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Demand Response for Integrating Photovoltaic Plants in Lampedusa Island

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Abstract— **This paper presents the results of a simulation study concerning different Demand Response logics applied to Electric Storage Water Heaters on the island of Lampedusa. Electric Storage Water Heaters are the devices that are primarily used on the island to produce domestic hot water. Starting from measured load profiles collected in Lampedusa, a domestic hot water consumption profile was derived, to simulate the energy usage of the Storage Water Electric Heaters during the day. This work was carried out as a preliminary feasibility study for the BloRin project, financed by cohesion funds in the Sicilian region. According to the project, which also includes the installation of domestic photovoltaic systems on the island, two development scenarios have been formulated. The results show that even a limited penetration of photovoltaic power in the energy system of Lampedusa can lead to steep load ramps and risk of power inversion in distribution substations. To overcome these problems, several Demand Response programs have been considered. By setting a higher value of the desired water temperature of the Storage Water Electric Heaters, in the hours of maximum photovoltaic generation, thermal loads can be shifted towards central hours of the day, with clear benefits in terms of power inversion containment and peak reduction.**

Keywords—small islands, flexible loads, micro-grids, aggregation, demand response.

I. INTRODUCTION

In the last years, Demand Side Management (DSM) has become a popular topic in Italy, particularly referred to prosumers, i.e. energy consumers who are also producers. This trend started thanks to experimentations encouraged by the Authority ARERA, which achieved interesting results [1], [2]. In these experimental projects, the aggregator is allowed to provide ancillary services to the power grid or to participate in Balancing Service Market (BSM) by aggregating users that are part of the power grid. Also, important Italian companies, such as Enel X, stepped into this new market taking the role of aggregator and collecting flexibility. The ultimate user of these services is the Transmission System Operator (TSO) [3], through Demand Respond (DR) programs.

DR represents an efficient solution to cope with power fluctuations due to the penetration of distributed and unpredictable generation in the electrical system. DR is a structured program of actions that can be performed by the final user/prosumer (industrial, commercial or residential) to modify the electric load diagram (lowering it, increasing it, or shifting it along time) in response to balancing problems occurring in the network, such as network congestion, temporary unavailability of power caused by failures or intermittent production from non-programmable RES, or in response to the dynamics of wholesale electricity prices [4]. To implement a DR logic, the first step is to identify the most suitable kind of loads to achieve this target. In the DSM field, thermal electrical load, such as Electric Storage Water Heaters (ESWH), Heat Pumps (HP), refrigerators, and Air-Conditioning (AC), play a key role. This is due to their thermal inertia time constants, which allow to temporary switch off the devices or to modulate their electrical consumption during some periods, without seriously affecting end-users' comfort. Furthermore, according to the International Standard EN 15232 [5], heating, air-conditioning, and ventilation systems are among those that can be equipped with sensors, actuators, and controllers that enable to switch ON/OFF these systems or to adjust their energy consumption to a specific percentage, corresponding to Buildings Automation and Control System (BACS) efficiency class of the automation system.

In North America, DSM is already a well-established option for either domestic or commercial end-users. Distribution grid operators and energy retailers offer DR programs to their customers, to obtain services such as peak shaving [4]. In many Midwestern states, such as Illinois, Ohio, and Texas, it is possible to subscribe a DR service contract, which includes the amount of flexible capacity available and the remuneration mechanism [6]; to date, thousands are the customers involved, mostly ESWH users. Also in Minnesota and North Dakota, DR was implemented since the eighties by Great River Energy (GRE), the major Utility in these states. It controls ESWHs to set load shifting programs for obtaining peak shaving during high peak periods [7]. Currently, more than 110,000 ESWHs are involved in DR programs supported by GRE. Hawaii is another example in this context; in this case, DSM is used to better manage the penetration of photovoltaic (PV) and wind energy on the islands. Thus, Hawaiian Electric Company manages ESWHs to implement regulation services to compensate for generation fluctuation of PV and wind plants [8].

