A Simulation Study for Assessing the Minimum Number of V2G Recharge Points in Favignana

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***Abstract*—Issues related to the stability of non-interconnected grids are of high relevance given the increasing presence of renewable sources in the power generation system. In order to ensure adequate levels of system's reliability, it is necessary to find new methods to ensure the stability of the electric grid. The present work proposes a methodology for the definition of the minimum number of Vehicle-to-Grid (V2G) charging points that would allow the integration of 1 MW of photovoltaic power in the power grid of the Italian island of Favignana, electrically disconnected from the continental grid. Primary frequency regulation simulations are carried out in Matlab/Simulink environment for different scenarios related to the generation park. The results show that with a limited number of V2G points levels of stability of the electrical system comparable to those before the installation of the photovoltaic plants can be ensured.**

***Index Terms*—non-interconnected grids, vehicle to grid, primary frequency regulation, renewable integration.**

I. INTRODUCTION

The great penetration of static converters-based energy sources in electrical power systems causes many issues related to grid stability and power flow management [1], [2]. The entity of these problems, although important in interconnected continental networks, is even greater when it comes to weak or isolated networks such as those of small islands. Italy is a country with many small islands disconnected from the national electric power system; in order to ensure in these islands an energy transition in line with national and European trends, it is necessary to look for innovative solutions for the integration of renewable sources in weak systems to keep their reliability at adequate levels. While the number of solar installations is increasing worldwide, the number of electric vehicles (EVs) is also growing rapidly. In 2020, approximately 3 million new EVs were registered worldwide, with 1.4 million EVs registrations in Europe, followed by China with 1.3 million EVs new registrations and the United States with 330 thousand new EVs registrations [3]. These numbers are expected to increase in the near future and the same applies to the Italian market (Fig. 1). During 2020, 59,875 electric cars were registered in Italy (+251% compared to the previous year), of which:

- 32.5k Battery Electric Vehicles, +203% compared to 2019;
- 27.4k Plugin Hybrid Electric Vehicles, +334% compared to 2019.

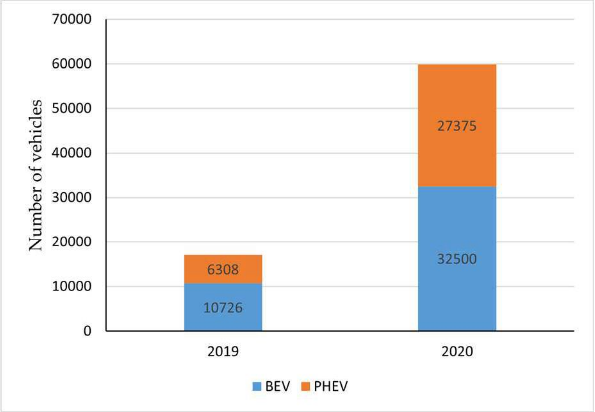

Fig. 1: EVs registrations in Italy, 2019 and 2020.

In this context, it is possible to use electric vehicles not only for mobility but also for the provision of network services according to the concept of Vehicle-Grid Integration (VGI) [4] [5]. The EV therefore becomes an exploitable resource for the above-mentioned purposes in two different modes:

1) ”Smart charging” (V1G), which involves the provision of network services exclusively through monodirectional flows of energy (from the network to the vehicle), appropriately modulated in time;
2) ”Vehicle-to-grid” (V2G), where the provision of grid services is achieved through the management of bidirectional flows of energy between the grid and the vehicle.

Through VGI, EVs can provide solutions to the power fluctuation of intermittent and variable solar systems, they can solve network congestion problems and they could play an important role in reducing the need for investments for the infrastructure of the future grids. Along with this, EVs can reduce the overall cost of the electricity by participating in the local load leveling, peak shaving, or valley filling operations and by offering primary regulation services.

The purpose of this paper is to determine the impact of V2G charging points in regulating Favignana's electrical system after the installation of a significant amount of PV. The final aim of the paper is to determine the minimum number of charging points which provide primary frequency regulation to ensure the same frequency deviations in the event of a disturbance as in the absence of photovoltaic (PV) plants. The study is done by applying a simulation approach in Matlab/Simulink environment for studying the dynamic of the isolated power system in the presence of 1 MW of PV installations and with the contribution of V2G EVs to the frequency regulation.

