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First steps towards micro-benchmarking the Lava-Loihi neuromorphic ecosystem

Original
First steps towards micro-benchmarking the Lava-Loihi neuromorphic ecosystem / Gallego Gomez, W., Pignata, A., Pignari, R., Fra, V., Macii, E., Urgese, G.. - ELETTRONICO. - (2023), pp. 462-469. (16th IEEE International Symposium on Embedded Multicore/Many-core Systems-on-Chip (MCSoC-2023) Singapore December 18-21, 2023) [10.1109/MCSoC60832.2023.00075].

Availability:
This version is available at: 11583/2981812 since: 2023-09-08T15:06:41Z

Publisher:
IEEE

Published
DOI:10.1109/MCSoC60832.2023.00075

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25 June 2026

Optimal scheduling of programmable appliances for demand management in energy communities

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***Abstract*—Increasing the share of Renewable Energy Sources (RES) in energy consumption is perceived today as essential to decarbonizing energy systems. In this context, the Renewable Energy Communities (RECs) have been recently introduced to create a more decentralized energy system, where each member may share RES-based energy production to increase local self-consumption. To maximize the benefits for each member, the RES-based energy generation should match the demand.**

Thus, demand management may contribute in this regard by introducing load-shifting for the electric appliances used by REC's members.

In this view, different modeling approaches are proposed as Mixed Integer Linear Programming and Mixed Integer Quadratic Programming. Solutions can be used to suggest possible changes to the end-users' current habits. Simulations are performed to compare energy, economic, and environmental Key Performance Indicators, including self-consumption, self-sufficiency, and CO_2 emission savings.

***Index Terms*—Renewable Energy Communities, MILP, MIQP, end-user engagement**

I. Introduction

In the last decade, increasing the share of Renewable Energy Sources (RES) in the customers' final consumption has become more compelling in the EU as one of the solutions for contrasting climate change issues [1]. More recently, the Directive [2] and its update [3] have stated targets for the EU Member States to achieve, respectively, 32% and then 42.5% share of RES in gross final energy consumption by 2030.

In this perspective, Renewable Energy Communities (RECs) [4] play an important role in reaching these goals. RECs are, in fact, legal entities where RES generation can be shared and, hence, locally self-consumed with costumers joining the community, stimulating local economic and contrasting energy poverty. Especially, in the Italian regulatory framework [5], an economic incentive is provided for the RES overproduction shared with the other members by means of the distribution grid.

In this context, the best performance from the economic, energy, and environmental point of view can be obtained when RES production fits the local demand as much as possible, and vice versa. The use of Battery Energy Storage Systems (BESSs) points in this direction, but one of the critical challenges in adopting BESS is still its profitability, as noted in recent studies [6]–[8]. On the other hand, demand management offers a different view, since the match between production and consumption is gained by reducing/shifting demand through modification of customers' consumption patterns. This can be achieved, for instance, by an appropriate energy pricing [9]. Alternatively, through the REC digitalization process, the interaction between people (e.g. households) and the energy system (i.e. the REC) can be also promoted, so that suggestions on when to consume energy can be provided to REC members. This strategy helps to identify the optimal usage of electric appliances by end-users for adapting their habits to more sustainable and profitable behavior. Currently, the majority of the literature focuses on using Linear Programming (LP), Mixed-Integer Linear Programming (MILP), and Mixed-Integer Non-Linear Programming (MINLP) to address the issue of load-shifting [10]. However, most of these studies have not fully explored the effects of load shifting introduced by demand management within the REC context. In fact, the rescheduling of the demand to maximize self-consumption may lead to possible overshooting with respect to RES production. In other words, this means that load-shifting may result in over-demand when RES is producing. Although this may reduce the demand during the rest of the day, this behavior is ineffective from an energy-sharing point of view within a REC. In this view, different modeling approaches to demand management are proposed in this study. Specifically, the impact of changing the consumption patterns of customers from the energy and environmental point of view is achieved by considering both Mixed Integer Linear Programming (MILP) and Mixed Integer Quadratic Programming (MIQP) formulation. The proposed modeling will show possible suggestions on how end-users could shift their current habits in using programmable appliances. Specifically, penalization factors will be introduced to reduce the possible overshooting effect due to demand management.

