A MILP Approach for Demand Management in Renewable Energy Communities with Residential End-Users

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A MILP approach for demand management in renewable energy communities with residential end-users

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Abstract:
Nowadays, the energy sharing of RES production within Renewable Energy Communities (REC) is promoting the diffusion of a more decentralized energy system, where dispersed renewable generation can be locally self-consumed by REC members. The maximization of self-consumption through the matching between generation and demand is thus fundamental to ensure higher economic and environmental benefits for residential end-users joining REC configurations. However residential electricity demand and the corresponding load profile are generally influenced by end-users' behavior. In fact, even if most of the household appliances can be assumed as fixed loads, the usage of some appliances depends basically on the residents' habits. The engagement of customers in changing their energy consumption patterns is then challenging to promote flexibility in electricity demand to further increase the benefits of adopting and joining renewable energy communities. In this view, a MILP approach is proposed to model end-users' flexibility for investigating how the changing in consumption habits can potentially improve the energy sharing by maximizing the match between RES production and demand. User's discomfort is evaluated consequently as the distance between the desired or usual consumption pattern and the optimized one. An Italian multifamily residential building case study, where end-users adopt a collective self-consumption scheme, is considered to highlight energy and economic results assuming different level of end-users' flexibility. Finally, a comparison between the maximization of energy sharing and the minimization of discomfort rate is pointed out through weighted sum method to identify solutions with different relevance of the end-users' flexibility.

Keywords:
Demand Management, MILP, Energy Community, Residential buildings.

1. Introduction

Energy Communities (ECs) in Italy are a relatively new concept that has emerged as a response to the challenges posed by climate change and the need for a more sustainable energy future [1]. In fact, these communities aim to promote the use of clean and sustainable energy, reduce greenhouse gas emissions, and foster local economic development contrasting energy poverty [2]. For these reasons, in a EC, public and private entities as well as citizens and households jointly and collectively own and manage renewable energy resources (RES) to locally increase self-consumption [3]. Hence, ECs are based on the idea that energy production should be decentralized and democratized, with people taking an active role in shaping their energy future and in driving the energy transition towards a more sustainable energy system.

Since the main goal of an EC is to increase the match between the local RES based production with the local electricity demand, battery energy storage systems (BESSs) are assuming a relavant role. Storage systems are in fact assets for decoupling the timing of energy production from its consumption. Thus, the use of this system has the advantage of leaving the end-user free to keep its own consumption habits, while overproduction can be stored and released when needed. However, one of the possible critical aspect in adopting BESS is still its profitability without incentives [4–6].

A different and complementary approach can be instead considered by promoting the cooperation between people (e.g. households) and the energy system (i.e. the EC). In particular, to increase self-consumption and self-sufficiency, changes in consumption habits may be proposed to end-users to modify the timing at which these consumptions occur [7]. This lead to the adoption of demand management where, through a simulation approach, the optimal usage of some electric appliances in the households can be identified and suggested to end-users for adapting their habits to a more sustainable and profitable behaviour. Consequently, also the BESS sizing could benefits on the adoption of demand management due to lower expected RES overproduction.

In this view, the work presented by [8] gives a wider overview on the different approaches adopted to model the demand management in the residential sector. Some of them are based on linear programming (LP) and mixed integer linear programming (MILP) for deploying load-shifting and then minimize the energy bills for end-users. For instance, a MILP smart home energy management model has been presented in [9] to arrange the operation of the household appliances for minimazing costs by considering time-varying pricing model to control the system. In particular, electrically controllable appliances are shifted to reduce electricity bought from the grid by harnessing RES production and storage usage. Similarly, a home energy management strategy to minimize the customer's billing is presented in [10], where different components and appliances are modeled by MILP. Shiftable loads are modeled again as components with a fixed operational time window that can be arranged to reduce the electricity bought from the grid.

According to these examples, a MILP modeling approach is proposed in this work to exploit the benefits due to load shifting in residential sector, but considering the perspective of an energy community (see Figure 1). In this case, the self-consumption of RES-based production is maximized by suggesting different end-users' habits, so that the aggregated load demand can more efficiently match the RES production. Results are compared with ones achievable by using a different approach based on the integration of an energy storage system to figure out also potential interoperability with demand management. Additionally, end-users' discomfort is also modelled to take into account the end-users' acceptability of the demand management. In fact, costumers perception on flexibility tools is still controversial [11]. Then, multi-objective optimization is also proposed to investigate how different willingness to participate in demand management can influence the benefits.

