Impact of flexible assets on a Microgrid

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Abstract – **The current decarbonization of the energy sector has led to an impressive increase in the variable renewable energy (VRE) capacity installed in the network. To provide the electric power system with the required flexibility to efficiently integrate the growing VRE capacity, new innovative solutions have to be developed. Additionally, the current energy sector is revolutionizing: its electrification, digitalization and decentralisation are offering more opportunities to tackle these challenges.**

This work studies how the introduction of a cluster of flexible assets – electric water heaters (EWHs) – affects a community energy self-sufficiency and, thus, how it could help to integrate VRE in the network. To pursue this goal, economic and self-consumption benefits have been studied and quantified selecting a well-defined sample of customers, composed by low voltage and medium voltage clients, fed by the grid and locally installed solar photovoltaic power plants. The cluster of EWHs has been controlled by a load-shifting demand response (DR) strategy aiming to increase the self-consumption – and consequently delivering economic savings – while maintaining the end-users' comfort. Finally, to quantify the flexible assets' impacts, it has been developed an energy balance simulation tool to analyse the changes in the demand profiles between the scenarios without and with DR implementation.

Keywords – Microgrid; Demand Response (DR); Variable Renewable Energy (VRE) system integration; Self-consumtpion

1. INTRODUCTION

In the last few years, the decarbonization of the energy sector has led to a significant increase in the renewable power generation capacity worldwide. The majority of the new renewable power plants, in 2015 over 70%, has been solar PV and wind – referred as Variable Renewable Energy (VRE) – and it has been forecasted a similar trend for the coming years. An increased share of VRE brings several advantages to the system, such as reduction of fuel costs and CO_2 emissions, but, where a proper system integration is not performed, it could also lead to significantly increased costs due to the need of infrastructure's improvements. Where highly deployed, VRE can significantly affect the network's and the other power plants' operation. Thus, the electrical grid requires to gain a certain degree of flexibility, therefore the ability to react to variability and uncertainty in the demand-supply balance, to successfully integrate these new technologies.

To enhance the electricity system to face the increased volatility in the supply side, new innovative solutions need to be implemented. Demand side management (DSM) is one of those and it has recently attracted a significant attention from many experts and researchers in the energy field. As reported in [1], DSM is referred to as the "[…] planning, implementation, and monitoring of activities designed to encourage consumers to modify patterns of energy usage, including the timing and level of electricity demand". Demand response (DR) is a type of DSM and, quoting [2], it can be defined as "a change in the consumption pattern of electricity consumers […] in response to a signal […] or due to other incentives or objectives […]". Compared to other solutions that could increase the electrical system flexibility, by adopting DR strategies, it is possible to exploit the flexible potential of several assets already present in the grid, therefore minimizing the need to implement other technologies or operational strategies.

Several studies have been performed to identify the benefits delivered by DR strategies related to the integration of VRE at different levels. The works focusing on communities tend to show complex energy networks with several solutions implemented to face the same challenges, thus leading to a hard understanding of the impact delivered by each single technology. This type of electricity systems are often referred to as microgrids. Specifically, they include locally consumers and prosumers considering their aggregated demand and supply as a single customer from the network perspective. This type of communities usually includes generation systems – such as solar, wind, combined heat and power – , storages and demand response. The aim of the microgrids is to optimize the usage of local energy resources to increase the efficiency of the energy distribution systems.

2. METHODOLOGY

For the scope of this work, it has been defined a microgrid in Portugal with only one type of generation technology – solar PV – and one type of flexible assets – EWHs – controlled by a set DR strategy. To evaluate the impact of the set cluster of flexible assets in the community, it has been adopted a bottom-up approach. The community demand has been considered as the sum of two different independent components: a fixed, non-controllable part and a flexible one, composed by the aggregation of the EWHs that are individually affected by the DR strategy adopted. To quantify the changes induced by the set DR program, it has been developed an energy balance simulation tool on Python. This considers the electricity exchanges among the grid, the locally installed PV panels and the microgrid on a time frame of 15 minutes assuming a perfect knowledge of the community consumption patterns and the power generation form the PV power systems. Due to a shortage of data availability, the analysis focused on four weeks representing the different quarters in the year, thus including the seasonal consumption differences. Then, the results have been properly weighted to obtain the outcomes from an annual perspective.

