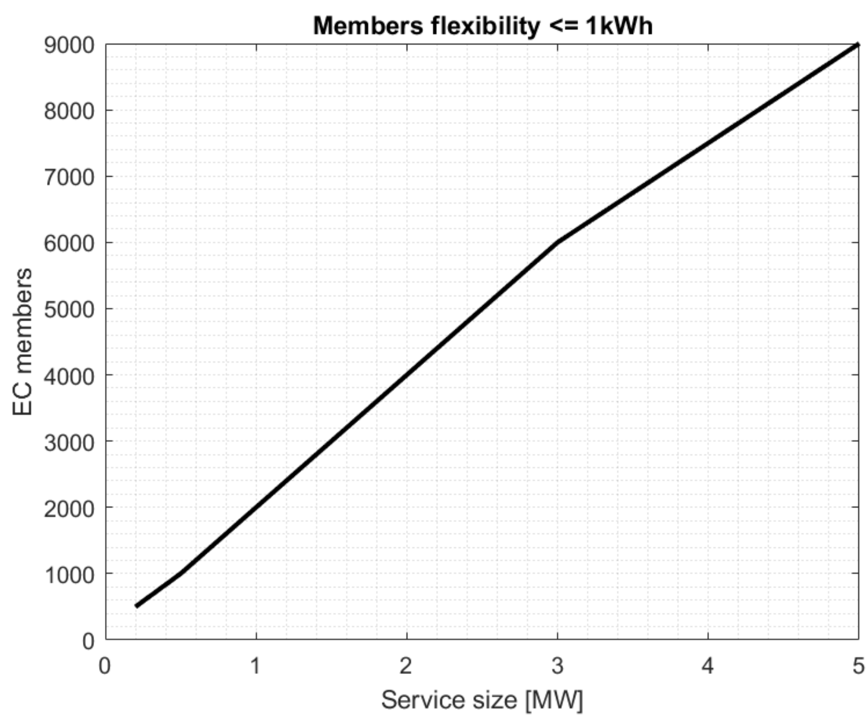

Figure 4.22: Flexibility threshold [kWh] - OF: eq(3.45)

Conclusion and perspective

After having analysed the European directives opening principles on energy communities and verified their current developing stage in terms of legislative alignment and projects actuation, the attention has been focused on the EC possibility to provide service to the grid, in particular flexibility ones. Even if it may seem untimely for energy communities, demand-side flexibility is becoming more and more relevant to support the power system transformation, and ECs are called to play their role: they can be seen as a particular resource, since they can take advantage of the EC aggregation itself and of their possible internal management. Therefore, an optimization model has been developed with the aim to assess their flexibility potential: the goal is to comply with grid needs and at the same time to fairly split the request among members, which owned assets and devices represented by MILP load models. Two objective function have been tested to see which can better meet the purpose: minimizing the maximum flexibility asked to a member in absolute terms [kWh] or relative terms [%], following equality or equity criterion respectively. An EC has been modelled with the hypothesis of four member types (consumer, prosumer, prosumer with storage and public building) to run some simulations with the two objective functions. The results showed that they are both valid options to be chosen, depending on which one between equality and equity, respectively, wants to be the leading criterion; it may depend also on the size and the composition of the EC. For the carried out simulation, minimizing the relative flexibility resulted to be a fairer choice, since it better exploit the big potential public buildings. In addition, some exploratory simulations have been performed varying the service size and the number of EC members. For a fixed service size, the maximum flexibility requested results to evolve with a trend of inverse proportionality for increasing number of EC members. The bigger the service request, the greater the minimum EC size has to be to comply with it.
The tool come up as an innovative as it considers the EC as a stand-alone provider for flexibility services. It represent a first approach to the case study of an EC participating in flexibility services, and wants to suggest a methodology for the coordination of its provision, considering the centralized role of an EC manager. It is a flexible and extendable tool, which can be used by new EC in pre-feasibility assessments or in order to quantify the potential of pre-existent ECs; anyway some improvement may be needed. For instance, some hypothesis that have been assumed for the sake of simplicity, should also be removed to ensure a more realistic assessment: among the others, the assumption of perfect information in case of flexibility calculation, or the neglected remuneration perspective. For the overall functioning of the model, also a change of the implementation environment can be recommended.

Some suggestion for future development to improve the tool are listed as follow:

- for a flexible and more user-friendly interface, an implementation in Python environment should be considered, keeping CPLEX as optimization solver: several libraries lead it to be more controllable and it opens the possibility for further differentiation of the customers characterization;
- to strive for more realistic representation, it can be useful to embed more detailed behavioral members' features, like preferences and non-complete rationality. It may

be done shifting to an agent-based model (AMB) with optimization;

- the assumption of perfect information in case of flexibility calculation needs to be substituted by a method that can also evaluate uncertainty in the provision forecasts;
- the economic perspective can be added in the optimization model and appended to the EC business model, with the aim to understand if it can act as a driver to enhance or to reduce the flexibility potential;
- to add the possibility of modelling shared assets (like storage), which may change the flexibility distribution and decrease the associated discomfort of the EC;
- looking further, electric vehicles, that has been modeled as simple load, can be modeled for bidirectional power exchange, like vehicle-to-home (V2H) or vehicle-to-grid (V2G), so to extend their flexibility potential.