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In Europe, DR is still a step behind with respect to the United States, however, the interest in DSM is now growing and all European countries are working to develop this field. The United Kingdom was the first European country to open several slots of its electricity market to consumers' participation. In particular, the whole balancing market in the UK is open to DR independent aggregators and there is also a dedicated program called Demand-Side Balancing Service. However, some barriers are still present, mostly for single domestic end-users; even if the presence of the aggregator is not mandatory, the conditions to participate in DR programs are often prohibitive for single domestic end-users [9] [10]. An important aggregator in the UK is Direct. - Energy, which is specialized in DR programs focused on ensuring financial savings to customers; this is accomplished thanks to load shedding logics that involve more than 1,500 ESWHs and aerothermal heating devices [11]. In Germany, many regulatory barriers remain, which prevent DR growth; the market is theoretically open to everyone, but with some heavy requirements which exclude domestic end-users [9]. Furthermore, there is a lack of clarity regarding the role and duties of every actor and how they can participate do DR programs and balancing market [10]. On the other hand, France is the most promising country, together with Italy. In France, in 2014, with the creation of NEBEF (in French, Notification d'Echanges de Blocs d'Effacement) mechanism, DR resources were allowed to be explicitly traded on the wholesale electricity market [10] [12]. The aggregator and single consumers are allowed to directly participate in the market if they have a minimum flexible capacity of 100 kW. According to the French TSO, under the NEBEF mechanism, the total DR traded volume reached 11 GWh in 2016, 27 GWh in 2018, and 22.2 GWh in 2019.

In the last decade, Italian small islands have become a valuable experimental test site to assess the potential of DR programs. To date, small Italian islands, not connected to the transmission power grid, have a supply system based on Diesel power plants [13]. This supply system is no longer sustainable and affordable because it implies a huge cost of production and a heavy environmental impact [14]. Hence, in 2017, with the law *Decreto Ministeriale 14 Febbraio 2017* [13], the Italian government established some measures that should accompany the transformation of the energy system of the small islands, thanks to the penetration of photovoltaic energy. As a result, in a few years, these islands could face the same situation as Hawaii or California [8], [15], with a high percentage of energy produced by non-programmable energy sources. In this scenario, DSM can be a valuable tool to balance the non-predictable quota of photovoltaic energy. In this context, small islands are the topic of many studies, which try to understand the possible impact of DR logics and load control on their power grid [16-20]. In [21], the authors focused on the consequences of changing all ESWHs in Lampedusa with more efficient Heat Pumps, HPs. HPs require less energy than ESWHs; hence, results show that DR logics are less effective when HPs are used, due to the smaller quantity of flexible power available.

The study presented in this work was carried out as a preliminary feasibility study for the BloRin project [22]. BloRin aims to develop a blockchain platform able to facilitate interactions between producers/consumers in the island of Lampedusa to manage domestic electric device consumption and coordinate exchanges with the electricity distributor in a decentralized, secure and transparent way, to mitigate potential problems on the grid due to renewable penetration. The blockchain platform used will be Hyperledger Fabric [23], which enables the implementation of Smart Contracts (SC) for the automatic execution of transactions following the occurrence of specific conditions or requests. SCs in Hyperledger Fabric also allow the implementation of transaction logics. In the context of the BloRin project they will be used to implement DR event logic. Thanks to SCs, the load reduction request from the electricity distributor will be automatically split to the users who decide to be part of the BloRin network. Subsequently, each user's load management system, reading from the blockchain the assigned reduction, will move certain loads over time in order to satisfy the system operator's request automatically.

In the present paper, using the same methodology reported in [21], simulations are carried out considering a single MV/LV substation of the Lampedusa power grid. This work aims to evaluate the benefits of a set of DR logics on a residential substation, which has a certain amount of PV power connected downstream. In particular, simulations are focused on demand-side strategies which can mitigate issues such as steep evening load ramp (Duck Curve) and reversal of power flows, which are linked to a high penetration of non-programmable Renewable Energy Sources, RES [4], [15]. The proposed DR logics will then be implemented through a specific SC on the BloRin platform.

This paper is structured as follows: Section 2 reports the methodology and all the underlying assumptions for the proposed scenarios, Section 3 summarizes the most relevant results and Section 4 reports the conclusions of the study.

II. METHODOLOGY

The methodology adopted in this paper follows the one developed in [21]. First of all, in the measurements campaign carried out by ENEA in 2016 [23], the daily load profile of a domestic end-user and its ESWH were acquired (Fig.2). As it can be seen, both curves have the same shape and peaks position, hence this suggests that ESWH consumption highly influences the overall domestic profile. Load profiles change with season and day of the week, hence measures were collected during a weekday of July, which is the month with the highest electrical consumption in Lampedusa. Once the load profile of an ESWH is known, starting from the results obtained in [21], a probabilistic Domestic Hot Water (DHW) consumption profile of a typical end-user was obtained, using an empirical method.

Fig.1 shows the extracted DHW consumption profile; Fig.2 shows the load profile of a simulated ESWH, compared with the real measured load profile. The thermodynamic model of heat exchange of an EWSH was derived from [25], [26], assuming a constant efficiency rate, to simplify the model. ESWH load profile was simulated using a Monte Carlo approach, as it was already done in [21], starting from the DHW consumption profile.