The developed simulation tool processes a set of inputs related to the economic parameters, the community load curve, the PV systems production and the DR strategy implemented and return the impacts on the network, the electricity cost and the community self-consumption. Just for the last two outcomes a sensitivity analysis is performed varying the number of PV capacity installed and the EWHs units available.

2.1. Economic Parameters

During the energy balance simulation, the whole community has been considered as a single MV customer from the grid perspective. The year 2018 has been selected as the reference for the electricity tariffs and the PV panels related expenses. The power generated from the locally installed PV panels can flow to the community or to the grid; all the surplus electricity injected in the network is paid back to the community through a Feed in Tarif (*FiT*). The FiT_m for each month m is set as the 90% of the average price in the Portuguese electricity spot market in the month ($OMIE_m$). For the scope of this analysis, due to the negligible differences, it has been considered a fixed value for the *FiT* based on the average values reported in [3], [4] of 4 years starting from 2014 included.

All the PV systems' costs, such as installation, operation and maintenance (O&M), are covered by the community. The values have been the result of research conducted on the Portuguese PV market, focusing on ground-mounted power plants with an installed capacity higher than 100 kW. Table 2.1 reports the costs and other related economic factors adopted for the analysis; the inverter replacement and O&M expenses are expressed as a percentage of the installation costs.

Table 2.1. Summary of costs and economic factors related to the PV power systems

Installation Costs [€/kW$_p$]	900
Inverter Replacement Costs	10%
O&M Costs	1.5%
Power Plant lifetime [years]	25
Discount rate (d)	7%
Inverter lifetime [years]	10

2.2. Community Load Curve

The demand load curve is composed of load profiles provided by Energias De Portugal (EDP), Estabanell Energia, relatively a Portuguese and Catalan DSO, and by the flexible assets load. The community considered is composed of 162 Low Voltage (LV) profiles gathered from EDP, a and 5 Medium Voltage (MV) provided by Estabanell Energia, including 1 school and 4 commercial sites.

Due to a complete lack of data related to EWHs consumption profiles, a simplified approach has been adopted to simulate them. All the thermal dynamics that are usually considered in the papers investigating TCLs' DR potential have not been considered in this analysis. To generate the load profiles related to EWHs, the following hypothesis have been taken into account:

1. Domestic Water (DW) consumption coming from the EWHs is only related to hot showers. The electricity required (E_{req}) to recover the heat used has been assumed considering the equation *(2.1)* and the followings:
    a. a total DW consumption (m) of 40 litres per shower, considering an average time per shower of 5 minutes;
    b. a constant power (P_{nom}) required to heat the water equal to 4.2 kW;
    c. a temperature flowing in (T_{in}) of 15 °C and a temperature flowing out (T_{out}) of 60 °C the tank's heater;
    d. a constant specific heat (c_p) for the water of 4.186 J/kg K and
    e. no conversion losses.

$$E_{req} = \frac{c_p \times m \times (T_{out} - T_{in})}{3600} \ [kWh] \tag{2.1}$$

2. Each appliance can provide a maximum of two hot showers per day, one per each half of the day. To determine when DW consumptions occur, for each time frame of 15 minutes it has been assigned a probability to have a hot shower based on a vector described as follows: it presents a morning and an evening peaks that have been assumed relatively at 8 am and 7 pm, then the curve follows a normalized Gaussian distribution around those two setpoint;
3. EWHs are "black boxes" that can only be fully discharged in a one-time frame and charged in two-time frames – no partial charges or discharges are allowed. In order to maintain the water temperature, the charges occur straight after the

water consumption, later also referred to as bus signal.

Finally, the total community demand has been built as the sum of the LV and MV profiles and the load profiles of 50 EWHs when varying the solar PV capacity installed.