In any case, several changes have to be implemented before ECs can participate to flexibility services and the tool can disclose its usefulness. The push toward a complete electrification of loads, for a less fuel-dependent satisfaction of energy needs, becomes in this case an essential condition to be fully responsive to electrical demand side flexibility in general. In Italy, this is still a limit, mainly for what concerns thermostatic loads. Among the others issues, the market policy framework needs to be clarified at national levels, and the adoption of IoT technologies may be needed within the EC for actions coordination and control. Moreover, the result of this new unlocked potential will depend on how regulators will managed it: if the EC could be obliged, or someway pushed to do provide the services (e.g. by incentives/penalties), or in alternative, a market value should be recognized for this service. In this case, it should be not only attractive for customers but also not in competition with other flexibility services (e.g. ToU) that could be more profitable. It may be needed to evaluate tailored strategy to incentivize the activation of this type of services, which are totally new for residential customers in general.

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Appendix

In this chapter a further discussion is proposed on the results obtained from the simulation of different service request size and the equality fair objective function $min[max(flex_i)]$ (o.f. 3.45). With reference to the maximum flexibility evolution map (figure 4.13), which is for convenience reported here, the curves reporting the maximum flexibility requested among members, for a certain AS size and EC size, are investigated.

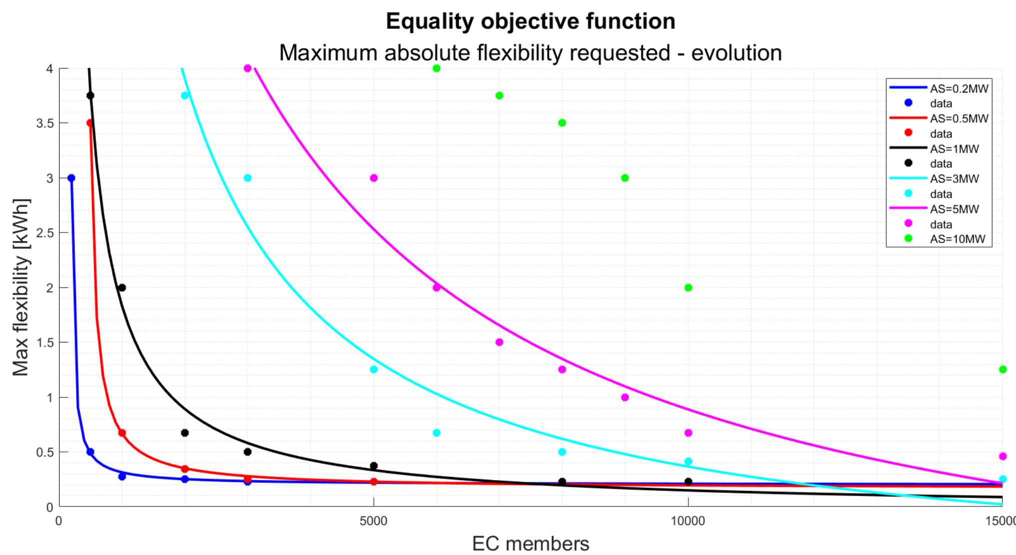

Figure 6.1: Maximum flexibility evolution map [kWh] - OF: eq(3.45)

For a requested service of 0.2 MW, the flexibility distribution can be observed in figure 6.2: the maximum amount of flexibility requested, provided by public buildings, is lower with respect to the 1 MW request case previously analysed (3 kWh instead of 3.75 kWh) because of the smaller request. The distribution is not homogeneous only in the case of 200 members, while it adjusts below 0.5 kWh for bigger ECs. Looking at figure 6.4 for the member's contribution in relative terms [%], it can be seen that the range of difference among members can reach up to the 50%, in which the maximum provision is given by prosumers with storage and the minimum by public buildings the (figure 6.3); moreover, also for big ECs the main effort remains a residential customers responsibility, in particular by prosumers owning the storage system in case of small ECs .

For a requested service of 0.5 MW, the flexibility distribution in kWh can be observed in figure 6.5, while the relative flexibility distribution and member's contribution can be grasped from figures 6.7 and 6.6. The comments on results are analogue to the ones made for 0.2 MW request; it has to be noticed that the smallest EC able to satisfy the request is made of 500 members.

In case of a requested service of 3 MW, the minimum EC size able to provide the request is 2000 members, and the maximum flexibility requested is 3.75 kWh. The flexibility