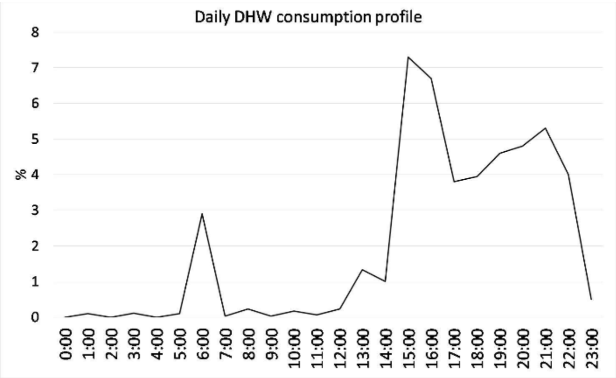

Fig. 1. Daily DWH consumption profile obtained with an empirical method.

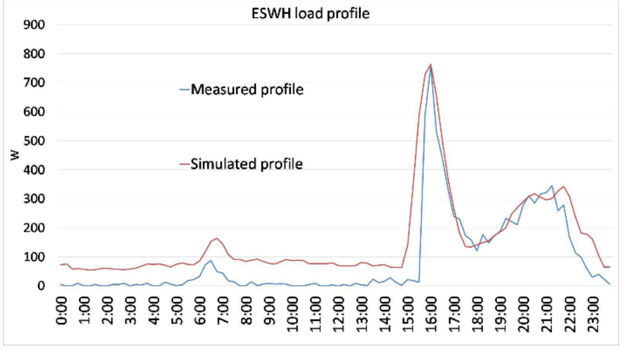

Fig. 2. ESWH load profile, derived through simulations, confronted with the measured one. ENEA data elaboration.

From Fig.2 it can be seen that the simulated ESWH load profile, obtained using the DHW consumption profile in Fig.1, is almost the same as the real measured one. The main differences, more evident in the hour characterized by lower consumption values, are due to the estimation of the stand-by power of the device. This evidence confirms that the found DHW consumption profile can be considered valid for the study. Hence, the DHW consumption profile was used to simulate ESWH under different load control strategies. Technical characteristics of ESWH used for simulation are shown in TAB. 1.

TABLE I. ESWH TECHNICAL DATA.

ESWH technical data	
Rated Power [W]	1200
Volume [l]	80
Efficiency	0.95
Water max Temperature [°C]	80

Fig.3 shows the load profile of an aggregate of 34 domestic end-users; this profile was measured in July in an MV/LV substation in Lampedusa, equipped with a 100 kVA transformer. From ENEA experimental campaign [23] emerged that in the island DHW is mostly obtained with ESWH; so, in this study, it is assumed that all 34 end-users have an ESWH installed and the profile in Fig.3 is set as Base Scenario.

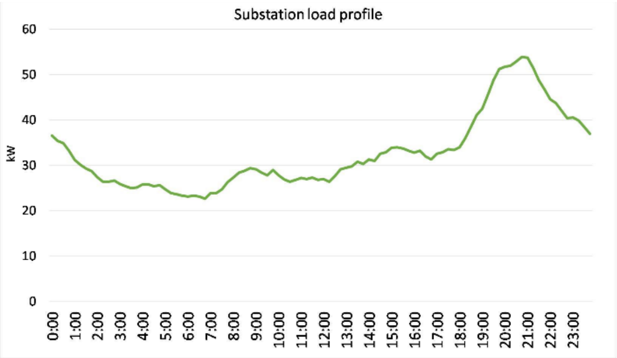

Fig. 3. Substation load profile measured in Lampedusa in July adopted as Base Scenario. ENEA data elaboration.

When the load profile showed in Fig.3 was measured (in 2016), Lampedusa produced almost all its energy demand with a diesel power plant, which consists of 8 diesel generators whose total rated power is 22.2 MW [27]. Such generation system is almost unchanged, although concerning PV installed generation, in 2020 there was around 142 kWp on the island [14]. The next step of the analysis regards the deployment of PV plants on the island. Two scenarios of short-term PV evolution are defined. These scenarios were developed based on the experimental project BloRin [22], active to date in the island of Lampedusa. Within this project will be installed by the end of 2022 between 75 and 115 kWp of residential photovoltaic systems distributed downstream of four MV/LV substations supplying residential end-users. Hence, these two scenarios are formulated as follows:

1. Scenario 1: it is assumed that 75 kWp of PV will be installed, so that each MV/LV substation has an increase of 19 kWp of connected PV power over the Base Scenario.
2. Scenario 2: it is assumed that 115 kWp of PV will be installed, so that each residential substation has an increase of 29 kWp of connected PV power over the Base Scenario.