2.3. PV System Production

To simulate the energy production of the locally installed PV power systems it has been set the location of the community in Martim Longo, a municipality in the region of Algarve, Portugal. Then, it has been defined a reference ground-mounted PV system of 5 kW to study technical and economic performance. The reference power plant is composed by 20 *Solar World Sunmodule 250* panels, arranged in 2 strings of 10 modules each, paired with an inverter *SunnyBoy 5000TL* from *SMA*. Finally, it has been assumed that all the panels are ground mounted, titled with an angle of 37° and facing south to maximize the energy yielded throughout the year.

The production has been simulated starting from the meteorological parameters gathered from Meteonorm [5] with a 1-minute resolution. To define the effective radiation hitting the surface of the panels it has been adopted the Perez model. Then, to simulate the related production of the system, a single diode equivalent model approach has been considered. Finally, the energy yielded has been clustered in 15 minutes time frames by summing up the minute resolution production. All the distribution losses have been assumed negligible.

2.4. Demand Response Strategy Implemented

The DR strategy adopted in this analysis aims to (1) increase the consumption of electricity locally produced while (2) maintaining the end users comfort. In

it is reported a simple sketch of the logic and the constraints considered for the simulation. The sun surplus, below graphically represented with the sun icons, is calculated for each time frame *i* using the formula *(2.2)*.

$$\begin{cases} \textbf{if } (PV_i - D_i) \geq E_{EWH} \textbf{ then } sun\ surplus_i = int\left[\frac{(PV_i - D_i)}{E_{EWH}}\right] \\ \textbf{else } sun\ surplus_i = 0 \end{cases} \quad (2.2)$$

In the above equation, E_{EWH} is the energy consumed by the water heater to re-heat the tank water in a time frame considering the P_{nom} defined in section 2.2, while the function *int[R]* rounds the real value *R* to the closer minor integer.

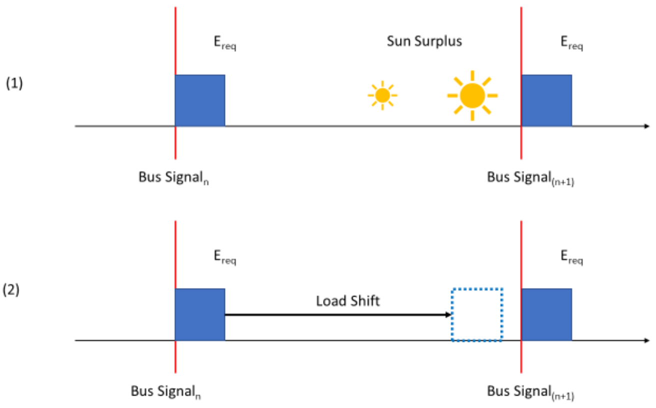

Figure 2.1. Sketch of the logic and the constraints used for DR strategy

Once created the time series of sun surplus for the studied period, for each EWH profile the following logic is adopted:

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identify all the Bus Signal for the selected EWH*
for n to total number of Bus Signal:
        search for sun surplus > 0 between Bus Signal_n and Bus Signal_(n+1) as shown in Figure 2.1(1)
        shift $E_{req}$ in time frame $i$ with max(sun surplus) as shown in Figure 2.1(2)
        update sun surplus time series and consumption for EWH*
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This operation is repeated until the sun surpluses finish or until all the EWH profiles have been checked.

2.5. Impact on the network

DR has the potentiality to positively influenced the grid in two different way: (1) by facilitating the system operations, increasing the local flexibility, and (2) by reducing the network size, due to the possibility to reduce the peak demand. To quantify the impact of the DR strategy implemented on the electrical network it has been analysed a scenario with a fixed amount of PV capacity installed and a fixed number of EWH units.

2.6. Electricity cost

To assess the total electricity cost for the community in the 4 weeks examined, the following equations system *(2.3)* has been used, considering all the 15 minutes time frame *i* for the four weeks analysed.

$$\begin{cases} \textbf{if } D_i > PV_i \textbf{ then } C_i = (D_i - PV_i) \times p_i \\ \textbf{else } C_i = (D_i - PV_i) \times FiT \end{cases} \quad (2.3)$$

In the above, C_i is the cost associated with each time frame, D_i is the energy required from the community in kWh, PV_i is the total energy produced by the systems installed in kWh, p_i the price of electricity delivered by the grid considering the 2018 tariffs for MV clients and *FiT* the feed-in tariff when injecting electricity in the grid, calculated considering the assumption of section 2.1.

