Decentralized blockchain flexibility system for Smart Grids: Requirements engineering and use cases

Luigi D'Oriano
Innovation Unit
Energy@Work S.C.A.R.L.
Brindisi, Italy
luigi.doriano@energyatwork.it

Giuseppe Mastandrea
Innovation Unit
Energy@Work S.C.A.R.L.
Brindisi, Italy
giuseppe.mastandrea@energyatwork.it

Giuseppe Rana
Innovation Unit
Energy@Work S.C.A.R.L.
Brindisi, Italy
giuseppe.rana@energyatwork.it

Giuseppe Raveduto
Research and Development Department
Engineering Ingegneria Informatica S.p.A.
Trento, Italy
giuseppe.raveduto@eng.it

Vincenzo Croce
Research and Development Department
Engineering Ingegneria Informatica S.p.A.
Palermo, Italy
vincenzo.croce@eng.it

Matteo Verber
Research and Development Department
Engineering Ingegneria Informatica S.p.A.
Trento, Italy
matteo.verber@eng.it

Massimo Bertoncini
Research and Development Department
Engineering Ingegneria Informatica S.p.A.
Rome, Italy
massimo.bertoncini@eng.it

***Abstract*— With the diffusion of smart metering devices and the increasing trend in renewable energy investment [1], the electrical grids are rapidly changing towards the adoption of decentralized energy networks in which consumers can be also producers (i.e. prosumers). The increased use of renewable and distributed generation is leading the development of Smart Grid and microgrid technologies. In this context new business opportunities can be developed provided that new critical issues for the traditional operators, introduced by decentralization, are addressed properly. As example, grid imbalances can generate Reverse Power Flow (RPF) that is harmful for the equipment since many of the protection and control devices are designed with the assumption that power always flows in one direction. In this paper, we present results from the ongoing project eDREAM (enabling new Demand REsponse Advanced, Market oriented and Secure technologies, solutions and business models) with some extent on requirements and use cases related a decentralized flexibility system based on ledger technologies.**

Keywords—demand response, flexibility, blockchain, smart contract, requirements, use cases, smart grid.

I. INTRODUCTION

A microgrid is usually connected to the local distribution power network in order to operate in either grid-connected or island-mode, depending on situation of energy production and consumption. Putting in operation these units, characterized by the flexibility given by the internal aggregation of multiple loads and generation as well as the two-way operating modes, can foster the integration of distributed and renewable energy sources in the power distribution network. Microgrids provide benefits in terms of i) reliability and resilience, ii) efficiency, iii) demand side management, iv) ancillary services, v) keeping control, privacy and autonomy and vi) environmental benefits [2]. End-user needs can be targeted by ensuring energy supply for critical loads, controlling power quality and reliability at the local level, and promoting customer participation through demand-side management and community involvement in electricity supply.

In this context, flexibility of energy resources can be evaluated as the capability of power adjustments provided by a microgrid connected to the power distribution network, by means of control of generators, load curtailment and charge/discharge of storage systems. Using forecasting engines together with trend analysis tools [3], a Distribution System Operator (DSO) can access microgrid resources, exploiting the microgrid flexibility in order to guarantee smart grid stability, providing flexibility-as-a-service. Another way to provide flexibility to the Distribution Grid is through the flexibility services made by aggregators, that can manage loads and production of a high number of prosumers.

Blockchain application

In this context, blockchain distributed ledger is adopted for storing energy transactions and for enabling Demand Response (DR) flexibility services at a microgrid level in a secure and trustful manner. The decentralization, transparency and reliability provided by design by blockchain technologies, are leading to a continuous increase in the interest on the possible application fields. Moreover, blockchains like Ethereum provide the ability to create "Smart Contracts": scripts that use a Touring complete language, deployed and run within the blockchain nodes.
Smart grid management through blockchain technologies is currently being investigated [4] and projects like NRGCoin [5] or TransActive Grid [6] are exploring the context of decentralized energy markets. In the context of a smart grid, the application of smart contracts enables the automatic control of single prosumers or consumers, controlling the neighbourhood market of energy and energy services, guaranteeing stability and security to the whole grid. An additional advantage provided by the blockchain technologies is the auditability and the tamper proof storage capability [7].