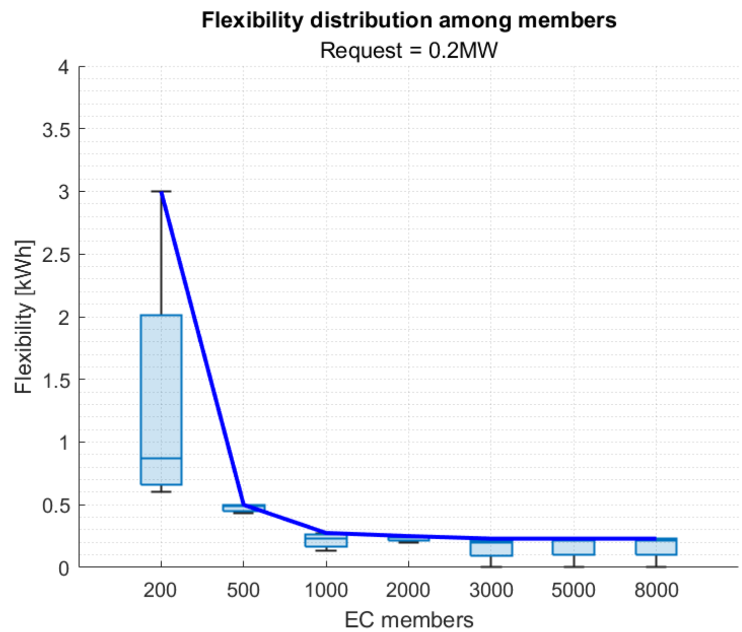

Figure 6.2: Flexibility distribution among members [kWh] - 0.2 MW

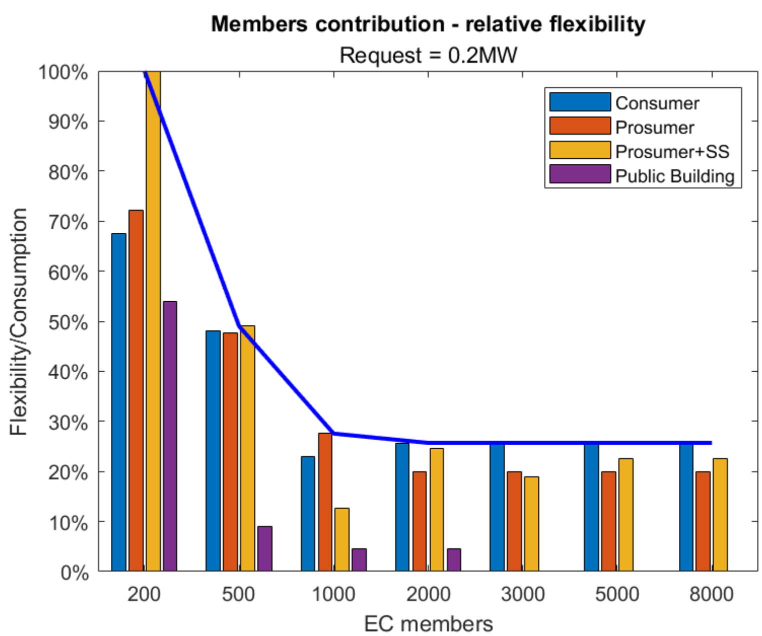

Figure 6.3: Relative flexibility contribution of members [%] - 0.2 MW

distribution in kWh can be observed in figure 6.8: boxplots start to narrow for EC with a members number higher than 6000, which means that, to satisfy bigger request with negligible efforts, the EC sizing changes consistently. The relative flexibility distribution and member's contribution can be grasped from figures 6.10 and 6.9: they show that still residential members, especially prosumers with storage, are the ones at which is requested the most in relative terms [%], and that the discrepancy between the maximum and minimum relative flexibility, namely the boxplots width in figure 6.10, remains wide also for bigger ECs.

For a requested service of 5 MW, the minimum EC size able to provide the request is 3000 members, and the maximum flexibility requested reaches 4 kWh. The flexibility