PV_i has been calculated accordingly to *(2.4)*, where pv_i is the electricity produced in the time frame *i* by the reference PV power plant described in section 2.3 and *n* is the number of systems installed.

$$PV_i = pv_i \times n \tag{2.4}$$

Finally, the total cost for the community is calculated using the *(2.5)* – 2688 are the total amount of 15-minutes time frames present in the studied four weeks.

$$C_{tot,n} = \sum_{i=1}^{2688} C_i + n \times LC \times 5 \tag{2.5}$$

$C_{tot,n}$ represents the total *Electricity Cost* for the community related to the PV power systems and the provision of the electricity from the grid, excluding the fixed expenses. *LC* is the levelized costs of the PV systems expressed in €/kW/year calculated following the method reported in Section **Error! Reference source not found.**. Finally, it has been evaluated the optimal PV capacity installed with an iteration, varying the number of the PV power systems *n* between 1 to 100, and defining the optimum value as the one that corresponds to the minimum $C_{tot,n}$.

For the purpose of this analysis, all the fixed costs related to the grid connection have been neglected since the introduction of the PV power systems in the community and the implementation of the DR strategy is not affecting the community peak demand. Therefore there is no impact in the comparison of the two cases.

2.7. Self-Consumption

Another important factor to be taken into account while analysing the impact of flexible assets in a community fed by locally installed PV systems is the impact of the DR strategies on the self-consumption. This value is of significant importance, especially in those countries where the surplus electricity produced is poorly paid and therefore corresponds to a loss of the invested money; higher values of self-consumption, in fact, lead to higher values of economic savings. Additionally, a micro-grid that can significantly rely on local energy sources increases the efficiency of the transmission and distribution systems and it reduces the CO_2 emissions when the on-site produced power comes from renewable sources.

The self-consumption has been evaluated considering the *Self-Sufficiency Rate* (*SSR*) and the *Self-Consumption Rate* (*SCR*), already adopted by [6], [7], also referred to as solar fraction or load fraction by other authors [8]. In this work, the self-sufficiency rate is defined as the ratio between the total energy self-consumed ($E_{SC,tot}$) and the total energy consumed by the community (D_{tot}), as shown by the equation *(2.6)*. The self-consumption rate is instead calculated using the *(2.7)* as the ratio between the total energy self-consumed ($E_{SC,tot}$) and the total electricity yielded by the PV systems (PV_{tot}). Finally, the equations in *(2.8)* have been used to calculate the values of $E_{SC,i}$, the energy self-consumed per each time frame *i*.

$$SSR = \frac{E_{SC,tot}}{D_{tot}} = \sum_{i=1}^{2688} \frac{E_{SC,i}}{D_i} \tag{2.6}$$

$$SCR = \frac{E_{SC,tot}}{PV_{tot}} = \sum_{i=1}^{2688} \frac{E_{SC,i}}{PV_i} \tag{2.7}$$

$$\begin{cases} \textbf{if } D_i \geq PV_i \textbf{ then } E_{SC,i} = PV_i \\ \quad\textbf{else } E_{SC,i} = D_i \end{cases} \tag{2.8}$$

3. RESULTS

Before analysing the obtained values of the outcomes described in Chapter 2, some general considerations have to be taken into account. First of all, the share of the EWH profiles' consumption is only the 6.5% compared to the total community. This would already limit the impact that the flexible loads could deliver to the whole system.

Another relevant factor that will affect the outcomes is the distribution of the load profiles of the single components of the community compared with the normalized PV production. The EWH profiles present a trend that follows the probability vector which has been used to define them. As the probability vector, the flexible load profiles reveal two peaks – both for the weekday and the holiday – that occur close to the hours when the PV production starts and ends. From this initial information, it is possible to qualitatively estimate the potential impact of a DR strategy that aims to maximize the self-consumption on the single community's components. The profiles that have already similar trends compared to the normalized PV production will be less affected; oppositely, the ones with significantly different shapes should potentially be more positively altered.