II. METHODOLOGY

The applied methodology consists of the simulation of the electrical system of Favignana through a dynamic grid model developed in Matlab/Simulink. The grid is simulated using the classical linearized single area model for load frequency control [6] with the inclusion of the blocks representing the fast frequency regulation provided by the V2G recharge points. Given the power of the generators, their dynamic characteristics and the load demand, the model provides as output the frequency variation resulting from a power disturbance. For a complete analysis of the grid in different load and generation conditions, several scenarios were simulated according to the following steps:

1) collection of total electric load data in summer and winter days;
2) evaluation of PV generation using the online software PV-GIS; [7];
3) calculation of the hourly electrical inertia of the system using the formula provided by ENTSO-E and described below. The inertia is needed to calculate the time constants of the dynamic model;
4) identification of the time at which the inertia value is lowest, both on summer and winter days. In these hours (critical timeframes) the most severe conditions for grid stability occur;
5) a scenario with only synchronous generation is considered: through the application of the dynamic model introduced above, the magnitude of the disturbance causing a steady-state frequency deviation according to ENTSO-E requirements for full activation of the primary control reserves [8] is evaluated. This step is performed for both winter and summer days;
6) once the power disturbances in the critical time slots are set, dynamic simulations are again performed considering the introduction of PV generation;
7) a certain installed power of the V2G charging columns is assumed, i.e., allowing both charging and discharging of vehicle batteries;
8) the dynamic model in Simulink is modified, adding a closed loop that simulates the contribution of the charging columns to the Fast Frequency Regulation (FFR);
9) the dynamic simulations are repeated with the same power disturbances assemed at point 5), but considering the contribution of V2G charging points;
10) the results are analysed and discussed.

The electrical inertia of the system is estimated hour by hour by applying the following equation provided by the ENTSO-E [9]:

$$H_h = \sum_{i=1}^{n} \frac{H_{sync,i} \cdot A_{n\,sync,i,h} + H_{PV,i} \cdot A_{PV,i,h}}{P_{l,h}} \quad (1)$$

Where the index *h* indicates the hour considered, the index *i* indicates the *i-th* synchronous machine or the *i-th* inverter, and the index *n* indicates the total number of generators. While:

- H_h is the overall system inertia at the hour *h* [s];
- $H_{sync,i}$ is the inertia of the *i-th* synchronous generator [s];
- $H_{PV,i}$ is the inertia of the *i-th* inverter of a PV generator [s];
- $A_{n\,sync,i,h}$ is the complex power supplied by the *i-th* synchronous machine during the the hour *h* [MVA];
- $A_{PV,i,h}$ is the complex power supplied by the *i-th* PV inverter during the hour *h* [MVA];
- P_{l_h} is the load demand in the hour *h* [MW].

Since inverter-based resources have no rotating parts, the value of $H_{PV,i}$ is zero [10], so equation 1 becomes:

$$H_h = \sum_{i=1}^{n} \frac{H_{sync,i} \cdot A_{n\,sync,i,h}}{P_{l,h}} \quad (2)$$

Equation 2 shows how the inclusion of zero-inertia generators such as PV generators leads to a lowering of the overall inertia of the system with a deterioration of the stability conditions of the power grid. The main assumption of the proposed method is to provide dispatch priority to solar-generated energy and to employ rotating generators only to feed the part of the load not covered by PV. To this end, the most severe conditions from the inertia point of view are considered, with the goal of restoring stability levels to the previous ones before the inclusion of PV through the use of V2G charging points. The following equation allows the calculation of the power to be supplied to the load by synchronous generators in the presence of PV generation:

$$P_{n\,sync,h} = P_{l,h} - P_{PV,h} \quad (3)$$

where:

- $P_{n\,sync,i,h}$ is the active power supplied by synchronous generators at the hour *h* [MW];
- $P_{l,h}$ is the load demand at the hour *h* [MW];
- $P_{PV,h}$ is the active power of the PV generators obtained as output of the PVGIS simulations [MW].