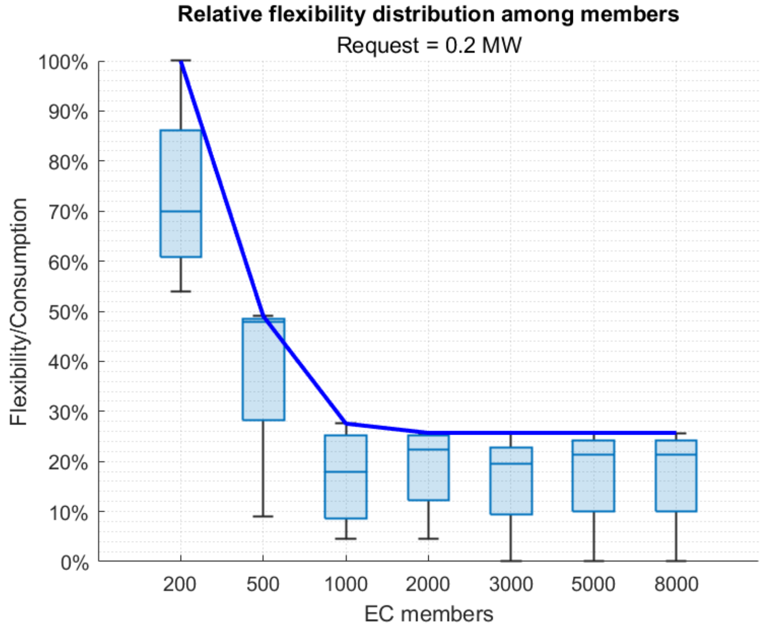

Figure 6.4: Relative flexibility distribution among members [%] - 0.2 MW

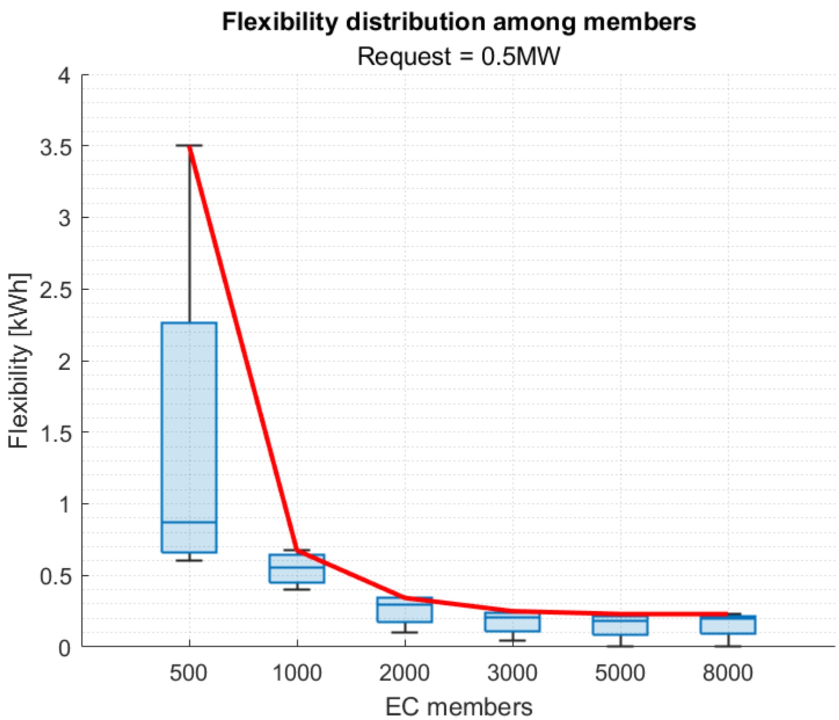

Figure 6.5: Flexibility distribution among members [kWh] - 0.5 MW

distribution in kWh can be observed in figure 6.11: it can be noticed that, increasing the EC size, the minimum flexibility provided remains at a value of 0.6 kWh and starts decreasing only foe community bigger that 9000 members. The relative flexibility distribution and member's contribution can be grasped from figures 6.13 and 6.12: the qualitative results are analogue to the one discussed for 3 MW, but it must be emphasized that the minimum relative flexibility for an EC 15000 members is almost doubled with respect to the 3 MW simulation (50% with respect to 25%).