3.1. General impact on the Network

Before looking at the specific outcomes related to the community, it is going to be analysed the effects of the DR strategy on the electricity network. To quantify the impacts, a fixed amount of EWHs and PV power system capacity have been set – respectively 50 units and 460 kW – and then, the community load has been studied for the scenario without and with DR strategy implemented.

The net load is the value that expresses how the electrical network perceives the community at the point of common coupling (PCC). Compared to the community load profile, the net load presents more evident ramp-ups and ramp-downs due to the presence of a significant amount of local PV power capacity.

Table 3.1. Impact of DR strategies on the net and regular Peak Load for the community

	Peak Load [kW]	Net Peak Load [kW]
Scenario with DR	343.64	306.74
Scenario w/o DR	307.15	307.15

The impact of the DR strategy is quantified in Table 3.1. It can be seen that the benefits of the DR strategy on the peak power demand is limited, especially when considering the net load. This result shows that, in this particular case study, the DR strategy adopted has no influence on the network design since the latter has to be sized to handle the highest expected load demand. This is partly due to the fact that reducing the peak demand is not in the aims of the control strategy adopted. Moreover, as reported in [9], the highest impact on the peak reduction has to be expected from other types of sources such as the traditional curtailment of big customers in the industrial or commercial sectors.

3.2. Impact in the Community varying PV capacity

The first tangible impact that can be measured while considering the implementation of a new technological solution is the economic benefit. The evolution of the electricity cost paid by the community has been studied varying the amount of the PV capacity installed for the two scenarios, without and with DR strategy. After a specific setpoint – 350 kW of PV capacity installed – the average distance between the electricity cost of the scenarios with and without DR strategy remains constant. This value – 137.57 €/year – can be considered as an indicator of the flexible loads' cluster's economic benefit.

Table 3.2. Comparison of Electricity Cost and Optimal PV Capacity in the scenarios with and without DR strategy implemented

	Electricity Costs [€/year]	Optimal PV Capacity [kW$_p$]
Scenario w/o DR	7 888	460
Scenario with DR	7 763	465
Δ [%]	- 1.58	+ 1.09

Table 3.2 reports the comparison between the values obtained for the scenarios without and with DR strategy implemented. It is possible to observe that the impact of the DR strategy on the costs and on the optimal PV capacity to be installed is irrelevant. The two outcomes' delta (*Δ*) has been calculated with the formula *(3.1)*.

$$\Delta = \frac{Outcome_{with\ DR} - Outcome_{without\ DR}}{Outcome_{without\ DR}} \qquad (3.1)$$

Figure 3.1 (a) shows the evolution of the SSR varying the PV Capacity installed while the graph (b) the one related to the SCR. In both (a) and (b) the blue line is associated with the scenario without DR while the dashed orange curve with the DR strategy implemented. The effect of the DR implementation starts to be significant after a certain threshold for both graphs as it was the case for the cost.

