A blockchain platform for Demand Response in Mediterranean islands: a smart contract for remuneration

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***Abstract*—The Blorin project started at the end of 2019 to support the implementation of a blockchain platform to support the energy services provision from end users by means of Demand Response and Vehicle to Grid programs. The experimental part of the project is being carried out on two Mediterranean islands and inside the University campus in Palermo. Customized smart contracts have been designed to support the active participation of end users to regulation services for the two weak electrical grids of the islands in the view of a deep penetration of renewable energy in the two energy systems. In particular, the smart contract for remuneration accounts for the very special energy situation of islands where TSO, DSO, energy seller and aggregator collapse in a unique market actor. Moreover, in islands the electricity provision is typically still relying on diesel generators thus strongly connecting the Demand Response programs benefit to the reduction of fuel consumption, as an effect of increased efficiency of diesel generators. Due to the critical international situation and to the climate crisis, fossil fuels get more and more costly, thus a speed up of the energy transition in small islands is highly needed. This paper addresses the problem of designing a customized smart contract for remuneration of Demand Response service provision in small islands.**

***Index Terms*—Energy blockchain, Demand-Response, Smart Contract, Business models.**

I. Introduction

The current geopolitical situation and the recent policies on the energy transition in Europe aiming at full decarbonization of Europe by 2050 set a new scenario in which renewable energy penetration is a priority in all settings. Geographical islands, that are far from the mainland, are very particular systems in which natural and cultural heritage protection have a strong relevance and in which, at the same time, it is difficult to provide high quality and fully decarbonized electrical service. It is well known that in weak grids, showing limited extension and limited inertia of the generation system (i.e.: number of rotating generation machines), perturbations can generate significant problems to voltage and frequency stability [1], [2]. Problems indeed arise when generation does not meet the loads demand and when this unbalance appears suddenly. Both phenomena cause frequency and voltage deviations, that can be compensated by restoring the balance between generation and load. For this reason, it is possible to act on technologies operating on the side in which energy is provided and on technologies settled at the demand side. Problems can indeed be handled with technological innovations in converters technology [3] interfacing generation and storage or through specialized Demand Side Management. Control of loads is indeed possible through Demand Response (DR), programs that are already implemented in many countries across the world especially in those areas where electrical systems are not so developed, such as in the US. According to the International Energy Agency, IEA [4], further developments in DR programs and their implementation occurred between 2020 and 2021. And after that, an increasing number of countries is removing barriers to the implementation of DR for energy services provision to the grid, while also increasing the capacity awarded in electricity markets. However, a tenfold on deployment level in 2020 in DR implementation is required as 500 GW of DR should be brought onto the market by 2030 to meet the requirements set by the European Net Zero Emissions by 2050 Scenario. DR can be further pushed through actions taken in this decade to disclose new markets to demand-side participation and support new business models, while defining controllability standards for equipment and appliances. According to IEA, more than 6 percent of the Buildings relative annual demand will be available for energy flexibility in the Net Zero Scenario by 2030. Meaning that DR will more and more need technologies to support its wide deployment while ensuring adequate remuneration to end users. DR provision is right now relying on intermediate energy market actors like aggregators, whose activity is not strictly needed if suitable digital technologies are used ensuring transparency, trust and data security.

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II. Demand-Response and blockchain