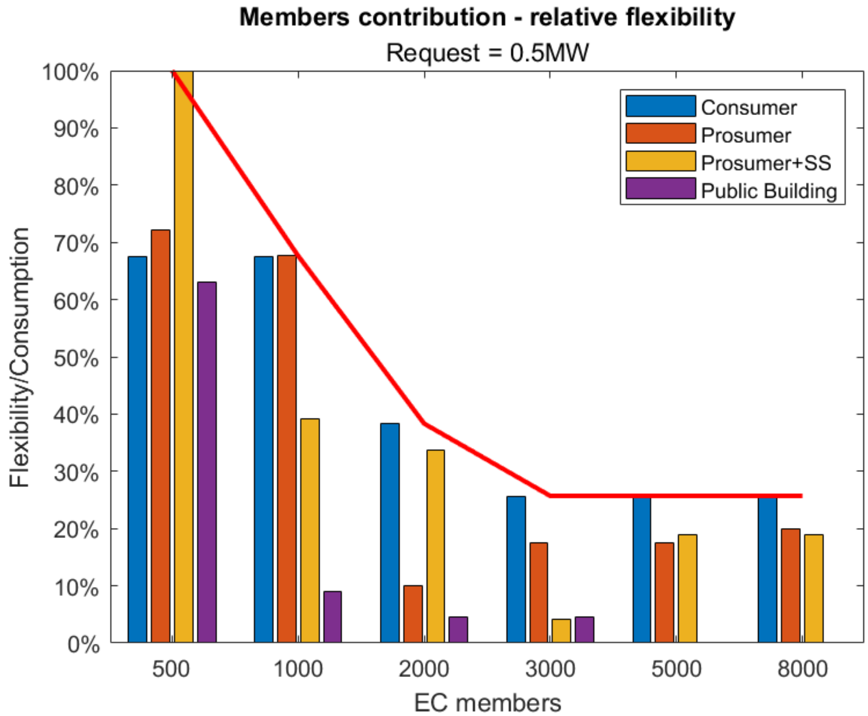

Figure 6.6: Relative flexibility contribution of members [%] - 0.5 MW

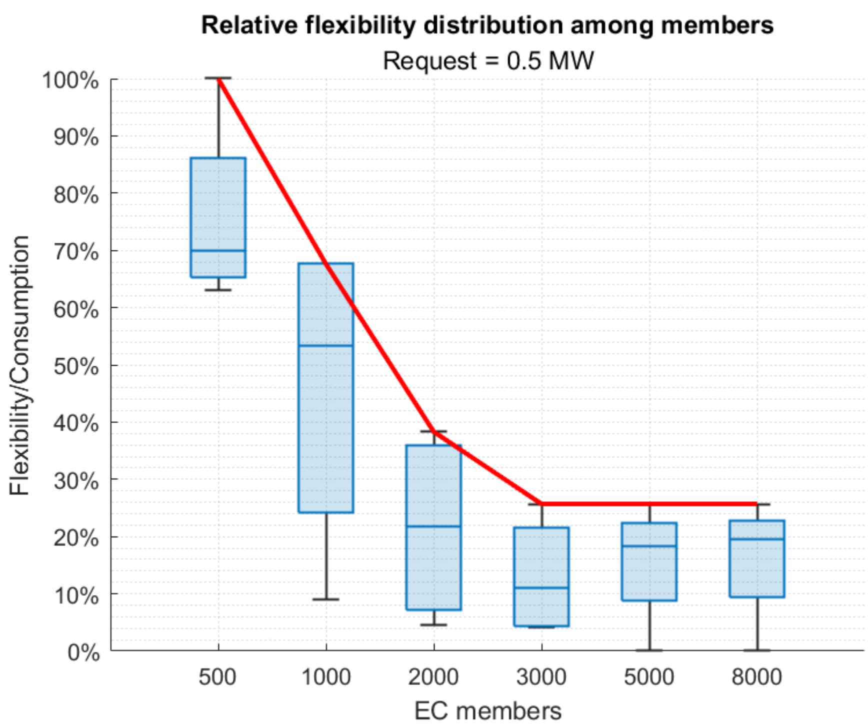

Figure 6.7: Relative flexibility distribution among members [%] - 0.5 MW

For a requested service of 10 MW, the minimum EC size able to provide the request is 6000 members, and the maximum flexibility requested reaches 4 kWh. The flexibility distribution in kWh can be observed in figure 6.14: it can be noticed that, increasing the EC size, the minimum flexibility provided remains at a value of 0.6 kWh also for

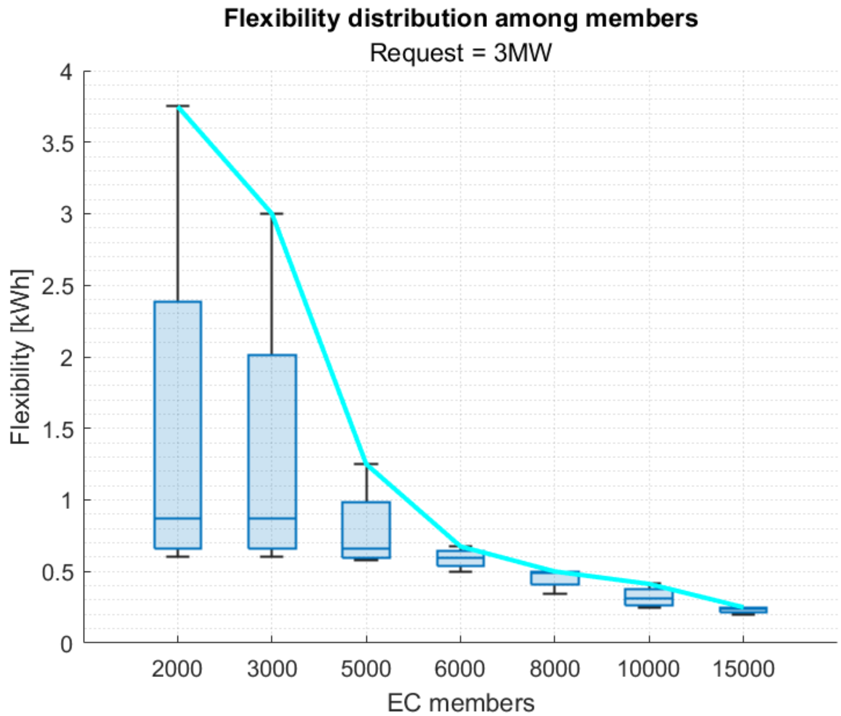

Figure 6.8: Flexibility distribution among members [kWh] - 3 MW

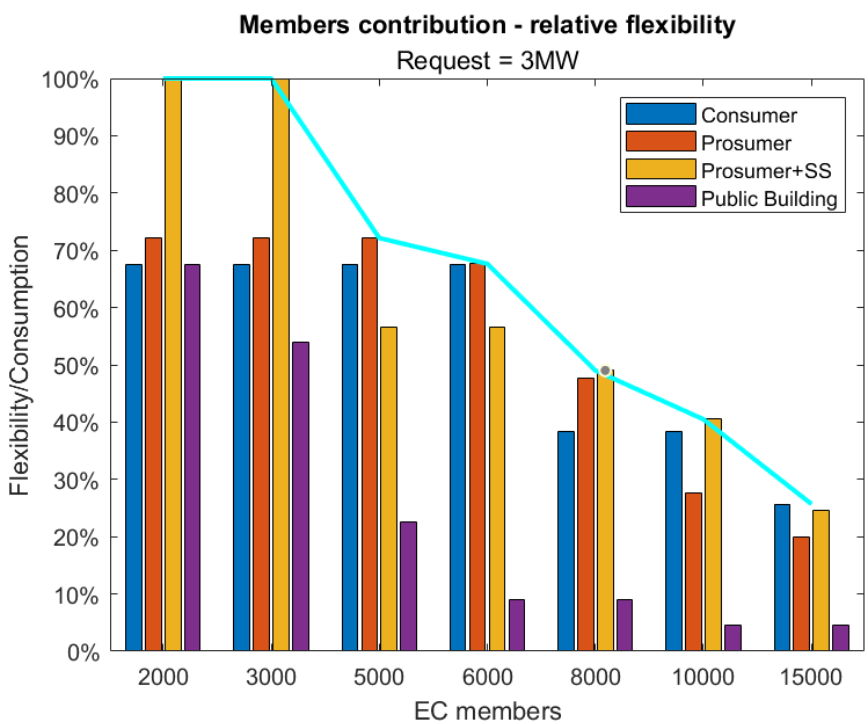

Figure 6.9: Relative flexibility contribution of members [%] - 3 MW

15000 member energy communities. The relative flexibility distribution and member's contribution can be observed from figures 6.16 and 6.15: they highlight that, despite of the EC size increasing, residential customers have to provide all the flexibility available to be able to satisfy the request. The public buildings contribution, instead, is scaled with