II. REC and Demand Management models

To understand how demand management can affect the performance of an energy community, it is essential to model a REC and simulate it. This involves describing the behavior of REC assets and their interaction with each other. The presented modeling approach is an improvement of the simplified one proposed by the authors in [11].

A. Demand Management

Demand management essentially introduced the possibility to shift the energy consumption of some programmable appliances in different time slots to improve the local self-consumption of RES production. Then, the load-shifting can be opportunely modeled by means of matrix $\mathbf{Q}$ for each appliance. Its main property is that each column represents a different load profile where the starting time for the duty-cycle of a given appliance is different. As a consequence, $\mathbf{Q}$ is defined, as follows:

$$\mathbf{Q}_{j,a} = \begin{bmatrix} \mathbf{q}_{j,a}^{(1)} & \mathbf{q}_{j,a}^{(2)} & \mathbf{q}_{j,a}^{(3)} & \cdots & \mathbf{q}_{j,a}^{(N_i)} \end{bmatrix} \tag{1}$$

where $\mathbf{q}_{j,a}^{(i)}$ is the i-th column of the matrix representing a load profile of the a-th schedulable appliances for the j-th end-user. The first column of the matrix can be conveniently selected as the usual consumption pattern (i.e. the hourly load profile of the appliance when used as usual by the user), while the others can be obtained by permuting the first one. It's important to note that only one load pattern can be selected for each appliance, meaning only one column from the matrix $\mathbf{Q}$, while the others must be disregarded. For this reason, a binary variable was introduced for each column, so that:

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

According to equation 2, $\alpha_{j,a,i}$ is zeroed if the i-th consumption pattern (i.e. the i-th column) is not selected by the optimization procedure. Vice versa is set to one.

B. REC Energy balance

The energy balance of a REC is strictly related to its boundary defined by the regulatory framework. In this regard, the RES production within a REC is used to supply the demand from its members by means of the distribution grid [12]. The overproduction is instead formally injected into the National grid. In this study, Photovoltaic (PV) generation is assumed as the main RES source. However, according to the demand management modeled in section II-A, end-users may opportunely shift load patterns to reduce these injections and increase REC self-consumption. Thus, the energy consumption for each household can be divided in two main components as fixed and flexible load and the REC energy balance is calculated, as follows:

$$P_{PV}(t_i) + P_p(t_i) = P_s(t_i) + U_{dm}(t_i) \tag{3}$$

with:

$$U_{dm}(t_i) = \sum_{j=1}^{N_u} U_{fix,j}(t_i) + \sum_{j=1}^{N_u} \sum_{a=1}^{N_a} U_{flex,j,a}(t_i) \tag{4}$$

Equation 4 is introduced to highlight how the aggregated demand of REC's members U_{dm} is composed of flexible and fixed components. Instead, P_{PV} is the production from PV, P_p is the electricity bought from the distribution grid by the REC, $U_{fix,j}$ is the overall fixed load of the j-th end-user, $U_{flex,j,a}$ is the flexible load of the a-th programmable appliance of each j-th REC member, while P_s is the overproduction injected and sold to the National grid. It can be noticed that, according to the modeling presented in Section II-A, each flexible load introduced in Equation 4 can be also represented as follows:

$$\mathbf{U}_{flex,j,a} = \sum_{i=1}^{N_i} \alpha_{j,a,i} \mathbf{q}_{j,a}^{(i)} \tag{5}$$

where $\mathbf{U}_{flex,j,a}$ is the vector describing the load profile for the a-th programmable appliance of the j-th end-user.