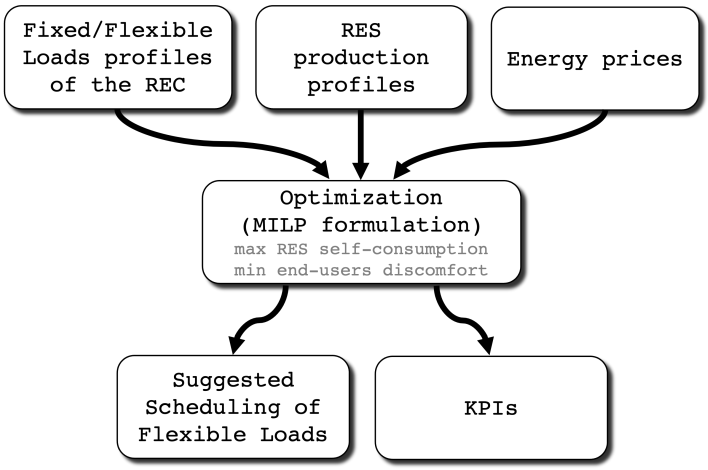

Figure 1: Scheme of the proposed MILP approach

2. Problem formulation

A Mixed Integer Linear Programming (MILP) formulation is proposed here to model the demand management of electric appliances used by residential end-users joining a collective self-consumption configuration. Consequently, equations and constraints representing this energy system are linear or alternatively should be linearized. In particular, two different kind of equations can be considered for describing the energy exchanges within an energy community, the interaction of the collective self-consumption with the grid and the management of the electricity demand: energy balance equations and constitutive equations representing the energy behaviours of the different assets. Binary (i.e., integer) variables are also introduced to describe the on/off status of the components and appliances and to consider their operational limits. A detailed description of this general approach can be found in [12].

The time horizon of the simulation is discretized by subdividing it in N_i intervals with length Δt equal to 5 minutes in this particular application for fully exploiting the potentiality of the demand management in residential end-users.

2.1. Modeling Demand Management

Demand management of the consumption aims at modify the end-users' habits in using electric appliances to meet specific goals of the energy community. As already pointed out, in this particular case, the objective is to increase the self-consumption of the RES production to maximize energy sharing and improve the economic benefits. Hence, end-users can actively participate by shifting the energy consumption for all those appliance that are programmable by definition as, for instance, washing machines and dishwashers [8]. These appliances, in fact, have a fixed duty-cycle whose start can be anticipated or deferred with respect to the end-users' usual habits. As a consequence, assuming a daily time horizon discretized on N_i time intervals, the duty-cycle of an end-user's appliance can potentially be started at any time intervals.

This condition can be modelled by a squared matrix where each columns represents the load pattern (or load profile) of the *a*-th programmable appliance by assuming a different starting time interval for the duty-cycle. Practically, the first column is the usual load pattern, while the other columns are obtained by cyclic permutation of the first one, as follows:

$$\mathbf{P}_{j,a} = \begin{bmatrix} p_{j,a,1} & p_{j,a,N_i} & p_{j,a,N_i-1} & \cdots & p_{j,a,2} \\ p_{j,a.2} & p_{j,a,1} & p_{j,a,N_i} & \cdots & p_{j,a,3} \\ p_{j,a,3} & p_{j,a,2} & p_{j,a,1} & \cdots & p_{j,a,4} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ p_{j,a,N_i} & p_{j,a,N_i-1} & p_{j,a,N_i-2} & \cdots & p_{j,a,1} \end{bmatrix} \tag{1}$$

where $P_{j,a} \in \mathbb{R}^{N_i x N_i}$ and $p_{j,a,i}$ is the consumption of the *a*-th programmable appliances in a given *i*-th time interval for the *j*-th end-user. Clearly, an appliance can only adopt one load profile from the matrix *P*, while the other must be ignored. For this reason, N_i additional binary variables have to be introduced, one for each columns, so that:

$$\sum_{i=1}^{N_i} \delta_{j,a,i} = 1 \tag{2}$$

where $\delta_{j,a,i}$ is equal to 0 if the *i*-th consumption pattern (i.e. the *i*-th column) is not selected and equal to 1 if the corresponding *i*-th consumption pattern is chosen. Hence, equation 2 ensures that only a load profile can be selected, while the others are not considered. As a consequence, this representation introduces flexibility in the usage of electric appliances to be considered in the demand management purpose.

2.2. Energy storage

A battery electric storage system (BESS) is also considered as an essential element to further introduce flexibility in the management of an energy community [13]. Even if its integration can be complementary to the demand management, because of BESS basically introduce flexibility by potentially leaving consumption habits unchanged, its operation need to be modelled as well to exploit the interaction with demand management. The BESS formulation adopted here is based on the one already introduced in [14], where the BESS is studied considering passive sign convention. Under this assumption, the electric power input to the BESS has positive sign (during charge), viceversa the output one (during discharge) has negative sign. As a consequence, the State Of Charge (*SOC*) of the battery (i.e. its energy conten) in a given time interval is defined; as follows:

$$SOC(t_{i+1}) = \eta_{sd} SOC(t_i) + \left(\eta_c P_{b,c}(t_i) - \frac{P_{b,d}(t_i)}{\eta_d} \right) \Delta t \tag{3}$$