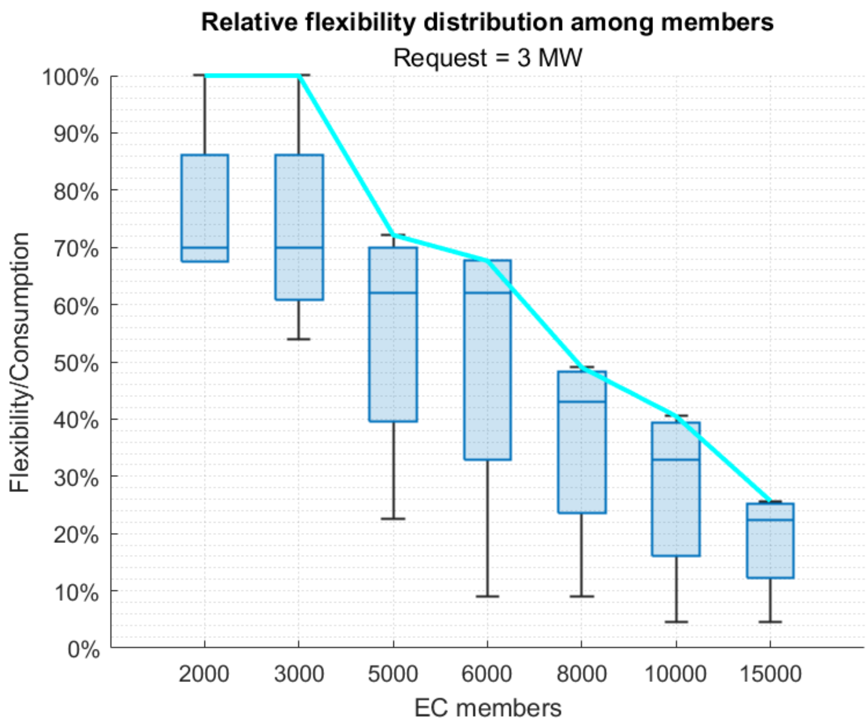

Figure 6.10: Relative flexibility distribution among members [%] - 3 MW

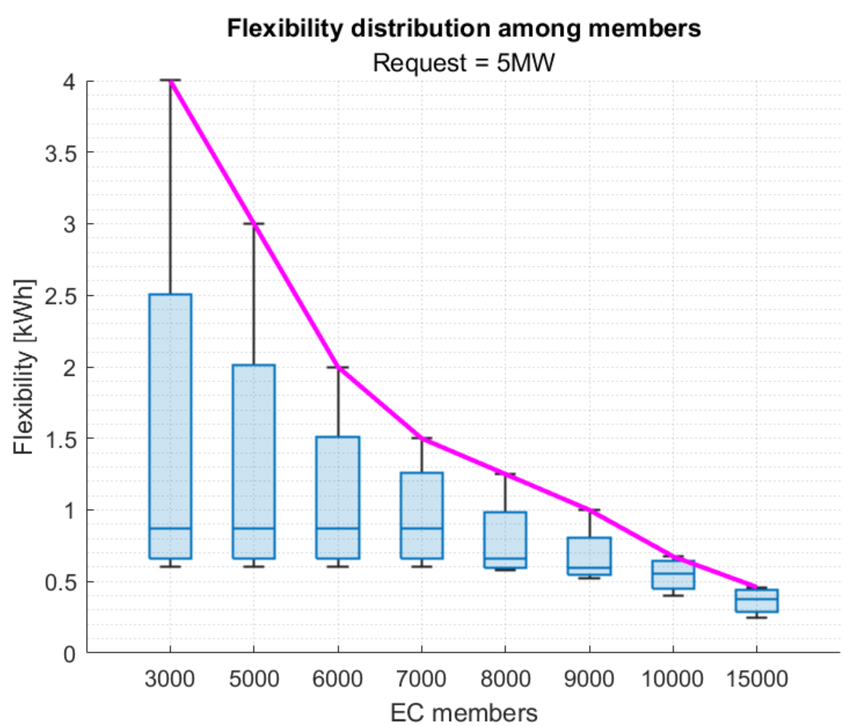

Figure 6.11: Flexibility distribution among members [kWh] - 5 MW

respect to the EC size.