However, the shifting of load consumption could potentially lead to an overload for REC members. To follow the suggestions offered by the optimization approach, REC user demand may exceed its contractually committed power P_c which is usually equal to 3 kW in Italy [5]. Thus equation 6 has been further introduced to prevent these possible overloads, as follows:

$$U_{fix,j}(t_i) + \sum_{a=1}^{N_a} U_{flex,j,a}(t_i) \leq P_c \tag{6}$$

III. Problem Description

The main rule of demand management in REC is increasing the match between RES-based production and the aggregated demand of members joining the community to improve economic and environmental conditions for all the REC members. Section II highlighted how the shifting of programmable loads is the key to obtain these goals.

From the energy point of view, facing increasing self-consumption in REC is equivalent to minimizing both the electricity injected into the National grid P_s (i.e., the one not self-consumed/shared within the REC boundary) and the electricity withdrawn from the grid P_p (i.e. the one needed to supply the demand within the REC boundary). Consequently, a preliminary objective function is defined, as follows:

$$OF_1 = \min \left(\sum_{i=1}^{N_i} P_s(t_i)\Delta t + \sum_{i=1}^{N_i} P_p(t_i)\Delta t \right) \tag{7}$$

Unfortunately, according to eq. 7, the load shifting can be operated equivalently by using any programmable load (even in different households) so that the aggregated demand of the building is greater than or equal to the local PV production. This could potentially lead to solutions where the aggregated demand overshoots, sometimes significantly, the RES-based generation, without essentially any further energy and economic benefits, as the shared energy will not increase anymore. Moreover, minimizing eq. 7 could show solutions with an increased aggregated demand even during nighttime since, in that case, the load shifting is still indifferent to the objective function.

Alternatively, modification of eq. 7 can be adopted to prevent optimization from finding these solutions. The idea is to operate the load shifting by penalizing the solution where the aggregated load demand is too far from the one without demand management. Thus, deviations from the initial aggregated load profiles are allowed if eventually compensated by the increase of self-consumption (i.e. the minimization of the energy exchanged with the National grid.). This approach can be implemented by adding in the objective function a term for measuring the distance between the aggregated load profiles before and after the demand management.

In this analysis, two different ways of measuring this distance are presented. Firstly, a linear term is considered, as follows:

$$OF_2 = \min \Bigg[\sum_{i=1}^{N_i} P_s(t_i)\Delta t + \sum_{i=1}^{N_i} P_p(t_i)\Delta t + \\ + \lambda_1 \sum_{i=1}^{N_i} |U_{dm}(t_i) - U_e(t_i)| \Bigg] \tag{8}$$

secondly a quadratic term can be instead adopted for measuring the distance, as follows:

$$OF_3 = \min \Bigg[\sum_{i=1}^{N_i} P_s(t_i)\Delta t + \sum_{i=1}^{N_i} P_p(t_i)\Delta t + \\ + \lambda_2 \sum_{i=1}^{N_i} \big(U_{dm}(t_i) - U_e(t_i)\big)^2 \Bigg] \tag{9}$$

In both cases, the additional term is used to keep the aggregated load profile due to demand management U_{dm} close to the one without demand management U_e. Nevertheless, deviations can be accepted only as a consequence of an increase in the shared energy. In fact, the excepted solutions will be essentially without an increase in the aggregated demand during nighttime, as these solutions increase the penalization without any benefit in terms of energy sharing. Contemporarily, modification of the aggregated demand is expected to increase energy sharing but smaller overshoots.

Clearly, while eq. 7 and 8 has the benefit of keeping the problem formulation as MILP, eq. 9 requires a change to a MIQP approach.

IV. Impact of Demand Management

KPIs are usually adopted to quantify and compare the impact of different solutions. In this analysis, the main goal is to quantify, on a yearly basis, the performances of the different modeling proposed (i.e. both MILP and MIQP) for the demand management within an energy community. Since demand management may have impacts on the energy, economic, and environmental aspects of an energy community, the corresponding KPIs are briefly described in the following sections.