where η_{sd} is the self-discharge efficiency, η_c is the charge efficiency, η_d is the discharge efficiency and $P_{b,c}$ and $P_{b,d}$ are the battery power respectively during charge and discharge. However, electric power during charge and discharge are typically limited, so further constraints need to be introduced, as follows:

$$0 \le P_{st,c} \le \delta_c \frac{SOC_{max}}{T_c} \tag{4}$$

$$0 \le P_{st,d} \le \delta_d \frac{SOC_{max}}{T_d} \tag{5}$$

$$0 \le \delta_c + \delta_d \le 1 \tag{6}$$

where SOC_{max} is the storage capacity of the battery, T_c and T_d are the minimum charge and discharge time, while Equation 6 is a operational constraint where δ_c and δ_d are binary variables that compel charge and discharge powers to be different from zero only one at a time.

2.3. Energy balance of the community with demand management

As already depicted in Section 2.4., an energy community is a scheme where local RES production, energy storage systems and the end-users interact each other to increase local self-consumption. In this context, where residential end-users jointly acting as renewables self-consumers, if demand management is also introduced for some of the appliances, the energy consumption for each end-users can be divided in two different main categories: fixed load and a flexible one. The corresponding energy balance for the community can be then defined in each time interval, as follows:

$$P_{PV}(t_i) + P_p(t_i) + P_{b,d}(t_i) = P_s(t_i) + P_{b,c}(t_i) + \sum_{j=1}^{N_u} U_{fix,j}(t_i) + \sum_{j=1}^{N_u}\sum_{a=1}^{N_a} U_{flex,j,a}(t_i) \tag{7}$$

where P_{PV} is the RES production from PV, P_p is the electricity bought from the grid, $P_{b,d}$ is the electric power supplied by the battery, $P_{b,c}$ is the electric power consumed by the battery, $U_{fix,j}$ is the overall fixed load of the j-th end-whikle $U_{flex,j,a}$ is the flexible load of the a-th programmable appliance owned by the corresponding j-th end-user. Then, the left hand side of Equation 7 represents the *sources* for the energy community, while the right hand side identifies the *loads*, where P_s has the role of representing power injected and sold to the grid.

However, according to the modelling of demand management proposed in Section 2.1., each flexible load can be represented by N_i possible load patterns where only one of them is not actually zeroed. As a consequence, each flexible load introduced in Equation 7 can be also represented as follows:

$$\mathbf{U}_{flex,j,a} = \sum_{i=1}^{N_i} \delta_{j,a,i}\mathbf{p}_{j,a}^{(i)} \tag{8}$$

where $\mathbf{p}_{j,a}^{(i)}$ is the i-th column of the matrix $\mathbf{P}_{a,j}$, while $\mathbf{U}_{flex,j,a}$ is the vector describing the load profile for the a-th programmable appliance of the j-th end-user. Of course, Equation 2 ensures that only one load patterns will be selected during the search of the optimal solution.

Additionally, limitations owning to the contractually committed power have to be considered for each end-user. In fact, demand management shifts the flexible loads and consequently power demand can exceed the available power for a residential end-user which is usually equal to 3 kW in most of the Italian domestic costumers [15]. This can be avoided by introducing for each j-th end-user and in each i-th time interval a further constraints, as follows:

$$U_{fix,j}(t_i) + \sum_{a=1}^{N_a} U_{flex,j,a}(t_i) \leq P_c \tag{9}$$

where P_c is the contractually committed power for domestic costumers.

2.4. Objective functions

In this paper, according to the recent Italian rules [16], a multi-family building is considered where a PV plant is used to supply the energy demand of the residential end-users jointly acting as renewables self-consumers. In this context, the energy demand of the some electric appliances are supposed to be schedable to increase and maximize the self-consumption of the RES production. This goal is equivalent to reduce or minimize the electricity produced by the PV and injected into the grid, so the objective function is evaluated, as follows:

$$OF_1 = min \sum_{i=1}^{N_i} P_s(t_i)\Delta t \tag{10}$$

where P_s represents the electric power sold to the grid. However, the management of some of the electric appliances according to this policy, may be potentially in contrast with the users' habits. For this reason a measure of the end-users' discomfort in adopting demand management is also introduced. This is represented by a sort of weighted distance between the scheduled path demand of the shiftable loads (e.g. the one suggested by solving equation 10) and the end-user usual consumption habits. Consequently, an alternative objective function has been introduced to minimize this user's discomfort, as follows:

$$OF_2 = min \sum_{j=1}^{N_u} \sum_{a=1}^{N_a} \left[\sum_{i=1}^{N_i/2} i \cdot \delta_{j,a,i} + \sum_{(N_i/2)+1}^{N_i} (N_i - i + 2) \cdot \delta_{j,a,i} \right] \tag{11}$$

In this objective function, the coefficients i and $(N_i - i + 2)$ are introduced to weight differently each consumption patterns represented by a column of the matrix **P**. In particular, the consumption patterns far from the usual habit (i.e. the first column of **P**) are more penalised with respect to the closest one. In fact, for instance, if the 10th column was selected as consumption pattern, its weight (i.e. 10) would be higher than the one obtainable by the 3rd column (i.e. 3). In this way, the objective function naturally force the solution to be close to usual habits of the end-users. Additionally, weights are symmetric with respect to the center of the matrix, since each column of **P** is generated by a cyclic permutation of the usual consumption pattern of a given appliance. Hence, for example, the second and the last column of **P** have of course the same weight, because they represent two patterns symmetrically close to the end-user's habit.