The analysed simulations performed with the objective function $min[max(flex_i)]$ varying the service request and the EC size showed that the trend commented for the 1 MW request have been confirmed: as set by the objective function, the flexibility distribution

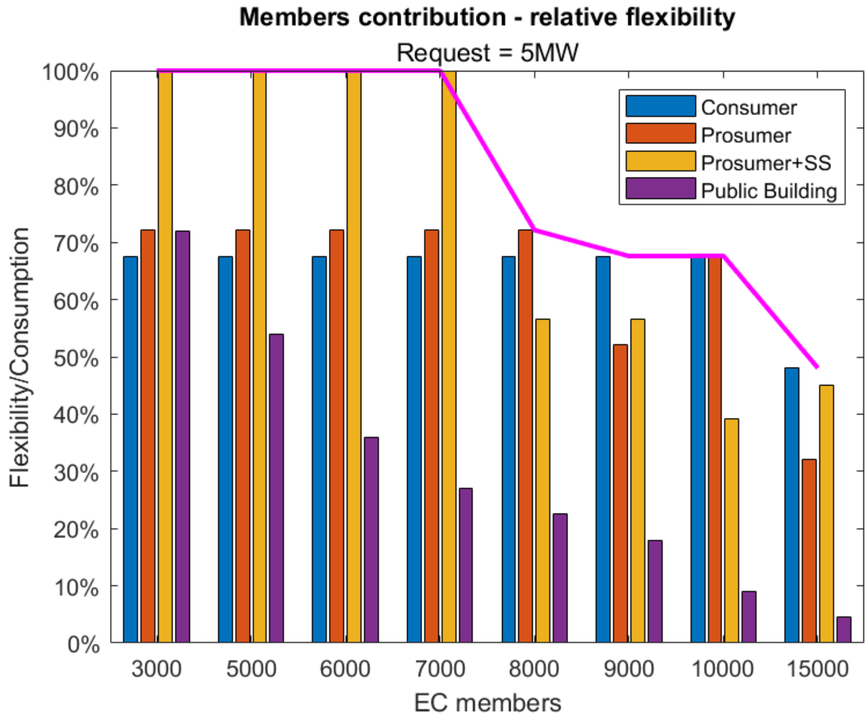

Figure 6.12: Relative flexibility contribution of members [%] - 5 MW

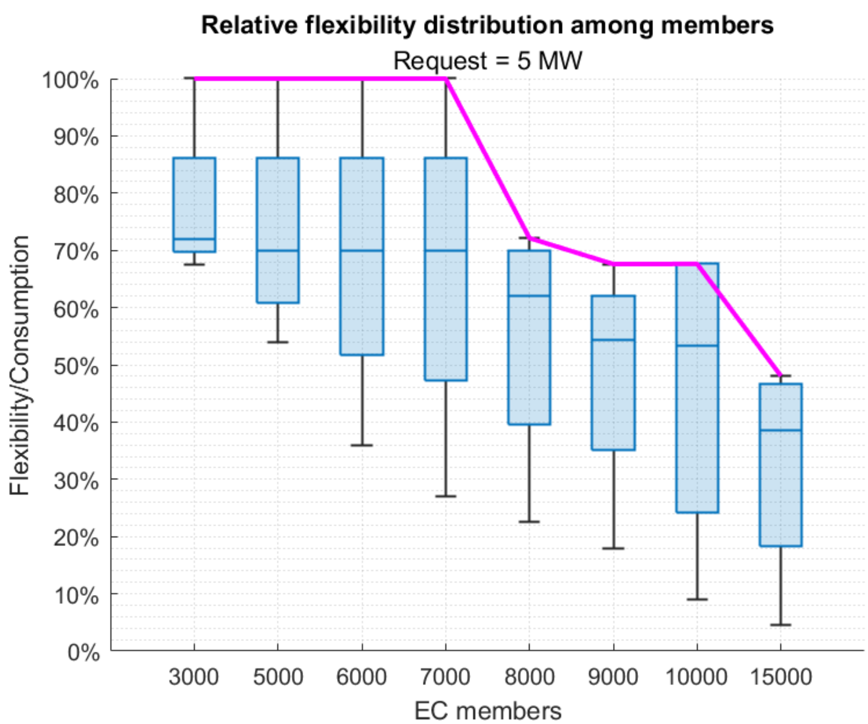

Figure 6.13: Relative flexibility distribution among members [%] - 5 MW

among members results to be fair in terms of kWh, but in relative terms it results to be extremely demanding for residential customers, while it does not take advantage of the public buildings potential, in particular for big EC sizes. A distinction can be made for requests smaller or greater that 1 MW: defining the range of the EC size that, in one