A. Energy KPI

As already depicted, one of the main goals of demand management in a REC is to increase the match between RES production and consumption or, in other words, to promote the self-consumption of RES generation produced by the REC and its members. Specifically, since PV generation is considered here, the energy impact of demand management can be measured by considering the indicators proposed in [13], namely the self-consumption (SCI) and self-sufficiency (SSI), but re-adapted for the REC context, as follows :

$$SCI = \frac{E_{sh}}{E_{PV}} = \frac{\sum\limits_{year} P_{sh}(t_i) \cdot \Delta t}{\sum\limits_{year} P_{PV}(t_i) \cdot \Delta t} \tag{10}$$

$$SSI = \frac{E_{sh}}{E_L} = \frac{\sum\limits_{year} P_{sh}(t_i) \cdot \Delta t}{\sum\limits_{year} U_{dm}(t_i) \cdot \Delta t} \tag{11}$$

where E_L is the whole yearly electricity demand of the REC obtained by aggregating the yearly fixed and flexible loads of each member. E_{sh} is instead the yearly self-consumed PV production within the REC boundary (also named shared energy), calculated by summing up the annual hourly based profile of the shared power calculated, as follows [14]:

$$P_{sh}(t_i) = min[P_{PV}(t_i), U_{dm}(t_i)] \tag{12}$$

B. Economic KPI

The economic impact of demand management is simply evaluated here by considering of yearly cash flows measured within the REC boundary. This practically means that other classical economic analysis, such as the one to investigate the return of investment in energy assets (e.g., PV installation), is not considered. In this view, only the yearly net costs borne by members' REC is evaluated as the difference between the cost for the electricity bought from the distribution grid and the earnings gained by injecting RES production into the grid and by self-consuming RES production within the REC boundary. Equation 13 shows the resulting yearly cash flows calculated, as follows:

$$YC = E_L C_p - E_{PV} C_s - E_{sh} C_{sh}. \tag{13}$$

where C_p and C_s are the per unit price for the yearly electricity E_L purchased from the National grid and for the yearly PV production E_{PV} injected into the grid, while C_{sh} is the economic National incentive for the yearly shared energy E_{sh}. Of course, an increase in local self-consumption E_{sh} by demand management clearly offers the possibility to improve economic benefits increasing revenue due to the incentive.

These variations can be measured through the yearly cost saving gained within the REC [15]. This KPI represents the relative variation of the yearly net costs YC_{dm} due to demand management compared to the reference costs YC_{ref}

for a scenario without the optimal scheduling of the electric appliances, as follows :

$$\Delta PCR = \left[1 - \frac{YC_{dm}}{YC_{ref}}\right] 100. \quad (14)$$

In this study, YC_{dm} and YC_{ref} are calculated considering 2019 as the reference year, where, for simplicity, the price C_s for the electricity injected into the grid is assumed fixed at approximately 50€/MWh [16], the incentive C_{sh} is equal to around 110€/MWh and the electricity retail price C_p is assumed equal to 200€/MWh [15].

C. Environmental KPI

From the environmental point of view, instead, the CO_2 emissions savings have been considered here as the KPI to measure the benefits due to the adoption of better energy behaviors by end-users following the hints provided through demand management. Specifically, the carbon saving is calculated, as follows:

$$\Delta CO_2 = \left[1 - \frac{CO_{2,dm}}{CO_{2,ref}} \cdot 100\right] = \left[1 - \frac{E_{p,dm} \cdot \mu_e}{E_{p,ref} \cdot \mu_e}\right] \cdot 100 \quad (15)$$

where μ_e is the CO_2 emission factor equal to 255 $kgCO_2/MWh$ for the electricity withdraws from the Italian grid [17]. $E_{p,dm}$ and $E_{p,ref}$ are instead the net yearly electricity demand of the REC when suggestions from demand management are adopted or not by REC users, respectively.

V. Results

In this section, the assessment of the different strategies introduced in Section III for demand management in a REC is presented. In practice, the differences between MILP and MIQP formulations are highlighted in terms of the energy, economic, and environmental KPIs introduced in Section IV.