This new PV production will affect the load profiles of the substations, revealing possible issues, such as the appearance of steep load ramps (Duck Curve) and the risk of reversal power flows. Based on these new profiles, shaped by PV generation, in the next section the load control logics required to address potential issues are described and simulated.

III. DEMAND RESPONSE LOGICS

As shown in Fig. 4, with 19kWp of PV power, the load profile of the considered substation takes the classic "Duck Curve" shape, with a steep load ramp. Considering 29 kWp of PV power, the Duck Curve is more pronounced and most importantly, a serious reverse power flow risk emerges. With just 29 kWp of installed PV, the substation load profile assumes a value very close to zero during mid-day hours; so, it is truly probable that, with a slight increment of residential PV, reverse power flow occurs.

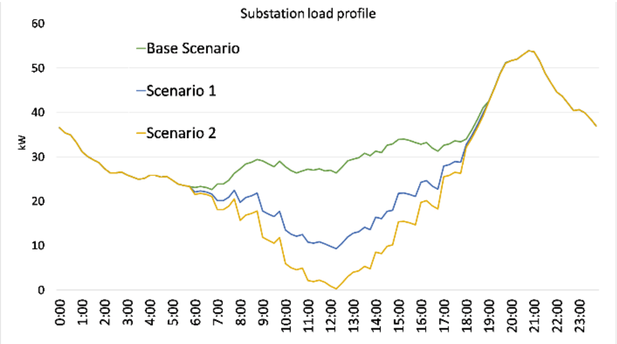

Fig. 4. Substation load profile shaped by PV generation.

To mitigate the effects of PV energy, several control logics are presented; these logics are then imposed into the ESWH simulation model, which is based on a Monte Carlo method with the DHW consumption profile showed in Fig.1. The following load management logics are applied only to Scenario 2, as it is the worst case. ESWH control logics are executed through the following DR events:

1. DR_1: all ESWHs are controlled to set the desired temperature to 80 °C instead of 65 °C, in the time between 11 am and 6 pm. The aim is to store the PV energy as thermal energy through ESWH.
2. DR_2: same logic as DR_1, but with only 50% of ESWH involved, in the period between 11:00 and 17:30.
3. DR_3: ESWHs are controlled to switch off 50% of the devices after 6 pm. The aim is to use ESWH during the central hours of the day.
4. DR_4: 35% of ESWHs are controlled to set the desired temperature at 80 °C instead of 65 °C, in the period between 10 am and 2 pm, while 30% of ESWHs are controlled in the period between 3 pm and 5 pm. During the rest of the day, the desired temperature is set at 40 °C, to still guarantee comfort for end-users.
5. DR_5: same logic as DR_4, but with 50% of ESWHs controlled in the period between 10 am and 6:30 pm.

The described DR events will be executed through a specifically-developed SC on the BloRin platform. Being a platform for decentralized RES management, following the recording on the blockchain of both users' consumption and PV production, the local distributor will be able to send DR signals in a fully distributed and transparent way. Following participation in the DR event, the user will be remunerated through energy tokens that can be turned into other energy services or as a reduction in the electricity bill. In this way, both the end-user and the distributor get a benefit.

IV. RESULTS

The control logic presented in Section III was applied to the Monte Carlo simulation model of the ESWH, together with the DHW consumption profile showed in Section II.

Fig.5 illustrates how the ESWH load profile changes with the different DR scenarios. As it can be noted, ESWH consumption is shifted towards central hours of the day, as it was expected, when DR_1, 2, 4, and 5 are executed; instead with DR_3, there is no evident adjustment. Despite the implemented control logics, a relevant load remains during the mid-afternoon; this is due to the DHW consumption peak in those hours. These new ESWH load curves were referred to as the aggregate of end-users connected to the substation under study. Fig.6 shows how the substation load profile is modified in the different DR scenarios, with respect to Scenario 2, where only PV generation is considered. DR_3 logic does not significantly impact the substation load curve, which in this scenario remains almost the same. This result can be explained by looking at Fig.5, where it is clear that, when control scenario DR_3 is applied to the single ESWH, its load profile remains almost the same as the one obtained in no control scenario. With DR_1 logic, the purpose of shifting load during the period of maximum PV generation is achieved, but the curve shape is not desirable due to the steep ramps that are present. DR_2, DR_4, and DR_5 are the scenarios that give the most promising results. As it can be seen, the reverse power flow problem is avoided in these scenarios, while the profile shape is improved and the maximum peak is reduced. In the following TAB.2, the shape factor, defined as the ratio between the average power and the maximum power of the load profile, in different scenarios and peak reduction with respect to the Base scenario is presented.