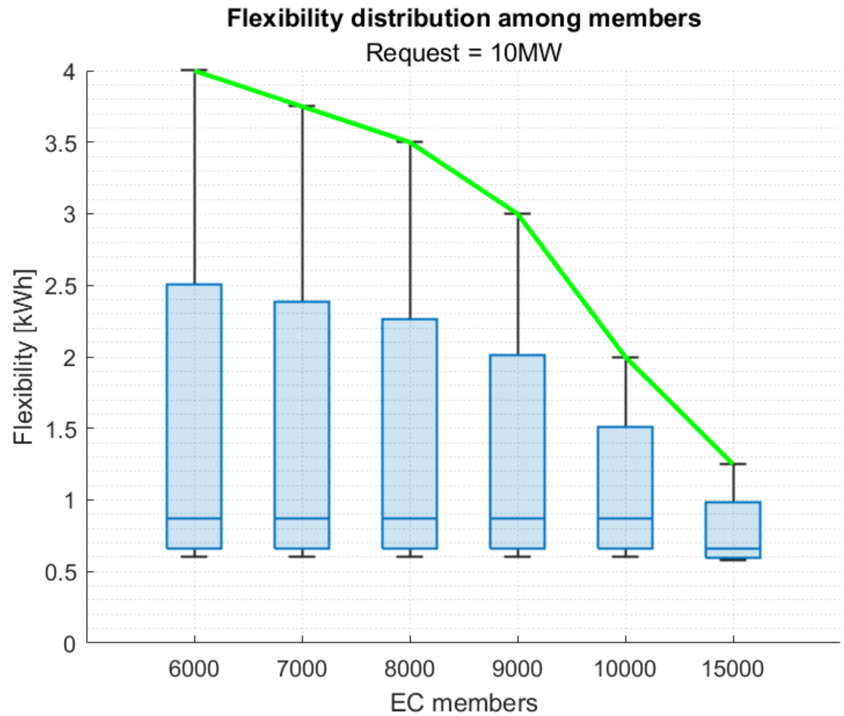

Figure 6.14: Flexibility distribution among members [kWh] - 10 MW

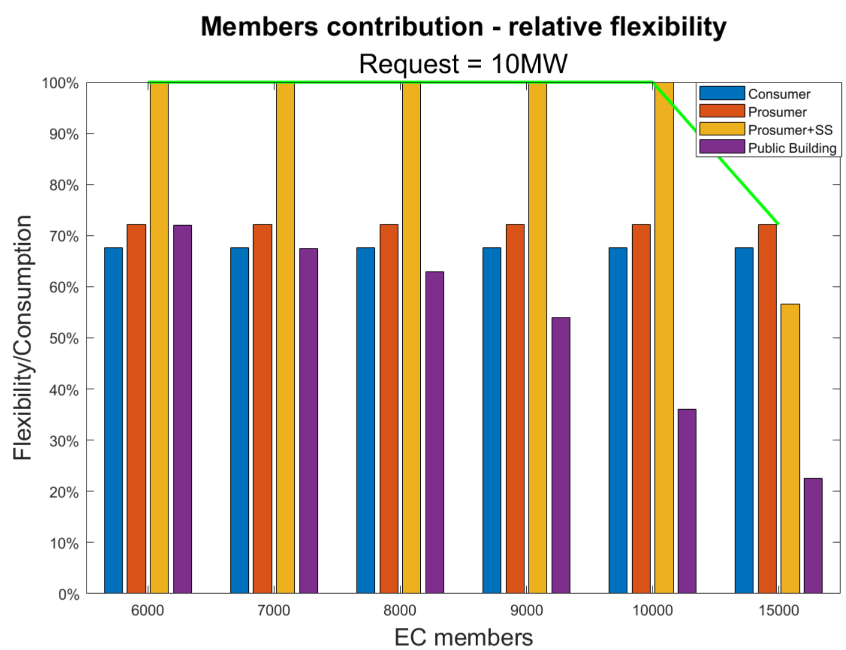

Figure 6.15: Relative flexibility contribution of members [%] - 10 MW

end is able to satisfy the request, and in the other does it with a negligible discomfort (around 30%), it can be set as [200-8000] members for services smaller than 1 MW, and as [2000-15000] members for requests greater than 1 MW. This means that, in general the EC size has to be scaled depending on the maximum service size it wants to provide. In addition, it can be noticed that, for request higher than 1 MW, the minimum flexibility amount requested in kWh remains constant or not relevantly decreases for increasing EC

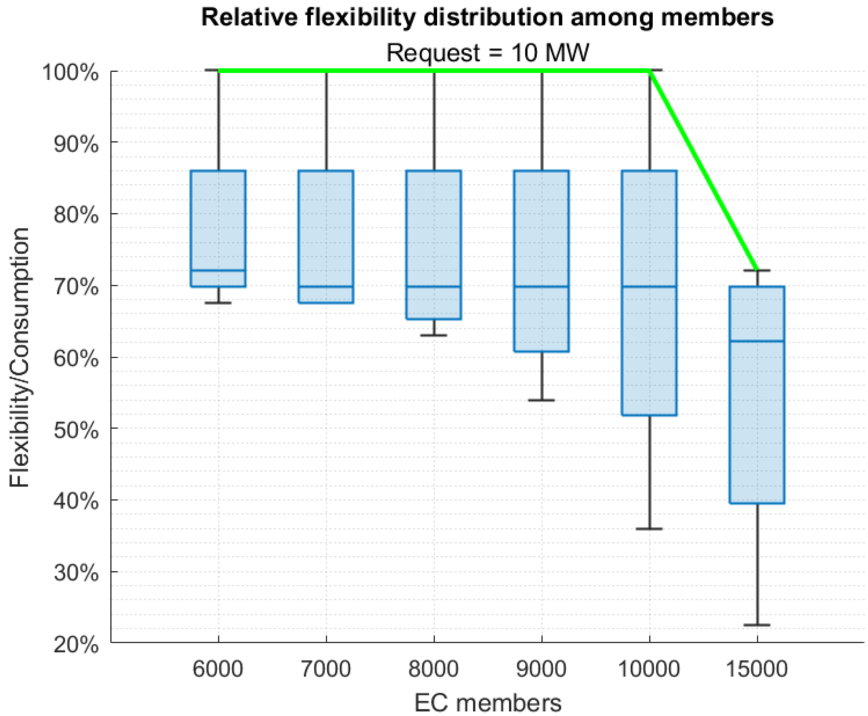

Figure 6.16: Relative flexibility distribution among members [%] - 10 MW

size: this is a sign of the bigger effort needed to provide a big request. These results are limited to the assumptions made for the simulation.