Many recent papers in the literature propose the use of blockchain technology for DR programs management. The blockchain is a recent technology relying on Distributed Ledger Technology (DLT), i.e. a distributed ledger [5]. In a classical trading system among peers, there is a third party, called trusted third party, that guarantees transactions between them. In this case, such as it happens for energy transactions, data are recorded on a centralized ledger managed by a unique trusted party. By the blockchain technology, a distributed ledger can be created, namely, a system in which each node of the network (peer) holds a copy of all transactions. In this way, no central trusted authority is needed, as trust is ensured by the participation of the peers to the so-called consensus process ensuring the validity of transactions. The five basic elements on which blockchain relies are: distribution, encryption, immutability, tokenization and decentralization. Decentralization and distribution allow to overcome an important issue of a centralized system, being the ledger manager and the central server a single point of failure. The same features together with immutability support the main innovation brought by the blockchain: the transfer of trust from a single entity to the whole network of nodes. Finally encryption ensures privacy and data protection, which is essential within energy transactions, while tokenization allows the virtual representation of any good or service and supports remuneration mechanisms. Since a few years, DR programs rely on a new actor of the energy market, interfacing the energy market with the end users, called aggregator. As shown in many papers, this latter role can be taken over by a blockchain platform, either public or private. In [6], a decentralized implementation of DR programs on top of a public blockchain is proposed. The main issue dealt with is the privacy of the prosumer's energy data using zero-knowledge proofs and validates on the blockchain the prosumer's activity inside the program using smart contracts. A public blockchain based on Ethereum is used in [7] to manage relations between end users exchanging a parameter called the Probability of the Next Hour that can support to maximize comfort levels together with energy efficiency and CO2 reduction. Other papers [8] use an Hyperledger blockchain to securely track DR provision, focusing on the validation aspect and IT energy consumption, keeping data integrity, origin, fast registry, and sharing within a permissioned system, between all relevant parties (including transmission system operators (TSOs), aggregators, distribution system operators (DSOs), balance responsible parties (BRP), and prosumers). In this paper, a further step is taken as compared to [9], as the particular case of small islands is considered and the formulation of a special remuneration system implemented in a smart contract is proposed.

III. The BLORIN project

Blorin project is designed to create a blockchain based platform for energy services provision. The platform relies on a Hyperledger Fabric blockchain and supports both Vehicle-To-Grid (V2G) and DR programs. V2G is a balancing service provided by recharging stations and supported by the batteries of electric vehicles. While, the DR is a program that allows consumers to increase or decrease energy consumption in response to peaks in electricity supply and demand, thereby providing greater grid flexibility and stability as well as more efficient use of energy infrastructure and resources. In the project remuneration laws for the two programs are proposed, implemented and tested experimentally.

It is well known that the blockchain supports the sharing of logics else than the sharing of data, through the implementation of Smart Contracts (SCs), which represent the contracts between two users under the form of a code which is executed and shared on the blockchain nodes. The latter implement actions when some established conditions are met [10]. No need of aggregator then as the decentralization and consensus mechanism ensure transparency, trust, and immutability [11]. In this paper, a SC implements the remuneration mechanism which is agreed between the grid operator and the single end-user and is tested in the Lab facilities of the Blorin project. In the Blorin platform, all members are enrolled through a trusted Membership Service Provider (MSP). As a result, transaction validation and network security do not need complex algorithms such as "proof of work" and this implies a substantial difference from open, so-called permissionless systems that allow unknown identities to access the platform with write capabilities. Among other innovations, this project offers several mechanisms and tools that can be combined allowing easy integration with existing technologies. The platform used is Hyperledger Fabric (HLF), an open source blockchain used in many other application areas which, in addition to its modular architecture, it is the first platform to support SCs written in generic programming languages such as Java, Go and Node.js, rather than specific programming languages such as Ethereum's Solidity. Unlike other platforms, HLF supports modular consensus protocols that can be switched on and off allowing for more flexible customization. Therefore, unlike consensus protocols that are favored by mining on a public blockchain, it is possible to leverage consensus protocols that do not require a cryptocurrency, which would otherwise be used to execute smart contracts. Avoiding the need for a cryptocurrency, in order to run the platform, reduces risk and attacks, and in the absence of crypto-mining operations, it is possible to run the platform at a reduced power consumption compared to other systems. Currently, the Blorin network includes 7 nodes, each representing specific interests in the energy scenario. As it can be seen from Fig. 1 the University of Palermo facility includes 2 nodes, at SNAPPLab (Security Network Applications and Positioning Laboratory) and at SMGLab (Smart and MicroGrid Lab). Each of the involved elements maintains a node, as follows. The SNAPPLab aims to develop and control the entire communication infrastructure between the different peer nodes and the blockchain itself. The SMGLab provides hardware components to test the energy services provided by end users (including V2G) and their tracking through an appropriate metering system. Two other nodes are maintained by Regalgrid, a system integrator and service provider, and Exalto, the coordinator of the Blorin project. Other stakeholders are the grid operators on the two islands involved in the project. The SEA distribution company on the island of Favignana is in charge of managing the V2G service and the SELIS distribution company is in charge of managing the DR service on the island of Lampedusa.