Although the REC spatial boundary has been recently increased by the Italian regulatory framework [18], the use-case being studied in this analysis is limited to a residential multi-family building where households participate as jointly acting renewable self-consumers in the form of Collective Self-Consumption. Specifically, a residential multi-family building with 40 flats located in the northwest of Italy with an installed PV capacity equal to 40 kW_p is considered here according to the characteristic pointed out in [15]. To evaluate the impact of demand management, however, load profiles for each household have to be generated according to the modeling presented in Section II, where fixed and flexible loads need to be identified. Thus, the demand for each apartment was estimated by an open-source simulator developed by the CADEMA research group of the Politecnico di Torino [19]. In particular, for the sake of simplicity but without loss of generality, the yearly demand is represented by 8 reference daily load profiles generated for each apartment. These reference days, with a time resolution of 5 minutes, differ from each other according to the season and the day of the week (i.e. weekdays and weekend days). In contrast, PV production profiles are identified by adopting the approach presented in [7] based on the usage of data from PVGIS [20]. As a result, an aggregated electricity demand equal to 101.52 MWh has been estimated for the residential building, including both fixed and flexible loads of each end-user, while the PV production is approximately close to 45.3 MWh/year for a South-oriented plant with an optimal tilt angle.

Each load profile generated by the open-source simulator has been then separated into a flexible and fixed part. Specifically, the duty-cycle of dishwashers and washing machines are used here to create flexible loads due to their ability to be programmed [10]. Additionally, according to the formulation proposed in eq. 8 and 9, the parameter λ_1 and λ_2 should be also set. For the case study, these coefficients have been fixed at 0.1 and 0.01, respectively. Lower values could otherwise lead to solutions where the impact of penalization is too weak, and vice versa.

Figure 1 shows the results of the different approaches during winter: in all cases, the energy injected into the National grid is zeroed with a consequent maximization of the shared energy. Nevertheless, differences exist.

It can be noticed how, without penalization (see Figure 1b), the demand management suggests shifting all the programmable loads during the daytime when the PV plant is producing, as figured out by the aggregated demand of the flexible loads U_{flex}. However, the resulting overall aggregated demand U_{dm} significantly overshoots the PV profile. As already mentioned, this solution is ineffective from the energy-sharing point of view, while it has a relevant impact from a social perspective, since drives all the end-users to change their habits. Differently, when OF_2 or OF_3 are used as objective functions, not all the flexible loads are involved. Moreover, a significant reduction in the overshooting effect can be observed in both cases. Specifically, the MIQP approach introduces a smaller reduction of the aggregated demand almost uniformly during evening and nighttime. On the other hand, OF_2 with a linear penalization performs a higher reduction of the aggregated demand in some time steps during evening and nighttime. This is a consequence of the quadratic formulation where a lower penalization can be obtained with a smaller reduction of the aggregated demand.

Figure 2 shows instead the results during a summer reference day. In this case, since the PV production is significant, the different approaches reflect similar solutions. All the flexible loads are, in fact, shifted to increase local self-consumption, and the resulting aggregated demand of the programmable appliances U_{flex} follows the PV production profile.

Results from the energy, economic, and environmental points of view are instead summarised in Table I. Essentially, all the objective functions lead to very similar results where the self-consumption, self-sufficiency, economic, and environmental performances increased if compared to the solution without demand management.