Clearly, equation 11 states that minimum discomfort has to be reached (i.e., end-users do not change their consumption habits) and practically this in contrast to equation 10. For this reason, also a multi-objective approach have been also explored. In particular, since the formulation proposed here is MILP based, a weighted sum method [17] is adopted to combine the two objective functions, as follows:

$$MOF = min[\alpha OF_1^* + (1 - \alpha) OF_2^*] \tag{12}$$

where $0 \leq \alpha \leq 1$, while OF_1^* and OF_2^* are the normalized objective functions. Different weight α in Equation 12 givea the possibility to explore solutions where demand management is less compelling, consumption patterns are closer to end-users' habits and discomfort is reduced.

3. Key Performance Indicators

KPIs are used here to investigate the performances of the proposed demand management within an energy community on yearly basis, considering scenarios with different sizes of the active assets (i.e. PV and BESS). In particular, these reference scenarios are designed by supposing no demand management, because the considered use cases should investigate the role of the demand management in existing configuration of the collective self-consumption scheme. Three groups of KPIs were considered: energy, economic, environmental and discomfort.

3.1. Energy KPI

The energy impact of the demand management in a multi-family residential building has been evaluated considering two different indicators: the self-consumption (*SC*) and the self-sufficiency (*SS*). The *SC* identifies the self-consumed PV production compared to the yearly PV production, while the *SS* identifies the self-consumed PV production compared to the yearly electricity demand of the building, as follows [18]:

$$SC = \frac{E_{sh}}{E_{PV}} = \frac{\sum_{year} P_{sh}(t_i) \cdot \Delta t}{\sum_{year} P_{PV}(t_i) \cdot \Delta t} \tag{13}$$

$$SS = \frac{E_{sh}}{E_L} = \frac{\sum_{year} P_{sh}(t_i) \cdot \Delta t}{\sum_{year} U_e(t_i) \cdot \Delta t} \tag{14}$$

where U_e is the aggregated yearly electricity load profile including fix and flexible loads, while $P_{sh}(t_i)$ and E_{sh} represent the self-consumed PV production within the energy community also named shared energy and calculated, as follows:

$$P_{sh}(t_i) = min[(P_{PV}(t_i) + P_{b,d}(t_i)), (U_e(t_i) - P_{b,c}(t_i))] \tag{15}$$

3.2. Economic KPI

The economic impact of the demand management in an energy community has been evaluated only in terms of cost savings for the end-users. In fact, as already pointed out, demand management is supposed to be adopted in existing scenarios of energy communities. Hence, economic feasibility and profitability of investing in the active assets of the community is not considered here, so economic indicators evaluating the return of investment are not included in this work.

In this light, the indicator named Percentage Cost Reduction (*PCR*) [19] is used to compare the yearly costs of the electricity bills YC_{dm} obtained by the energy community adopting demand management with the ones YC_{ref} where demand management is not adopted. Practically, *PCR* is calculated as follows:

$$PCR = \left[1 - \frac{YC_{dm}}{YC_{ref}}\right] 100. \tag{16}$$

Both yearly costs are calculated considering the per unit cost for the electricity bought from the grid E_L and the economic benefits and incentives offered to energy communities by the current Italian regulatory framework, as follows:

$$YC = E_L C_p - E_{PV} C_s - E_{sh} C_{sh}. \tag{17}$$

Specifically, the PV production injected into the grid E_{PV} is economically valued at the wholesale market price, while the shared energy E_{sh} benefits of an incentive. The former, considering 2019 as reference year, is assumed fixed at approximatively 50€/MWh [20], while the latter is equal to around 110€/MWh and the electricity retail price is assumed instead equal to 200€/MWh on average [19].

3.3. Environmental KPI

Environmental KPI measure instead how demand management influences the reduction in the primary energy consumption or, alternatively, in CO_2 emissions in an energy community. The carbon saving is in fact calculated by comparing the carbon emissions with and without demand management, as follows:

$$\Delta CO_2 = \left[1 - \frac{CO_{2,dm}}{CO_{2,ref}} \cdot 100\right] = \left[1 - \frac{E_{p,dm} \cdot EF_e}{E_{p,ref} \cdot EF_e}\right] \cdot 100 \tag{18}$$

where EF_e represents the national CO_2 emission factor for the electricity bought from the grid [21], while $E_{p,dm}$ and $E_{p,ref}$ are the yearly electricity demand of the building not fulfilled by RES production when DM is adopted and not implemented, respectively.