The application is run by the network nodes installed at the university's premises.

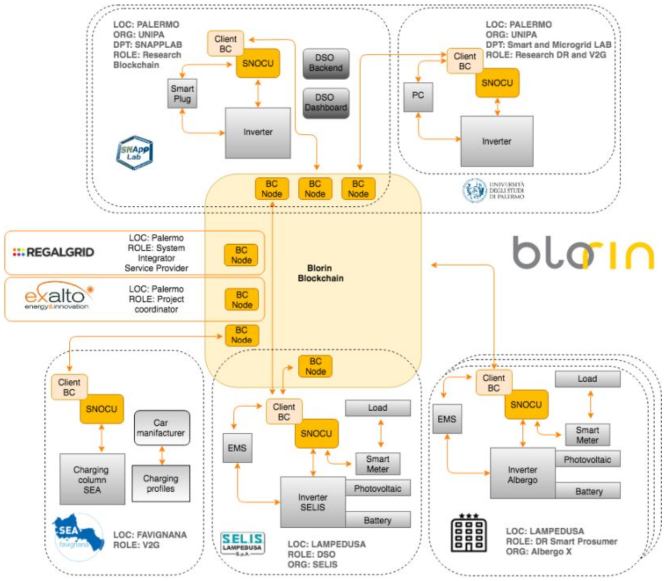

Fig. 1. Blorin architecture and main actors

IV. Demand Response Economic Value

One of the goals of this work is to propose a remuneration mechanism for household users that participate in DR events in small islands. The BloRin platform involves the implementation of a specific SC that allows to calculate the remuneration of the DR service, thus quantifying the economic value of DR. In recent years, public opinion is much more sensitive to the issues of energy efficiency and integration of renewable sources to support climate neutrality and, more recently, to the independence from politically not reliable countries [12], [13]. However, DR is, in some respects, an invasive policy, as it asks a user to give up or modify its consumption of electricity according to the needs of a third party, namely the power system. Therefore, it is important to define the economic terms under which this service can be requested from a user, commercial or residential. The remuneration of DR depends on several factors: the type of user involved, the aim of the DR program and the presence or absence of an aggregator [14]. In the following, the value that can be attributed to the DR service is discussed in general. Then, the specific case of the island involved in the BloRin project for the DR, i.e. Lampedusa, is considered. In particular, the analysis focuses on which can be the economic benefits of DR for the Lampedusa power network operator, and what mechanism can be developed to remunerate the users who participate in the program. DR enables management or modulation of the electrical load, allowing load-shifting or peak-shaving during certain periods of time; this service is valuable for several reasons:

- Avoid costs for new installed generation capacity;
- Avoid costs for new installed transmission or distribution capacity;
- Improve generation system efficiency by reducing costs due to fuel consumption;
- Reduce costs of ancillary services;
- Potential to reduce environmental impacts and CO_2 production from the electric system