III. CASE STUDY

In this section the method described above is applied to the case study of the island of Favignana. The island is located at 7 km from the western coast of Sicily and it is not connected to the national power grid. Loads on the island are fed through a distribution grid with a rated voltage of 10 kV managed by a local DSO, Societa` Elettrica di Favignana (SEA) [11]. The power plant consists of 7 diesel generators with power ranging from 1290 kVA to 1800 kVA for a total rated power of about 10 MVA. To date, generation from renewable sources does not have a significant impact on the system in terms of installed capacity, however the renewable production is supposed to increase in the next future as defined by the targets of the Ministerial Decree published on February 14, 2017 (Minor Islands Decree) [12]. In this study, it is assumed that 1 MW of PV production will be installed on the island: the target of the simulations is to predict the behavior of the electrical system of the island in terms of stability after the installation of the PV plant, to verify the new frequency parameters after a disturbance and to evaluate the amount of V2G charging points required for an optimal integration of these solar plants. In order to achieve this goal, three scenarios are considered:

- Scenario 1: load supply only through diesel generation;
- Scenario 2: load supply through diesel and PV, but with priority dispatching of energy produced by the solar source;
- Scenario 3: same supply conditions as in Scenario 2 but with the presence of V2G charging points supporting frequency primary regulation.

V2G charging points are assumed to have a rated power of $P_{CP} = 10$ kW with an efficiency of $\eta_{CP} = 96\%$. It is also assumed that charging points are available to provide regulation service, i.e., that a car with sufficient energy availability is connected to each point to provide both absorption and power. An average load condition of the island power system is assumed according to several measurement campaign and technical reports [13], then simulations for typical summer and winter days are conducted. In Scenario 1, the inertia of the system is considered to be constant during the day, since it depends entirely on the dynamic characteristics of the operating synchronous machines. Although the inertia is constant during the day, the large differences in terms of load that occur on an island like Favignana generate the need to consider different values of inertia in the summer and winter periods: in summer, in fact, the load of the island reaches its annual peak and, to meet this demand, generators with larger size and greater inertia are used. In winter, the opposite occurs: due to low demand, generators with a smaller size and less inertia are used. Considering these observations, in order to evaluate the two periods separately, simulations were conducted assuming two different inertia values of the rotating generators [10]:

- summer inertia $H_s = 2s$
- winter inertia $H_w = 1.5s$

In Scenario 2, instead, the overall inertia of the power system is calculated hour by hour according to equation 2, since the PV energy production is relevant. Fig. 2 and Fig. 3 show the trend of overall inertia during the summer and winter reference days: blue lines represent the inertia in Scenario 1 (that is constant) while orange lines represent the inertia in Scenario 2. As can be seen from the diagrams, in Scenario 2 the inertia variations are more relevant in winter than in summer: this is caused not by a higher production of photovoltaic generators during winter, but by a lower energy demand from the loads that, for the most part, are supplied by renewable sources. The hours in which the smaller values of inertia are recorded have been considered as *critical timeframes* (11:30 AM in summer and 4:30 PM in winter) and were used to run the simulations in the three scenarios defined above.

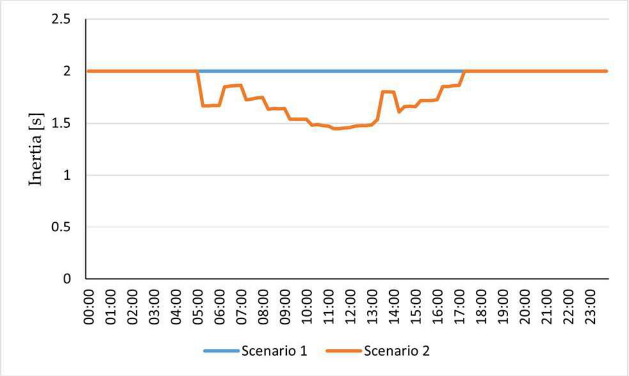

Fig. 2: Inertia daily trend, summer reference day.

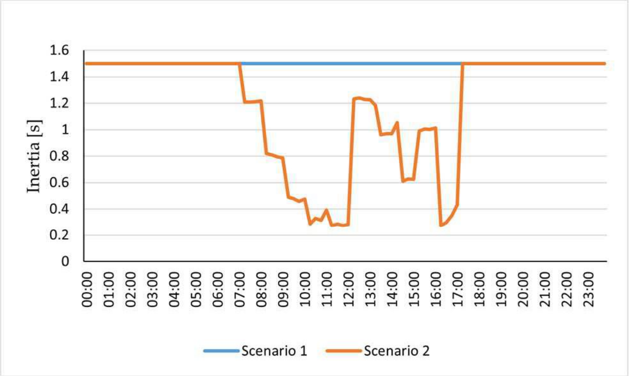

Fig. 3: Inertia daily trend, winter reference day.