This highlights once more the point already discussed in Figure 1. All the proposed objective functions are capable

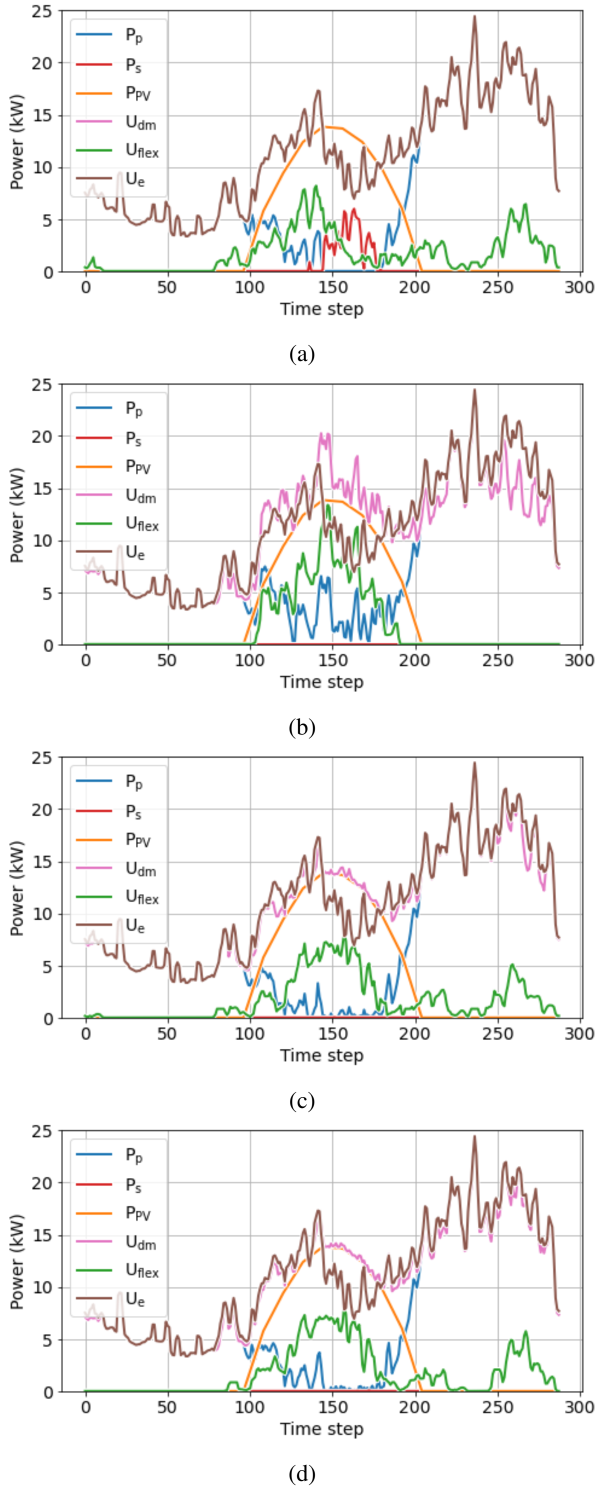

Fig. 1: Results without demand management a) and for b) OF_1, c) OF_2 and d) OF_3 in a winter day.