If DR is used to reduce the load during peak hours, new generation capacity and grid expansions can be avoided, or at least delayed, resulting in substantial savings [14]. Regarding supply system efficiency, if a supply operator wants to reduce fuel consumption, it can decide to use a DR program with the aim of reducing peak load and avoiding using inefficient generating units to supply power demand. DR also has a social and environmental value, as it can help decommissioning of inefficient and pollutant power plants and favor renewable sources, with a significant decrease in greenhouse gas emissions. On the island of Lampedusa, the electrical system is managed by a single company, SE.LI.S S.p.a., which deals with all aspects of electrical energy, from production to distribution and sales. The island's electrical system has an important critical issue, which has emerged from the joint studies of ENEA and the University of Palermo [15], concerning the diesel-based energy supply system. Diesel supplies a power plant consisting of 8 groups, for a total of about 22 MW. Diesel generation is very expensive and inefficient, and has also a great environmental impact in terms of pollution. The second critical issue concerns the stability of the power grid in the summer season; in fact, between June and September the overall load of the island is much higher than in winter, and during peak hours some lines may be overloaded and cause blackouts in some areas. From this context, it is clear that the DR in Lampedusa has as first objective the load reduction during peak hours, thus allowing a flattening of consumption and therefore a better management of lines and generation groups. In fact, in addition to overloading the power lines, there is a higher consumption of fuel, as it is often necessary to operate generation groups with low efficiency in order to meet demand. The remuneration model in Lampedusa must take into account two factors: reduce fuel consumption by increasing the efficiency of diesel generators, and avoid the costs of upgrading the lines. As partner of the BloRin project, the company SE.LI.S also endorses this analysis. Hence, in a small non-interconnected island like Lampedusa, DR remuneration is closely linked to fuel savings generated by a more efficient operation of diesel groups; this is the principle on which DR remuneration is based in the BloRin project.

V. Methodology

As described in the previous section, to identify the value of DR, the impact of load management on the efficiency of the generating units and thus on fuel consumption must be quantified.

The assessment on the impact of DR is done by applying the following steps:

1) determination of the average load profile of the island in a typical summer week.
2) Determine which production generators are active and therefore should be considered in the simulation;
3) Perform a simulation to determine the optimal dispatch with the average load chosen in step 1; that is, determine the power each group must generate to meet the load while consuming the least amount of fuel.
4) Repeat the simulation considering a certain amount of flexible power, which represents the power that can be modulated during a DR event.
5) Calculate the difference between the fuel used in the simulation in step 3 and the fuel used by applying DR (step 4). The difference in fuel translates into a difference in production cost.
6) Determine the value of the DR as the difference between the production cost without DR and the cost with DR.

Fig. 2 below shows an average load profile for a summer week in Lampedusa.

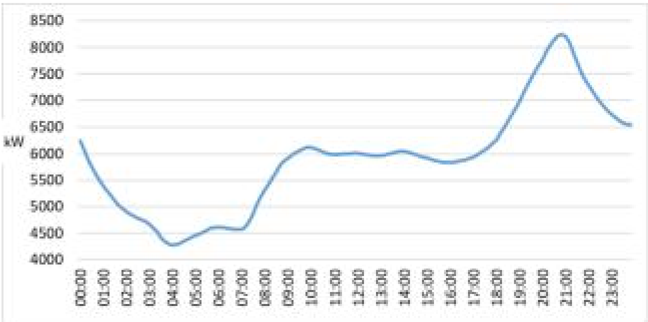

Fig. 2. Average load profile of the Lampedusa network in a summer week.

Step 2 is determined thanks to the information provided by SE.LI.S; in fact, the 8 generators of the Lampedusa plant are not active at the same time, but are used according to maintenance plans. Therefore, only a part of these groups are in operation during the same period.

Step 3 consists of a constrained nonlinear optimization problem; the goal of the optimization is to minimize the fuel consumption function, taking into account the physical constraints of the system. The unknowns to be determined are the powers generated in each time interval by each generation group. The cost function to be minimized is as follows:

$$fmin = \sum_{h=1}^{N} \sum_{i=1}^{n} \frac{c_{i,h} * P_{i,h}}{\eta_{i,h}(P_{i,h})} \tag{1}$$

Where *i* is the generator index, *n* is the number of generators considered, *h* is the time interval index, *N* is the total number of intervals, *c* is a constant that quantifies the fuel to produce each megawatt hour, and is defined as:

$$c_{i,h} = \frac{kgdiesel}{MWh} \tag{2}$$

$P_{i,h}$ is the value of power generated by the *i-th* generator in the considered time interval, while $\eta_{i,h}(P_{i,h})$ is the efficiency value of the generator, which depends on the working point, i.e., the power P_i generated. The efficiency $\eta_{i,h}$ is defined by the following equation:

$$\eta_{i,h} = \eta_{max,i} - (\eta_{max,i} * e^{-2*(\frac{P_{i,h}}{P_{n,i}})}) \tag{3}$$