IV. SIMULATION RESULTS

Once critical timeframes for summer and winter days are identified, dynamic simulations of Favignana's power system are initially performed in Scenario 1; the goal of this first simulations is to evaluate the magnitude of the power disturbance that causes a steady state frequency error equal to:

$$\Delta F_{stat} = 0.2Hz \tag{4}$$

Furthermore, in order to simulate a major load disconnection or the failure of a medium voltage line, the disturbance in question is assumed to be negative. From this point, the following indexes will be used to identify the different quantities:

- *S* indicates Summer;
- *W* indicates Winter;
- *1* indicates Scenario 1;
- *2* indicates Scenario 2;

- *3* indicates Scenario 3;

In Table I the data for the simulations are reported. Specifically, the disturbances that causes the target steady-state frequency deviation are equal to:

- $\Delta P_{D,S} = -335$ kW for summer day;
- $\Delta P_{D,W} = -110$ kW for winter day.

TABLE I: Simulation data for scenarios 1 and 2.

Scenario 1, Summer	
Initial load $P_{load,0}$	3692 kW
Disturbance ΔP_d	-335 kW
System Inertia H_{sys}	2 s
Scenario 1, Winter	
Initial load $P_{load,0}$	1113 kW
Disturbance ΔP_d	-110 kW
System Inertia H_{sys}	1.5 s
Scenario 2, Summer	
Critical Timeframe	11:30 am
Photovoltaic power P_{PV}	1017 kW
System Inertia H_{sys}	1.45 s
Scenario 2, Winter	
Critical Timeframe	4:30 pm
Photovoltaic power P_{PV}	910 kW
System Inertia H_{sys}	0.27 s

The following network parameters correspond to these disturbances:

- $\Delta F_{stat,S,1} = 0.20$ Hz, $f_{nadir,S,1} = 51.07$ Hz for summer day;
- $\Delta F_{stat,W,1} = 0.20$ Hz, $f_{nadir,W,1} = 51.30$ Hz for winter day.

Figures 4 and 5 show the frequency trends in scenario 1: as can be seen from the steady-state frequency value, the simulated disturbance generates a steady-state deviation of 0.20 Hz.

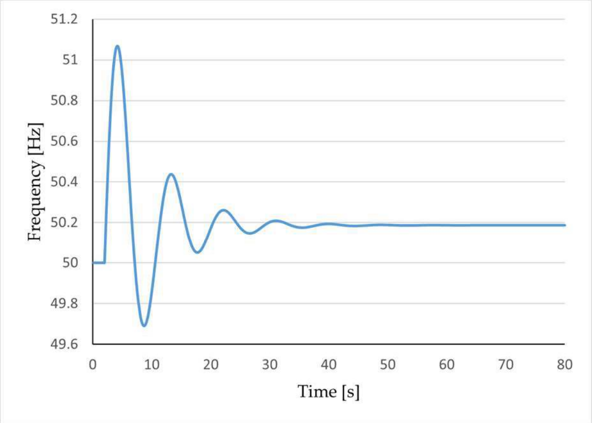

Fig. 4: Frequency trend in scenario 1, summer reference day.

Once the magnitude of the disturbance is known, the primary control simulations are conducted in Scenario 2.

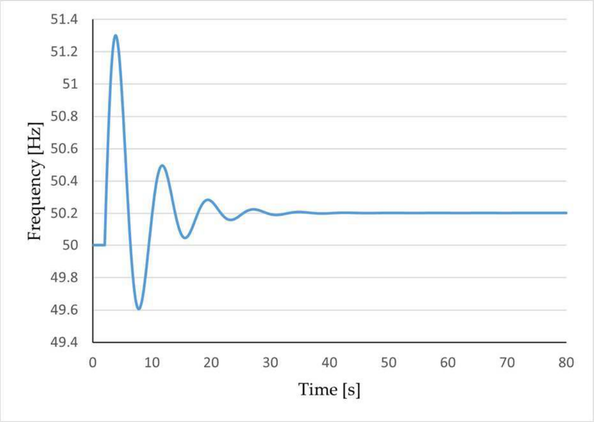

Fig. 5: Frequency trend in scenario 1, winter reference day.