The Proposed Approach

Although the benefits provided by blockchains, often these technologies have a cost. It's estimated that both Bitcoin and

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Ethereum burn over $1 million worth of electricity and hardware costs per day as part of their consensus mechanism. To ensure the platform functionalities, blockchain network nodes (the so called “miners”) have to prove their right to participate to the network through the resolution of a computationally expensive mathematical problem, this is the “Proof-of-Work”[8] mechanism, brought to popularity by Bitcoin. To control a resource optimization process, the usage of an highly resource expensive mechanism seemed counterintuitive, so in this work we propose a platform relying on “Proof-of-Stake”[9] validation mechanism (PoS), with no need to consume large quantities of electricity in order to secure a blockchain. The PoS platform will be used for the execution of the smart contracts ensuring the flexibility marketplace. Each of the participants in the flexibility marketplace, will be equipped with a smart metering device, able to store the monitored data in the blockchain distributed ledger.

The decentralized flexibility marketplace will be managed by a dedicated smart contract, collecting flexibility requests and offers and matching them together. Once the bids and offers are accepted, the agreed amount is stored in the blockchain. Prosumers smart contracts will act as a decentralized control mechanism, continuously monitoring the expected energy profile against the actual monitored energy values, penalizing the prosumers violating the smart contract and rewarding the prosumers providing the flexibility requested. The rate to be applied for incentives or penalties in each time slot, is defined by a function comparing the flexibility request against the actual monitored energy values. Penalties and incentives will be provided as Ethereum based tokens, and will be transferred automatically, making the smart contract “self-enforcing”. Since blockchains are designed to be controlled by not cooperating nodes without the need for trusted third parties [10], it will act also as a “common ground" for the different stakeholders involved.

II. CONTEXT AND SCENARIO

The main objective of the proposed scenario is to transform the system into a decentralised system when appropriate and to ensure stability by balancing load and generation operating in island mode. In this scenario, smart contracts will enable prosumers to offer their flexibility resources (production and loads modulation) directly or through aggregators. The aggregators activate in real time the contracted flexibility services and the DSO is able to assess and trace the services provided.

These smart contracts will be defined to manage the levels of energy demand flexibility (i.e. from aggregators and enrolled prosumers on one side and from aggregators to the DSO on the other side), associating incentive and penalty rates. The corresponding smart contracts can be evaluated after estimating the difference between the expected power flexibility curve and the flexibility actually delivered (as measured by monitored energy values). In this way, each smart contract will act as a decentralized coordinated control mechanism at the grid level, maintaining the balance of supply and demand, reducing the overloading and contributing to the power network stability.

The aggregator is responsible to create and send the forecast of the aggregated power demand of all his registered prosumers to the DSO. The DSO then uses the forecast to calculate the total load, identifying congestion points and related grid connections. Then, the aggregator contracts the prosumers to offer flexibility in the identified regions. The marketplace platform collects and then matches both the flexibility requests by the DSO and the flexibility offers by the aggregators. The smart contract will finalize the matched requests and offers, and the agreed baseline will be used as reference, so the involved prosumers will adjust their load to fulfil the flexibility request.

Based on this scenario the smart contract is in charge for the automatic selection of each prosumer in the DR event. Then, the agreed baseline is compared with the actual monitored energy values, to verify in near real time the monitored energy consumption data against the DR signal and notify the aggregator in case of detection of any significant deviation. If notable deviations are detected, the smart contract calculates the associated penalties for the prosumer, otherwise the prosumer is rewarded, considering the DR revenue rates and how much the prosumer power demand profile has been adapted during a DR event. The incentive and penalties are established by the aggregator considering the energy flexibility order received at its turn from the DSO. To determine how much a prosumer has adapted its power demand to the DR, having as reference its Baseline Power Profile, it is possible to use a metric power curve adaptability to monitor the actual adjusted power demand during the DR event time interval. The incentives that the aggregator recognizes to the prosumer for its adaptation during a DR event, is calculated for each kW of energy shifted and can be provided as a daily revenue or a discount rate on the regular electricity bill. The rate to be applied for incentives or penalties is defined by the following formula:

$$I''(t,R,M) = \begin{cases} \frac{1}{R}\,(R - |r_t - d_t|)e^{-\frac{|r_t - d_t|}{|r_t - f_t|}}, when\ |r_t - d_t| \leq R\ and\ |r_t - f_t| > 0 \\ \frac{1}{R}\,(R - |r_t - d_t|)e^{-|r_t - d_t|}, when\ |r_t - d_t| \leq R\ and\ |r_t - f_t| = 0 \\ \frac{M}{R}\,(R - |r_t - d_t|)e^{-\frac{|r_t - f_t|}{|r_t - d_t|}}, when\ |r_t - d_t| > R \end{cases} \quad (1)$$

The formula operates time discretely on integer values and considers as input: i) the flexibility request r_t, ii) the actual monitored power values d_t and iii) the forecasted energy values f_t. The smart contracts will take these parameters as input, together with a tolerance range R and a multiplier M to be applied on penalties. In detail, the chart in Fig.1 represents the incentive (or penalty) variation based on the distance from the original request, while Fig.3 represents the determined amount of the incentive or penalty for each time slot in relation with the monitored power values (Fig.2).

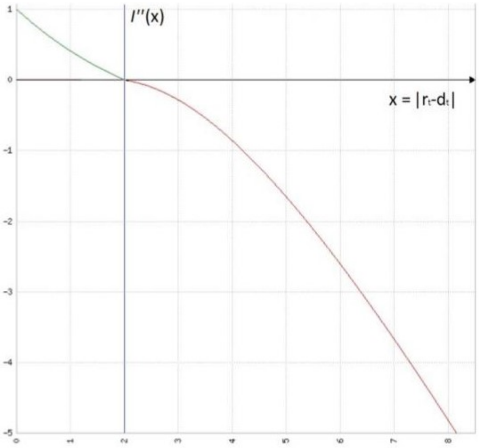

Fig. 1 Incentive behavior based on the distance from the flexibility request

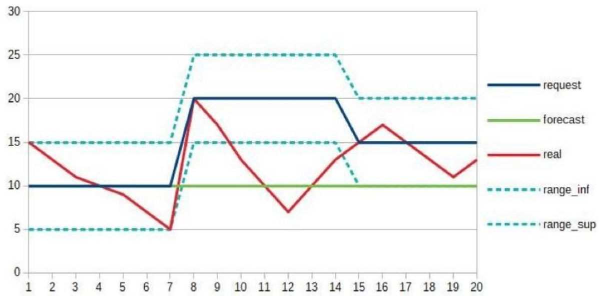

Fig. 2 Monitored power values vs. flexibility request (performed in simulated environment)

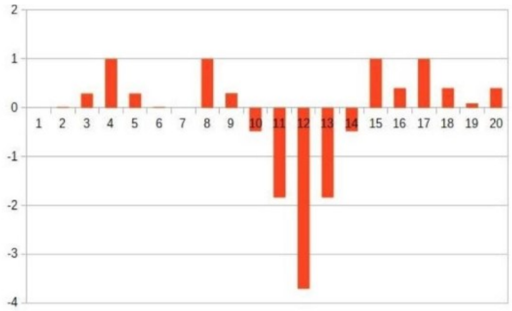

Fig. 3 I(t,R,M) as incentives generated by applying the flexibility as in Fig.2

III. SPECIFIC REQUIREMENTS AND USE CASES ENGINEERING AND ELICITATION

To envision the described scenario, the elicitation of the requirements, must be tackled with extreme care, since many systems fail due to wrong or inefficient elicitation practices.

A requirement can be defined as a stakeholder need and the elicitation is all about knowing the wishes of the stakeholders. It provides a success basis for a project and the delivery of the expected system and often reduce the gap between developers, stakeholders, and end users [11].