Where η_{max} is the maximum generator efficiency of the *i-th* generator and P_n is the rated power of the same generator. The cost function is minimized by considering the following physical system constraints:

- $(P_{load,h} - P_{DR}) \leq \sum_{i=1}^{n} P_{i,h} \leq (P_{load,h} + P_{DR})$, for each time interval considered.
- $\sum_{h=1}^{N} \sum_{i=1}^{n} P_{i,h} = \sum_{h=1}^{N} P_{load,h}$;
- $P_{i,min} \leq P_{i,h} \leq P_{i,max}$, for each time interval considered.

Where $P_{load,h}$ is the power required by the load in each time interval *h*, as determined in step 1; $P_{i,min}$ and $P_{i,max}$ are the minimum and maximum power that the *i-th* generator can operate at. The cost function is minimized in each time interval, resulting in the optimal dispatch of the generating groups.

At this point, the simulation can be repeated considering the presence of a hypothetical DR event (step 4). The difference between the fuel used in the two simulations is calculated (step 5). Then it is estimated the difference in the cost of production of the two scenarios and it is determined the value of the DR (C_{DR}) like difference between the production cost without DR and the cost with DR (step 6).

These analyses are performed by the grid operator as the owner of the power plant and distribution lines. The problem of optimizing the generators' operation is an activity that is carried out by the grid operator, and it is too complex to be performed as a smart contract on the blockchain. Moreover, optimization is based on parameters that are owned solely by the grid operator and there is no reason to provide trasparency on such optimization process to end users, who are free to join or not the DR program. For these reasons, the determination of the value of the DR program, C_{DR}, as output of the optimization problem, is executed by the grid operator outside the blockchain. Once the C_{DR} and the related DR event is established, it can be shared on the blockchain with the users who decide to participate in the service.

VI. Application

In the case of residential users, the DR programs available on the market are always focused on thermal loads, precisely because they are the only loads whose interruption does not affect comfort too much. The user makes an agreement with the system operator (DSO or retailer), where it is made clear in what terms the load can be controlled (time, maximum power variation, duration, etc.). Once this is done, a monitoring and control system (Energy Management System - EMS) with an integrated optimization module is installed, which receives the DR signal from the DSO through the blockchain, and then acts on the user's load according to the defined support logic. In this case, the loads controlled by the EMS device can be multiple, from the water heater to the air conditioning, and it is the EMS that decides how to manage them according to the operator's DR requests. The logic may have different objectives, such as preserving comfort, or maximizing economic savings, or even meeting an assigned quota of consumption over a certain period (daily or weekly). The same system can also be used to improve the integration of renewable sources such as photovoltaics. In fact, the control system can program some loads to consume energy during the hours of maximum photovoltaic production (middle hours of the day) and to limit absorption during nighttime. Some loads (such as electric water heaters) can even store electrical energy in the form of thermal energy, providing a service similar to that provided by storage, at least in energy terms. In this way, after the user decides to participate in the blockchain, the EMS allows to automate and optimize the response to maximize the remuneration. The implementation of the DR event logic is performed through a customized SC, which also establishes the roles of the various actors on the Blorin network. In this case, the actors involved are the DSO and the users who decide to join the service by providing their flexible loads or production/storage systems. Specifically, for each user the next steps are executed:

1) During a generic day, the EMS records the user's load profile and sends it to the blockhain.
2) The DSO notifies the DR event on the blockchain with the purpose of increasing the efficiency of the power plant or mitigating any expected problems in a given hour due to production from renewables.
3) The SC evaluates the load baseline of users participating in the service and distributes the DSO request.
4) The DR event takes place.
5) Through the EMSs, users will be able to automatically respond to the request by turning off some loads or managing generation/storage during the hours when the DR event is expected.
6) The users' load consumption during the DR event is recorded on the blockchain as explained in steps 1).
7) After the DR event, the DSO triggers the SC to check if users' consumption has been compliant with the request.
8) If the users' consumption has been compliant with the request, the SC remunerates them with energy-tokens.