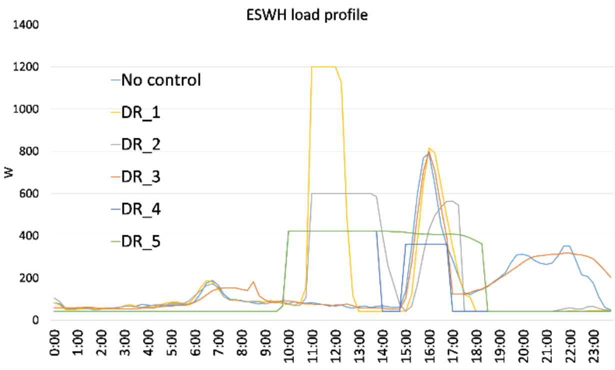

Fig. 5. ESWH load profiles under different control logics, compared with the no control scenario.

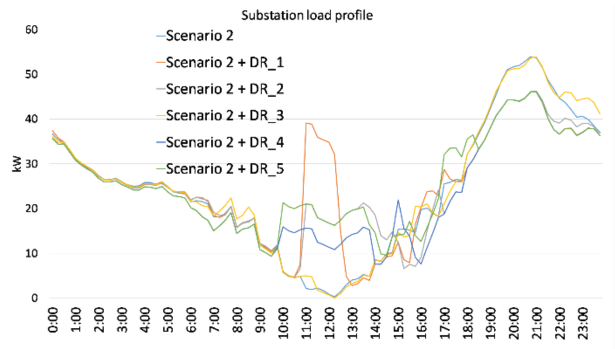

Fig. 6. Substation load profiles under different ESWH control logic scenarios, compared with BloRin 115 scenario. Our data elaboration.

TABLE II. SHAPE FACTORS AND PEAK REDUCTIONS IN THE ANALYZED DEMAND RESPONSE SCENARIOS.

Scenario	**Shape Factor**	**Peak Reduction [%]**
Scenario 2	0.45	0
Scenario 2 + DR_1	0.55	14.54
Scenario 2 + DR_2	0.54	14.16
Scenario 2 + DR_3	0.46	0.06
Scenario 2 + DR_4	0.52	14.54
Scenario 2 + DR_5	0.56	14.54

When control scenarios DR_1, 2, 4, 5 are applied to ESWH, the substation load profile has a peak reduction of nearly 14%; otherwise, Scenario 2 + DR_3 presents a minimal peak reduction, for the same reason explained above. Regarding the Shape Factor, Scenario 2 + DR_5 has the best value, followed by scenarios DR_1 and DR_2. Also, in this case, scenario DR_3 brings a negligible improvement to the load profile Shape Factor.

V. CONCLUSIONS

In this work, DR logics were analyzed as a solution to the penetration of unpredictable RES energy in the Mediterranean island of Lampedusa. The DR logic are to be integrated in the BloRin project, which aims at the creation of a blockchain platform for the optimal management of energy produced from RES, also through the management of DR events, by usign SCs. Simulations were performed considering load profiles of a generic substation. First of all, a Base Scenario was defined, based on a measurement campaign; then, a method to simulate the ESWH consumption profile was described. After that, PV penetration scenarios were formulated and applied to substation load profile, showing that some relevant issues arise from using just a small amount of PV power. In particular, simulations pointed that with 29 kWp of PV installed power, substation load profile presents a danger of reversal power flow and steep load ramp (emerging of a Duck Curve). Starting from these results, five DR scenarios were implemented in order to control the ESWH. Control logic aims to shift ESWH load in those hours of the day when PV generation is the highest. By adjusting the desired water temperature in the central period of the day, and involving different quotas of ESWH in the DR event, the single end-user ESWH load profile appreciably changes. This phenomenon then affects the aggregate load profile downstream the substation, which is also modified by control logics applied to ESWH.

When the desired temperature is set at 80 °C instead of 65 °C, in 50% of ESWHs (DR_2), the substation load profile has a strong improvement: the reversal power flow issue is avoided and the load peak is reduced. Also when the desired temperature is set to 80 °C instead of 65 °C during central hours of the day, while it is set at 40 °C in the rest of the day (DR_4 and 5), results show evident benefits. Simulations in this work prove that a control strategy applied to thermal loads such as ESWH could be an effective way to avoid issues linked to high PV generation, without compromising end-users comfort.

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