The Requirement Elicitation (RE) is a process to discover the stakeholders' needs and collect the relative requirements. It addresses many problems such as user involvement and perfect documentation. Wrong or missing requirements lead to different system than expected, unreliable or more expensive than alternative solutions. The quality of the requirements phase affects the overall quality of the entire software production cycle and therefore the produced platform.

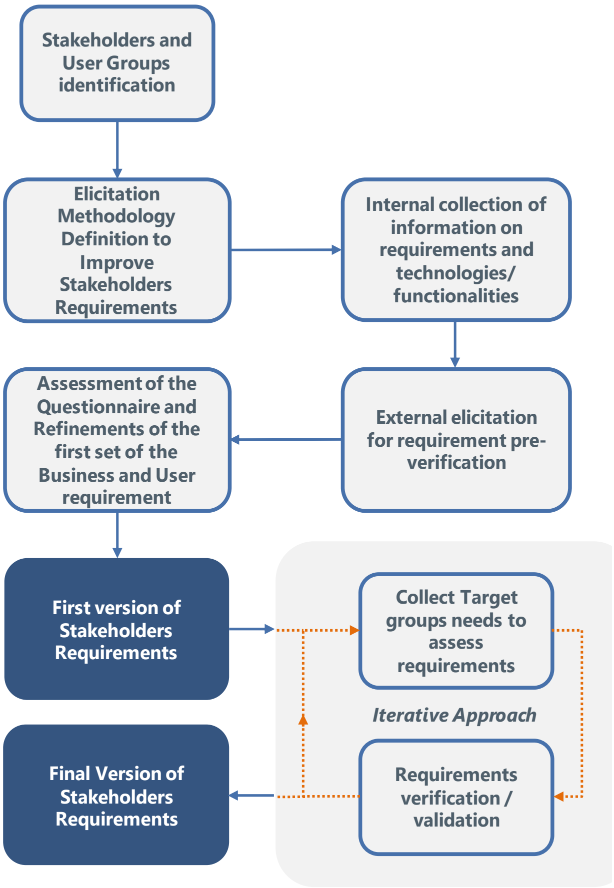

Fig. 4 Flow of the RE process of the eDREAM project

Thus, it is essential to write a good Stakeholder Requirements Specification [12] defining in a clear and correct way the system capabilities. For all these reasons, in the context of the eDREAM project, an iterative approach to elicit and assess the requirements has been defined in Fig. 4.

The essential eDREAM RE process was driven by stakeholders' needs, having involved them according to the approach based on several techniques [13] [14] such as: the study of the literature, the definition of a first set of requirements through the internal interrogation of the pilots by the internal technology providers in order to create a project presentation and a survey / questionnaire for the external stakeholders, the organization of workshop, conference and public consultation with particular focus on the specific stakeholders.

The functionalities provided by the eDREAM platform are compared continuously with the different stakeholders' requirements: stakeholders and end users of the set of eDREAM technologies and components are involved in all phases of the project. Therefore, it is important to use a common method and elicitation techniques and to provide a set of clear requirements for the developers of the system. Within the eDREAM project, the RE process has been structured in several phases as shown in Fig. 4. The first phase aims to provide the definition of the methodologies for identifying the stakeholders and elicit the requirements. A first set of the requirements has been defined through the study of the literature and the internal consultation of the pilots by the internal technology providers and, subsequently, it has been validated through a first round of external consultation in which other Horizon 2020 project consortia has been involved in order to create the requirements' base, useful for subsequent activities.

TABLE 1 PHASE 1 OF THE RE PROCESS

Phase 1: Elicitation preparation and definition of the first set of requirements
• Definition of the methodology for the identification of the potential stakeholders; • Definition of the Elicitation methodology to retrieve information for the Stakeholders Requirements; • Internal Elicitation for the identification and categorization of the first set of Stakeholders Requirements; • Preparation of a short, clear and informative presentation of the project for the stakeholder groups identified; • Preparation of the questionnaire to retrieve needs from external stakeholders; • Use of the presentation together with the questionnaire for the external elicitation to pre-verify the requirements and to release the first version of the Stakeholders Requirements.

In the Second phase, the requirements previously defined are consolidated through the application of the RE techniques as well as the further involvement of external stakeholders.