3.4. Discomfort KPI

Finally, also a further KPI is introduced to measure how demand management changes the usual habits of end-users and contemporarily create discomfort. This can be basically measured by comparing the suggested optimal path demand (gained by solving Equation 10) with the end-user's habits. Since each of the programmable appliances considered in this study have a specific duty-cycle, this comparison is equivalent to measure the distance between two duty-cycles with different starting time or, in other words, this distance is the difference of two starting time, as follows:

$$Dis = \sum_{d=1}^{N_d} \sum_{j=1}^{N_u} \sum_{a=1}^{N_a} \frac{1}{N_i} \mid t_{j,a}^{us} - t_{j,a}^{op} \mid \tag{19}$$

where $^{us}_{j,a}$ and $t^{op}_{j,a}$ are the usual and optimal starting time of the duty-cycle for the *j*-th user and its programmable appliance *a*, while N_d is the number of the reference days adopted to represent a whole year. Clearly, $t^{op}_{j,a}$ is get from the solution obtained by solving Equation 10.

4. Case study description

A multifamily residential building of 40 apartments, located in the North-West part of Italy, was selected as reference use case in this study. In fact, this building typology is the most representative according to the current Italian building stock [19, 22]. The electricity demand of each apartment was estimated considering an open-source simulator developed by the CADEMA research group of the Politecnico di Torino [23]. The open-source simulator creates the daily load profiles of the main electric appliances for an aggregate of households. Then, different load profiles were generated for a whole day according to the season, the day of the week (i.e. weekdays and weekend days) and the energetic labels of the appliances with a time-resolution of 5 minutes.

In particular, the simulated load profile of each appliances are based on statistical data obtained from past load measurement campaign in National research project, so the generated patterns can be assumed as related to end-users' habits. The appliances considered in the simulator are vacuum cleaner, dishwasher, washing machine, tumble drier, audio-video devices (tv, hifi stereo,...) and other electronic devices (laptop, personal computers) and lighting. Among the others, dishwashers and washing-machines were assumed as the ones suitable for the application of demand management due to their ability to be programmed [8]. Figure 2 shows on the left an example of the resulting aggregated electricity demand estimated for the residential building (including both fix and flexible loads of each end-users) with a focus (on the right) for a given end-users where fix demand (blue line) and the consumption of programmable appliances (red and yellow lines) are highlighted. Hence, loads that can be rescheduled have a duty cycle that can be anticipated or delayed with respect to the habits depicted in Figure 2 (right side).

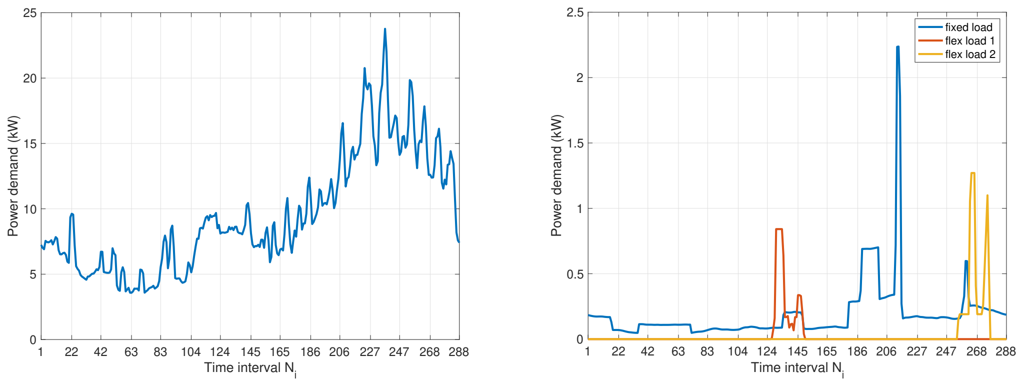

Figure 2: Load profiles of the case study: aggregated demand (left), consumption of a single end-user with fixed and flexible demand (right)

On the other hand, PV production was estimated by adopting the PVGIS database [24] to take into account the effect of the solar beam at the considered location of the case studies. Specifically, PV size was estimated a priori by adopting the sizing criteria proposed in [14] but assuming no demand management. In this light, the PV size is selected on energy basis according to the simultaneous maximization of the self-consumption (*SS*) and self-sufficiency (*SC*) for the energy community, so that the chosen PV size ensures the lowest distance with respect to the Utopia point in the $SC - SS$ plane. The maximum PV size was also limited to 70kW$_p$ due to the available roof surface of the residential building being studied [19]. Of course, since the open-source simulator is on a daily basis, also PV production was estimated on the same timeframe. However, to limit computational effort in simulating the proposed model, reference days were then identified to represent a whole year. In particular, two days (i.e., a weekday and a weekend day) for each seasons have been considered.