Figures 6 and 7 show the frequency trends in Scenario 2 on summer and winter days, respectively. As can also be observed graphically, the frequency-related parameters of the system are significantly worse due to the reduction in inertia.

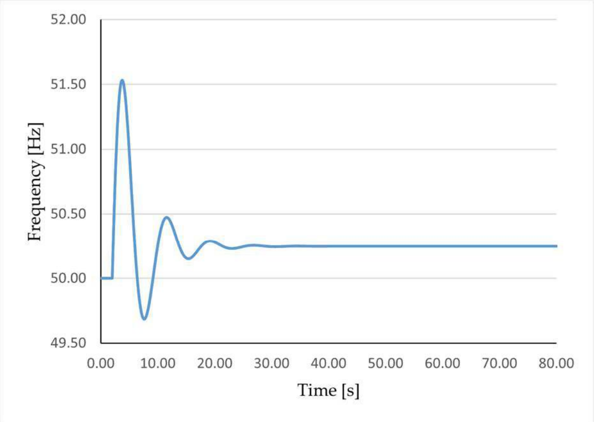

Fig. 6: Frequency trend in scenario 2, summer reference day.

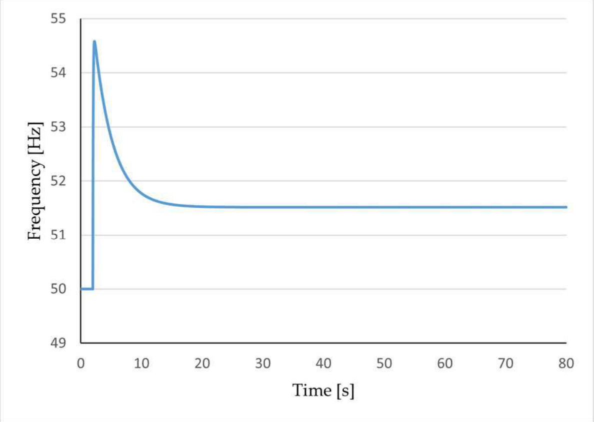

Fig. 7: Frequency trend in scenario 2, winter reference day.

The problem occurs to a lesser extent in the summer: the frequency nadir and the frequency deviation at steady state are respectively:

- $f_{nadir,S,2} = 51.53$ Hz
- $F_{stat,S,2} = 0.26$ Hz

thus comparable with the values of Scenario 1. In winter, on the other hand, the minimum stability conditions for operating the network would not be respected: the frequency nadir and the frequency deviation at steady state are respectively:

- $f_{nadir,W,2} = 54.27$ Hz
- $F_{stat,S,2} = 0.96$ Hz

Since in Italy the upper frequency limit is 51.5 Hz [14], a disturbance of this magnitude would lead to the intervention of the maximum frequency protections with the resulting loss of synchronism and, therefore, the detachment of the generators.

Several simulations were conducted for Scenario 3, in each assuming an increasing number of charging points participating in regulation. Figures 8 and 9 show the values of the steady-state frequency deviations as a function of the number of V2G columns. As can be seen from the graphs, the steady-state frequency deviation value shows a decreasing trend as the number of used charging points increases, and reaches a value equal to that of Scenario 1 in the presence of at least 6 active V2G charging points in summer and 9 in winter.

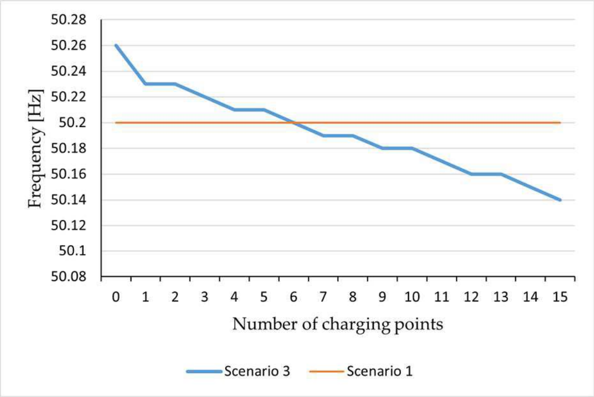

Fig. 8: Steady state frequency deviation as a function of the number of V2G columns, summer.