Through the EMS, the user's consumption/production data is sent to the blockchain; this is necessary in first place to calculate the customer baseline and then to certify, and therefore consequently remunerate, the load modulation service implemented by the user. The methodology implemented by the SC, to first evaluate whether the user has satisfied the DR request and secondarily to give the corresponding remuneration, consists of comparing the user's baseline with the load profile measured on the day in which the DR event occurs. Based on this difference the remuneration is calculated and given to the end user.

After the DR event, the power measurement data is sent to the blockchain, and the SC implements the following formula:

$$r = C_{DR} \cdot \sum_{h=1}^{n} |(P_{b,h} - P_h)| \quad (4)$$

Where:

- n is the total number of time intervals into which the DR event is divided;
- h is the index indicating the single time interval in which a power measurement takes place;
- r is the total user remuneration [€];
- C_{DR} is the remuneration coefficient of the DR service, linked to the actual power variation [€/kW];
- $P_{b,h}$is the user's baseline value in the interval h [kW];
- P_h is the user's power value measured in the interval h [kW].

The difference between $P_{b,h}$ and P_h is evaluated in absolute value, so that both increasing and decreasing power variations can be remunerated. Then, during the DR event, the blockchain receives the consumption data and records them. At the end of the event, the SC applies a function that calls the value of C_{DR}; this value is evaluated as in the previous section and registered in the BloRin platform by the grid operator, which can update it on a daily, monthly or seasonal basis. However, during the DR event the value of C_{DR} remains constant. The following Fig. 3, shows the SC's function used for users' remuneration in the Blorin project. The programming language used is Javascript.

```
async CalRem(ctx, id, c_dr) {
    const id_p_day = id + "_p_day";
    const id_baseline = id_p_day + "_baseline";
    const asset_d = await ctx.stub.getState(id_p_day);
    const asset_p_day = JSON.parse(asset_d.toString());

    var p_day = asset_p_day.P_day;

    const asset_b = await ctx.stub.getState(id_baseline);
    const asset_baseline = JSON.parse(asset_b.toString());

    var baseline = asset_baseline.Baseline;

    const v_c_dr = c_dr

    var rem = baseline.map((a, i) => (a - p_day[i]) * v_c_dr);

    const key = id + "_Rem";

    const asset_rem = {
        ID: key,
        Remunerazione: rem
    };
    return ctx.stub.putState(key, Buffer.from(JSON.stringify(asset_rem)));
}
```

Fig. 3. Blorin Smart Contract function for DR remuneration

As it can be seeb, the first step is to fetch from the blockchain the load profile related to the day when the DR event occurred and the baseline of the user, identified with a specific *id*. Next, the value of C_{DR} is fetched and then the remuneration is evaluated with the equ. 4. Finally, the new asset representing the user's remuneration the specific DR event is stored on the blockchain through the *putState* function. Once the event is concluded and the remuneration is evaluated and stored on the blockchain, the user can query the reward earned. In Fig. 4 is showed an example the user's client response after the function of the SC is invoked to query the reward stored in the blockchain.


```
{
    "response": "{\"ID\" : \"Utente-1-44Bd85bf74594cfb5e48bbe82c87e52b_Rem\",
                 \"DRevent\" : \"12.04.2022\",
                 \"Remuneration\": \"1,83\"
                }"
}
```


Fig. 4. Response from user's Client

In the BloRin platform, the role of the island grid operator in the remuneration mechanism is to provide the remuneration coefficient to the platform. The grid operator determines this coefficient by developing the principle described in the previous section, i.e., by running the optimization and estimating the fuel savings due to DR.

VII. CONCLUSION

In this paper, a blockchain platform enabling secure and transparent aggregation of domestic users for the provision of energy services, by DR programs, is proposed. DR is needed to overcome power grid issues caused by RES or aggregation of local resources for participation in balancing markets. In this aim, the BLORIN project addresses the issue for what concerns the implementation of Vehicle To Grid and DR programs. This paper shows how the grid operator establishes a DR event and its cost and how the latter is used for remuneration through a specific SC of the users who participate in the service.

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