The resulting PV size were then considered to identify a reference configuration for the case study where the energy community exploits the RES production for increasing local self-consumption but without demand or BESS management. This reference scenario is firstly compared with one where the demand management is adopted to evaluate its impact without BESS. Later, other scenarios assuming the same PV size, but parametrically increasing BESS size without demand management, were compared to the reference configuration. In this way, demand management is also compared with a different approach based on the BESS management as described in Section 2.2..

5. Results

The assessment of demand management in an energy community with a collective self-consumption configuration is presented in this section. The use-case considered is a residential multi-family building with 40 flats located in the North-West of Italy [19]. According to the sizing approach proposed in Section 4. the installed PV capacity for maximizing both *SS* and *SC* is equal to 40 kW$_p$. Starting from this reference configuration (i.e., Scenario 0) without demand management (DM), the scenarios being studied are summarized in Table 1.

Table 1: PV and BESS size in different Scenarios

Scenario	0	1	2	3	4
PV	✓	✓	✓	✓	✓
BESS (kWh)	-	-	15	30	30
DM	-	✓	-	-	✓

In particular, Scenario 1 highlights the impact of the demand management, while Scenarios 2 and 3 points out the impact of BESS management with increasing BESS sizes. Scenario 4 has been further included to exploit also potential interaction between two different flexibility approach within the energy community. The main BESS characteristics considered in the simulations are also reported in Table 2. In this case, a round-trip efficiency of approximately 90% is assumed, the rated fully charging and discharging time are equal to 3 hours, while self-discharge effect is substantially neglected.

Table 2: BESS characteristics assumed in the simulations [5].

η_c	η_d	η_{sd}	T_c (h)	T_d (h)
0.95	0.95	1	3	3

Table 3 shows the KPIs obtained by the different Scenarios. It can be noticed that demand management in Scenario 1 has a positive impact from the economic, energy and environmental point of view. In fact, the shift of energy consumption for the programmable appliances can improve the match of the demand with the PV production. In other words, the aggregated demand of the flexible loads should mainly occur during PV production, as depicted in Figure 3, leading end-users to more virtuous behaviours for the energy community perspective. Consequently, self-consumption and self-sufficiency can be enhanced up to 12.7% and 5.7%, respectively, while energy cost and CO_2 emission can be reduced by 4.6% and 9.1%.

Clearly, the positive economic impact can also contribute in increasing cash-flows and, consequently, in making more profitable the PV investment for the community.

Table 3: KPIs obtained for different Scenarios

Scenario	0	1	2	3	4
SC (%)	83.2	95.9	91.7	96.3	99.4
SS (%)	37.2	42.9	41.0	43.0	44.4
PCR (%)	-	4.6	3.1	4.9	5.8
E_{sh} (MWh/y)	34.7	42.9	38.2	40.1	41.4
ΔCO_2 (%)	-	9.1	6.1	9.3	11.5
Dis	0	91.5	0	0	94.8

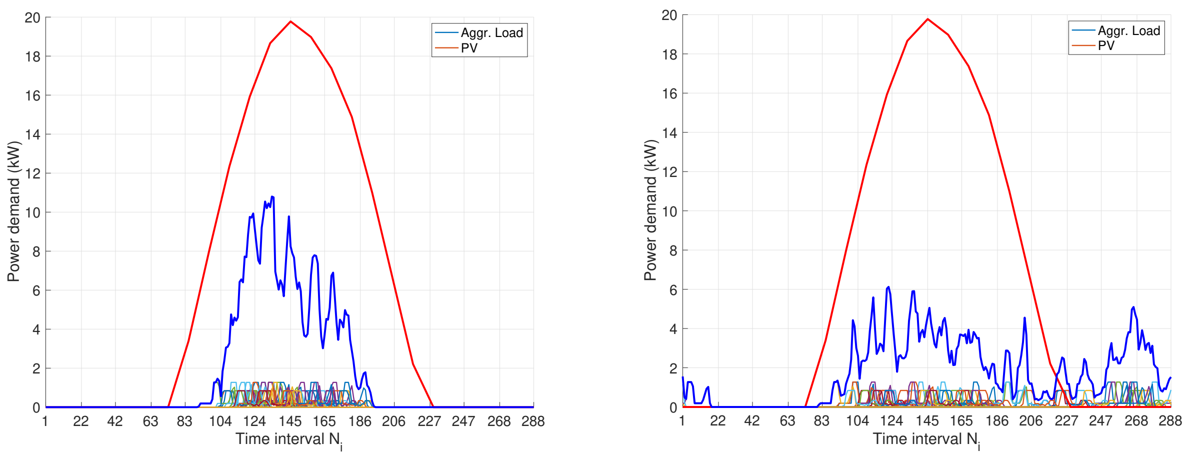

Figure 3: Aggregated load of all the programmable appliances in Scenario 1 with (left) and without (right) demand management during a spring day.