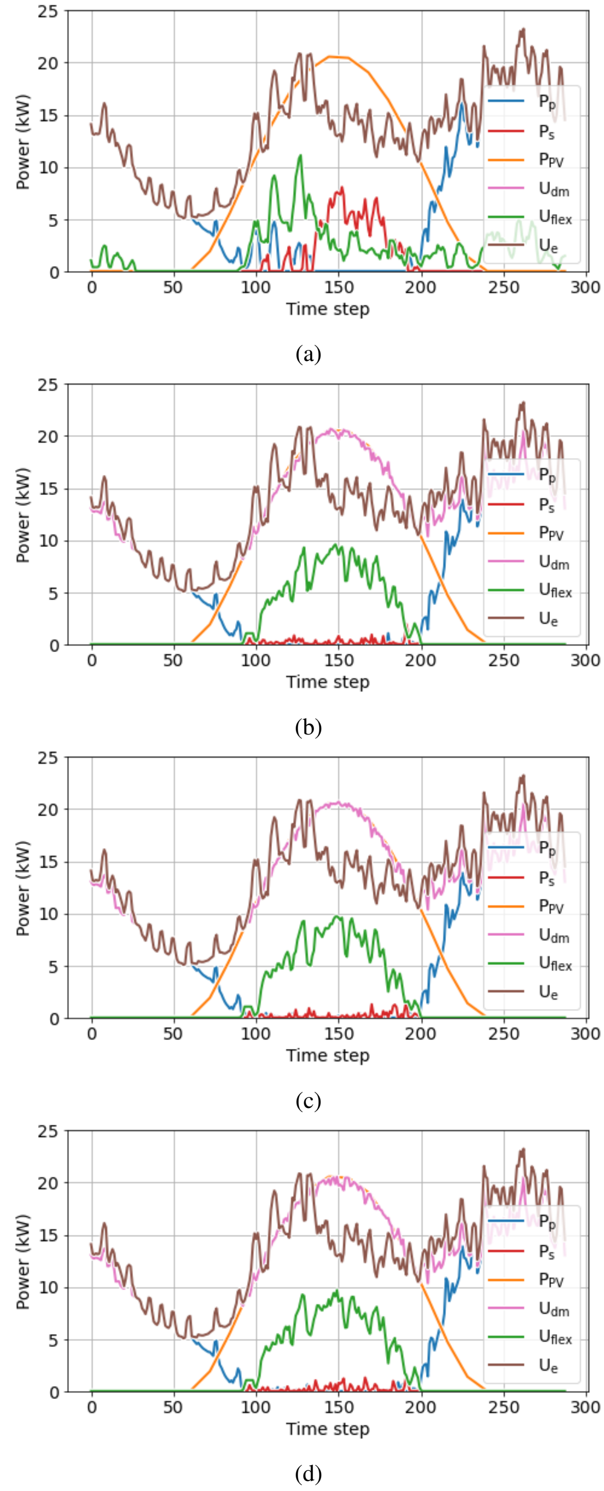

Fig. 2: Results without demand management a) and for b) OF_1, c) OF_2 and d) OF_3 in a summer day.

of improving energy sharing and, consequently, all the KPIs. However, if penalization is not included, solutions have a relevant impact from a social perspective. In fact, a larger number of end-users should be involved in changing their habits, even if this solution is ineffective from the energy-sharing point of view. Differently, the introduction of penalties in the objectives function leads to a more acceptable adoption of the suggestions gained by the optimization approach.

TABLE I: KPIs obtained considering different objective functions in the demand management

		$ObjectiveFuntions$		
KPI	w/o DM	OF_1	OF_2	OF_3
SCI (%)	83.22	95.94	95.93	95.90
SSI (%)	37.18	42.86	42.86	42.84
ΔPCR (%)	-	4.57	4.57	4.56
ΔCO_2 (%)	-	9.05	9.04	9.02

VI. CONCLUSION

The Renewable Energy Community has been recently introduced in the European regulatory framework to increase the use of RES while reducing billing costs for its members fostering the adoption of greener technologies. This can help both sustainability and economic competitiveness in contrasting energy poverty. Energy flexibility is a crucial factor in this regard, as it enables the matching of RES-based energy production and local demand from REC members.

Specifically, this study considers an approach where the management of energy demand is supposed to be implemented by changing the consumption habits of REC's end-users. The problem is formulated both by Mixed Integer Linear Programming and Mixed Integer Quadratic Programming to model demand management of programmable electric appliances used by REC's members. In both approaches, penalization was also introduced to avoid possible solutions that are ineffective from the energy-sharing point of view. This has an impact also on the social perspective either reducing the number of REC members to be involved in load shifting or requiring only small changes in the habits. An Italian residential multi-family building, with 40 flats and a 40kW$_p$ PV plant in its premises, is assumed to exploit the energy, economic, and environmental benefits of flexibility due to demand management. The simulations found that demand management can effectively encourage energy sharing within a community, resulting in a significant increase in local self-consumption from 83.22% to around 96% and leading to a reduction in energy costs and CO_2 emissions by approximately 4.6% and 9.1%. Specifically, introducing penalties in the objective function leads to a more acceptable adoption by end-users of the suggestions gained through optimization.

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