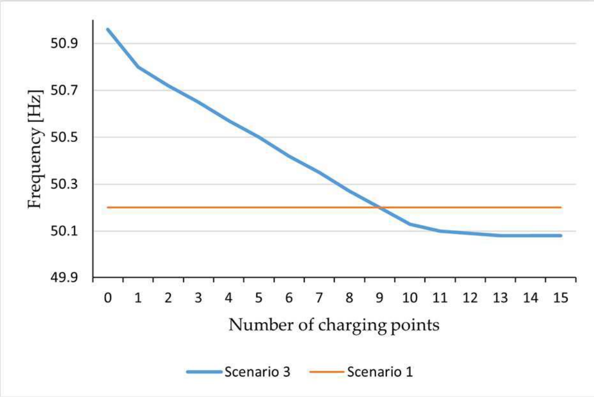

Fig. 9: Steady state frequency deviation as a function of the number of V2G columns, winter.

Finally, Figures 10 and 11 show the frequency trends in Scenario 3 in which the presence of the minimum number of V2G recharge points just identified is assumed, while Table II shows the data from the simulations performed for all the considered scenarios.

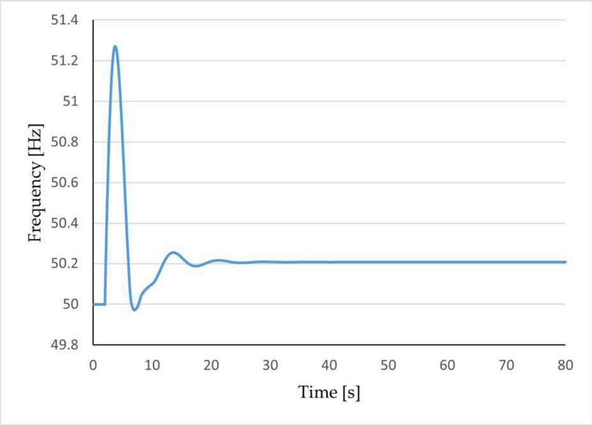

Fig. 10: Frequency trend in scenario 3, summer reference day.

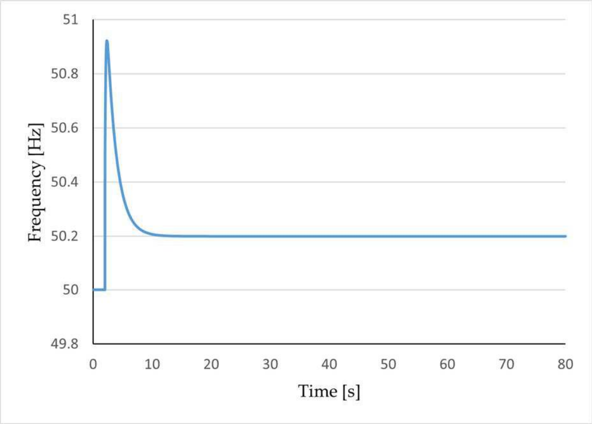

Fig. 11: Frequency trend in scenario 3, winter reference day.

TABLE II: Simulations results for all scenarios.

Scenario	PV [kW]	V2G points	f_{nadir} [Hz]	Δf_{stat} [Hz]
1.S	0	0	51.07	+ 0.20
1.W	0	0	51.30	+ 0.20
2.S	1017	0	51.53	+ 0.26
2.W	910	0	54.27	+ 0.96
3.S	1017	6	51.10	+ 0.20
3.W	910	9	50.57	+ 0.20

V. CONCLUSIONS

The paper shows the application of a step by step method for the definition of the minimum number of V2G charging points that allows an optimal integration of renewable sources with attention to the stability of the network. The case study considered concerns the electrical grid of Favignana in the hypothesis of installation of a photovoltaic plant of 1 MW, in compliance with the objectives set by national legislation. The simulations of primary frequency regulation have highlighted how, in the identified critical timeframes, a small number of V2G charging points allows the complete integration of the above mentioned photovoltaic power without compromising the grid stability, bringing the frequency indicators to levels comparable to those of a system based on diesel generation. However, the study does not consider the allocation of charging points on the island or the availability of electric vehicles to provide regulation service. From the point of view of power flows in the network, previous studies show that, according to different scenarios in terms of number of vehicles and charging times, the network of Favignana is available to meet this load demand without the need for invasive interventions [15]. Once the minimum number of V2G charging points has been identified, the natural prosecution of the study involves the identification of the service remuneration for those owners that would offer their vehicle to provide grid services and the economic feasibility of the associated business model.

VI. ACKNOWLEDGEMENT

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