The resulting net load is then significantly close to zero during daytime, so that RES production is mainly self-consumed within the community and not injected into the grid as reported in Figure 4. Furthermore, demand management can also reduce the net load during the afternoon and evening hours, still due to load shifting effects. However, discomfort inevitably increases, since end-users' habits should be changed.

Similar benefits can be gained in Scenario 3 by optimally managing BESS to increase self-consumption, as noticed in Table 3 and Figure 4. In fact, even without demand management, the adoption of BESS with a rated capacity of 30 kWh can contribute to reach high levels of *SC* and *SS* close to 96% and 43% respectively, while cost and emission savings can be close to 4.9% and 9.3%. Nevertheless, this approach needs of the installation of a costly asset (i.e. electrochemical battery) while the end-users' behaviour is not involved at all. Additionally, BESS needs to be replaced once its cycle life is reached, making not yet totally profitable its usage in residential applications without the adoption of incentives [4, 25].

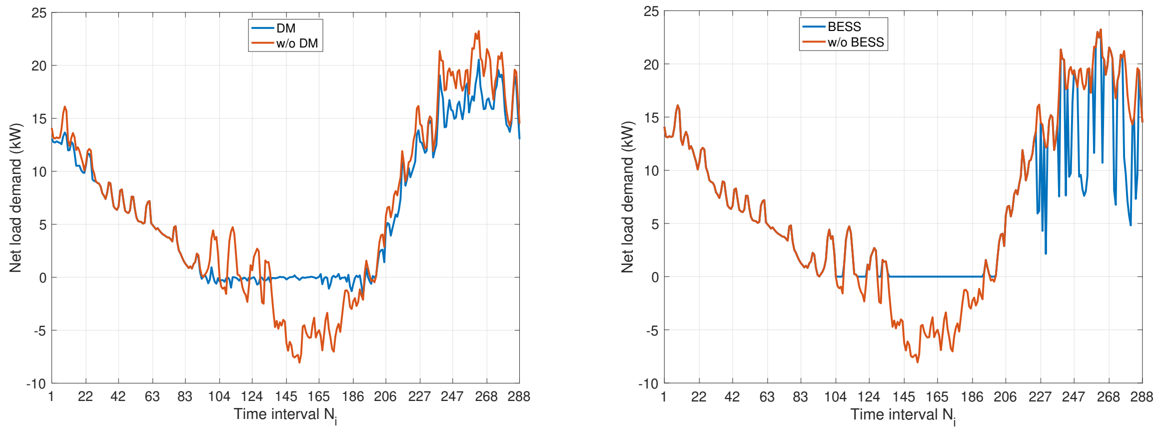

Figure 4: Net load of the energy community during a summer day for: Scenario 1 with (blue curve) and without (red curve) demand management on the left; Scenario 3 with (blue curve) and without (red curve) BESS management on the right.

However, when the interaction of the two different flexibility approaches is considered (i.e., Scenario 4), all the KPIs benefit of the demand management. In this case, a fully self-consumption of PV production is almost reached, while cost and emissions savings can be close to 6% and 11.5%, respectively. Specifically, the demand management allows a lower battery usage while ensuring a longer technical lifetime, postponing the need of investment for its replacement. Furthermore, demand management contributes in contrasting the injection of PV overproduction, as pointed out by the net load shown in Figure 5, while BESS benefits of a lower

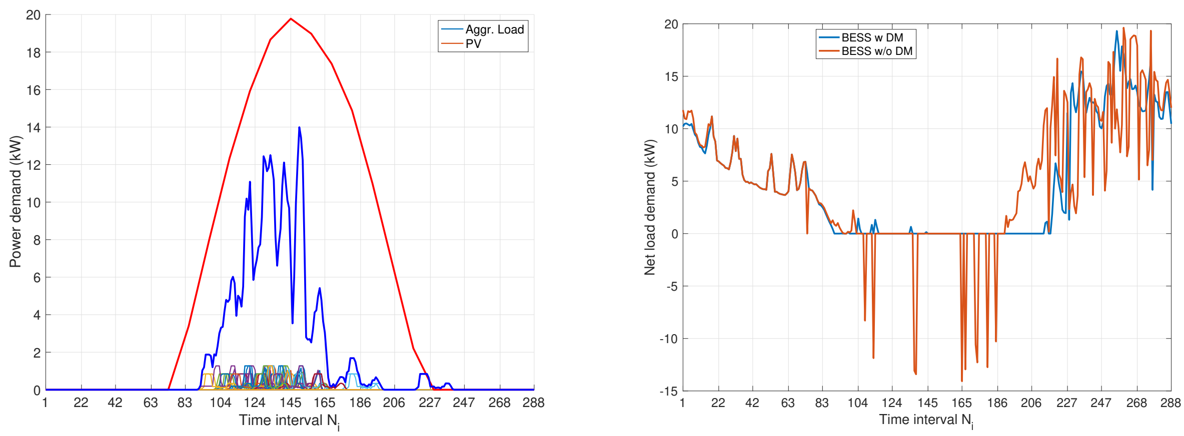

Figure 5: Scenario 4: aggregated load of the programmable appliances with and without demand management during a spring day; net load of the energy community during spring with and without demand management.