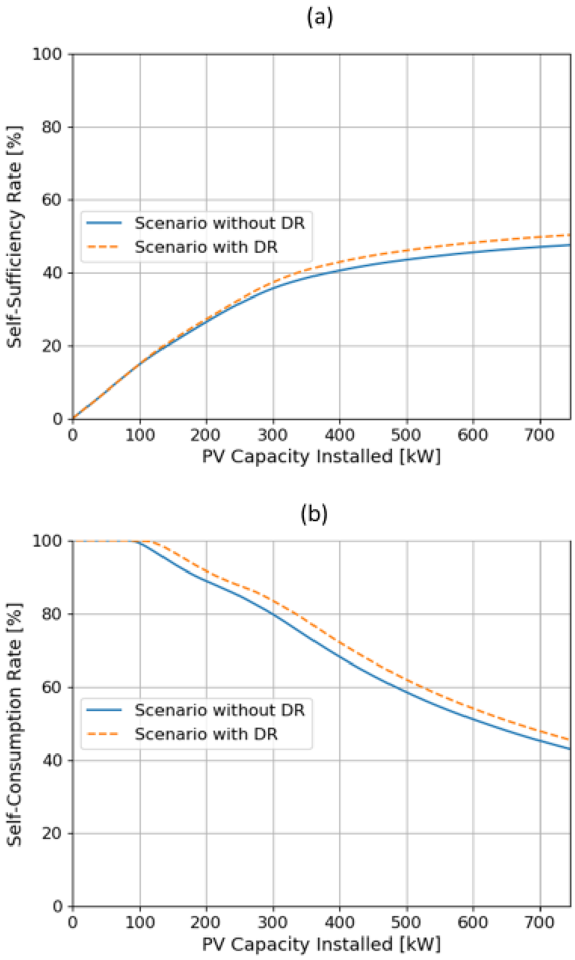

Figure 3.1. Evolution of the Self-Sufficiency Rate (a) and the Self-Consumption Rate (b) varying the PV capacity installed

For the SSR, the setpoint is around 350 kW of PV capacity installed as it was for the electricity cost; this correlation is due to the fact that the community savings are directly correlated to the amount of consumed electricity coming from the locally installed power systems. Regarding the SCR, the threshold is around 150 kW; from this point, the extra electricity produced by the PV power systems that are added each iteration becomes higher than the electricity consumption shifts due to the EWHs' flexibility and therefore the dashed orange line decrease with a similar trend as the blue curve.

Table 3.3 reports the values at the optimum for the scenario without DR implemented and the average difference between the two curves from a fixed setpoint: for the SSR from PV capacity 350 kW while for SCR from 150 kW.

Table 3.3. Comparison of Self-Sufficiency Rate and Self-Consumption Rate in the scenarios with and without DR strategy implemented

	Self-Sufficiency Rate [%]	Self-Consumption Rate [%]
Scenario w/o DR	42.47	62.10
Scenario with DR	44.97	65.75
Average Difference	+ 2.57	+ 3.26

As from the previous outcomes, even in this case, the impact of the DR strategy is not significant considering the effects on the overall community.

3.3. Impact in the Community varying the number of Electric Water Heaters

The same outcomes, fixing the number of PV Capacity Installed as the economic optimal for the Scenario without DR reported in Table 3.2 – 460 kW, can be evaluated varying the number of EWHs instead of the local renewable power capacity.

By growing the number of flexible assets, the energy balance simulation developed has reported an increase in the electricity cost for both scenarios due to the increased electricity consumption. With the highest diffusion of EWHs, the impact of the DR strategy is more significant due to the increased share of the flexible load in the community. In the scenario with 200 flexible units the electricity cost drops by -4.67% in the scenario with the DR strategy.

Similar to the electricity cost evolution, the difference between the two scenarios is directly related to the increasing number of the EWHs, reflecting the increased share of the flexible load in the total community consumption. The increases registered with the DR strategy in the self-sufficiency rate and in the self-consumption rate are relatively +7.25% and +12.67% in the scenarios with 200 units installed.

3.4. Impacts considering the Electric Water Heater only

To have a better understanding of the effects of the DR strategy adopted during this work, it has been also analysed its impact related only to the cluster of the flexible loads. Every comment about the impact on the electricity cost has been avoided because of the significant difference between the PV power system yearly costs and the consumption cost of this specific single component. For this reason, the focus has only be set on the SSR regarding the impact on the self-consumption; the PV production derived from the power systems sized to feed the whole community is remarkably higher than the consumption of the EWHs, therefore any changes would be barely noticeable looking at the SCR.

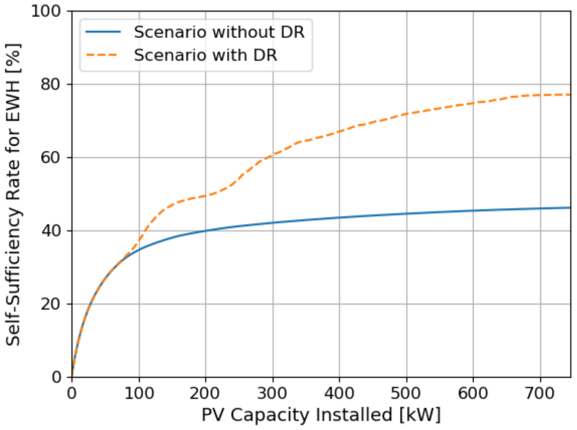

Figure 3.2. Self-Sufficiency Rate evolution for the EWH profiles varying the PV capacity installed

The average difference between the two scenarios shown in Figure 3.2 is more than 10 times higher compared with the Community scenario; the average gap after the 350 kW threshold is, in fact, + 27.65 % against + 2.57%.

4. CONCLUSION

This thesis assessed the benefits of introducing a cluster of flexible assets in a specific microgrid use case: a Portuguese community equipped with a relevant capacity of solar PV and composed by LV and MV profiles. To quantify the impacts of the behind-the-meter flexibility, a DR strategy was developed and implemented. The load control logic aims to shift the electric water heaters' consumption under growing PV penetration toward periods of local overproduction to increase the self-sufficiency of the community. The results of the DR strategy were presented and discussed to gain insights into the possible future impacts of flexible loads in a context of high RVE penetration scenario. Specifically, it has been analysed the improvements related to the network connection capacity, the community's self-consumption and the related economic savings.

The specific use case analysed has highlighted that the DR strategy adopted delivered positive benefits to the community, though not significantly. The model developed reported the following variation between the scenarios with and without DR implementation: -0.13% related to the net peak load, +2.50% and +3.65% respectively for self-sufficiency and self-consumption rates and a -1.58% in the yearly electricity cost. The irrelevant simulated impact on the net peak load, thus on the network connection capacity, is due to the fact that the DR strategy implemented aims only at increasing the self-consumption without any other specific purposes. Among the three indicators analysed – electricity cost, self-sufficiency rate and self-consumption rate – the one that varies the most is the self-consumption rate, representing the share of electricity consumed on-site compared to the total production deriving from the PV systems. By increasing the relative share of flexible loads, however, it is possible to obtain more relevant impacts. When the flexible load consumption share is around 20%, it has been estimated a self-sufficiency rate above 45% and a self-consumption rate of about 79% with an increase of over 7% and 12% relatively compared with the scenario without DR strategy implemented. The DR program's effect becomes even more evident when analysing its impact on the flexible assets individually: in this case, the self-sufficiency rate increase by +25.77% while adopting the load control strategy.

From the obtained results, it is possible to state that DSM cannot provide alone the required flexibility to face the increasing supply volatility driven by the growing deployment of VRE. This corroborates the findings reported in the literature. DSM will, however, play an important role in the electricity system transformation; the increasing number of available flexible assets due the electrification of the transportation and the heating sectors combined with the reducing costs of advanced control and monitoring technologies are offering a new innovative way to transform the traditional consumers into active prosumers.

4.1. Future work

Similar works could be performed by substituting or integrating in the microgrid other types of flexible assets controlled by the same DR strategy proposed in this thesis. Such appliances could be EV charging stations, washing machines or dish washers. Similarly to the EWHs' cluster, they could be studied with the simple methodology adopted in this work.

To improve the results of the work developed on the EWHs' flexibility, the probability vector adopted in this thesis could be updated assigning the values looking at a real database of water consumption related to the analysed community. If a continuous data flow could be provided, machine learning algorithms could be adopted to maintain the DW consumption behaviours up to date. At this point, to simulate the EWH performance it could be developed a physical model that could take into account (1) the water usages – in terms of energy – during the day, (2) the thermal losses due the temperature difference between the water in the tank and the ambient temperature and (3) the energy gains due the thermal resistance of the EWH. The constraints of such a model would be then based on the water temperature in the tank to (1) maintain the water temperature above a certain minimum in order not to impact on the comfort of the end users and to assure the elimination of the legionella bacteria and (2) not to surpass the maximum temperature allowed by the component material of the tank. This more realistic model should lead to an increased electrical consumption for the EWH and asset's flexibility, thus the DR impacts should become more evident.

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