Finally, multi-objective simulations have been also explored to evaluate the impact of different end-users' availability in changing their habits for following or adopting demand management. As already observed, different end-users adaptability can be obtained by considering different weights α in Equation 12. In fact, a lower α represents a decreasing willingness to participate in demand management and vice versa. Table 4 shows the results of the multi-objective simulation for Scenario 1 considering different weights. As expected, the greater is α the better the economic, environmental and energy KPIs, while the higher the discomfort. Correspondingly, the net load of Figure 6 has more negative values (i.e., reduced self-consumption) when OF_2 (i.e., the discomfort) is weighting more than the OF_1 (i.e., the self-sufficiency). These results suggest that some trade-off solutions can be achieved where end-users' acceptance or availability in following demand management is not fully agreed. Nevertheless, positive results can be still obtained and then end-users acceptability can be thus promoted to increase the willingness to participate in flexibility [7].

Table 4: KPIs obtained for Scenario 1 considering different weight in multi-objective simulation

α	0.75	0.5	0.25
SC (%)	95.8	92.4	88.6
SS (%)	42.8	41.3	39.6
PCR (%)	4.5	3.3	1.9
E_{sh} (MWh/y)	39.9	38.5	36.9
ΔCO_2 (%)	8.9	6.5	3.8
Dis	38.9	19.7	7.1

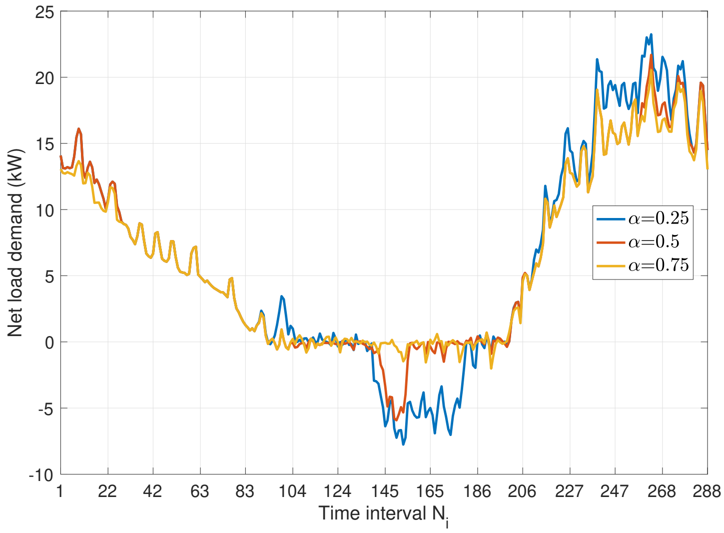

Figure 6: Scenario 1: aggregated load of the programmable appliances with and without demand management during a spring day; net load of the energy community during spring with and without demand management.

6. Conclusion

The energy communities represent a great opportunity to increase self-consumption of RES based production, fostering more sustainable energy ssystems with lower operational costs capable to contrast energy poverty. In this context, flexibility is assuming a relevant role for reaching these goals, because it can improve the match between consumption and production. Classically, storage systems are considered for decoupling the timing of energy production from the demand, so that overproduction can be stored and released when needed, leaving the costumers habits unchanged. In this work, instead, a complementary approach based on demand management was considered, by promoting changes in consumption habits that may be proposed to end-users. In particular, a Mixed Integer Linear Programming formulation is proposed here to model the demand management of electric appliances used by residential end-users joining an energy community under the Italian regulatory framework. An Italian residential multi-family building with PV is assumed for exploiting the economic and environmental benefits of the flexibility. Discomfort was also evaluated to highlights how demand management impacts the households habits.

The results figured out how demand management can effectively increase local self-consumption with a corresponding reduction in terms of energy costs and CO_2 emissions up to 4.6% and 9.1%, respectively. Similar results could be potentially obtained by using electric storage systems, but investment and operational cost increase as well, making stil less profitable this solution. Interoperability between battery and demand management can instead be supported, because storage units can be potentially undersized or alternatively less stressed, while energy, environmental and economic KPIs are improved. Of course, discomfort is being penalized, then multi-objective simulation has been also introduced to evaluate how KPIs are influenced by a different willingness to participate in demand management. Results show that potential trade-off solutions can be still found, even thought benefits are reduced. In this case, future work will be further developed to investigate how to economically enhance end-users availability according to their rate of flexibility.

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