TABLE 2 PHASE 2 OF THE REQUIREMENTS ELICITATION PROCESS

Phase 2: Consolidation of the external requirement elicitation process
• Use of different RE techniques to involve external stakeholders; • Release of the final version of the Stakeholders Requirements.

The same process for requirements analysis and definition will be repeated on the same level of the system definition procedures, providing specific requirements outcomes for the other part of the iteration, i.e. the architectural design process, and for the definition and implementation of the eDREAM system following the methods and the specifications defined in [15] and [16].

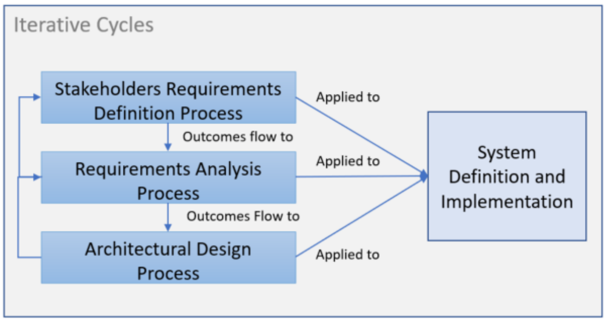

Fig. 5 Iterative application of processes for the Requirements Elicitation and System Specifications

In parallel to the work on the requirements, the internal and external elicitation process was used to define the use cases of the eDREAM project following the general specification defined in the IEC 62559-2:2015 [17] and the specific methodology for the smart grid sector [18], adopting two representation categories for the use cases, each one with a different level of abstraction and different level of granularity:

- High level use case (HL-UC): describes a general idea of a function;
- Low level use case (LL-UC): addresses functional requirements implemented in a specific sub-system characterized by a defined boundary.

In the overall eDREAM context has been identified three high-level scenarios: (1) prosumers flexibility aggregation via smart contract, (2) Peer-to-peer local energy trading market via smart contract and (3) Virtual Power Plant (VPP) in energy community. The particular use case of interest for this paper is the use case (1) related the prosumer DR flexibility aggregation via smart contract that allow to enable the prosumer to offer via smart contracts their flexibility resources, both production and loads modulation. A specific template, based on the "basic use case template" suggested by Alistair Cockburn [19], has been adopted for the definition of the use cases.

IV. MACRO FUNCTIONALITIES AND USE CASES

With the aims to facilitate the use cases definition and thus the system development of the eDREAM platform, in the consideration of the two pilot sites of the Project (one related to the microgrid and one related to the VPP), as well as the framework architecture [20], ten different functionalities grouped under three macro-functionalities came up after the business requirement engineering process. The three identified macro-functionalities go through the entire process needed for the provision of Blockchain Based Decentralized Management of DR services for providing energy flexibility in Smart Energy Grids. Among the ten functionalities, eight are reported as essential for the realization of the project objectives with the reference on High-Level Use Case of interest for this paper.

MF1: DR optimal design

DR potential pre-assessment: The aggregator will be able to use drones to assess the potential application of Demand Response in a specific zone (i.e. a district).

DR strategies assessment: The market operators (aggregators or coalitions) can show to prosumers and to DSO the energy consumption/production patterns, forecasts the production/consumption for each prosumer and evaluate the baselines on different scales as well as reward mechanisms for the end users, with the aim to dynamically formulate and validate their DR strategies and their business models, and show cost and benefits to potential clients.

MF2: DR Services and big data technologies for optimizing flexibility

Load and Generation profiling: The system will consent to a system or market operator (i.e. retailers, aggregators, DSO etc.) to profile the load of customers/prosumers at different scale. For instance, an aggregator can load the profile of the customers/prosumers based on their behaviours and then profile them according to some Key Performance Indicators (KPIs) (i.e. estimation of the potential available for DR strategies), assigning the consumers/prosumers to a particular customer group by recognizing the customer's load profile pattern defined according to the selected demand response strategy to be adopted (price-based programs, incentives, Time of Use etc.).

Active grid System flexibility DR services: The prosumers, directly or via enabling aggregators, will be able to offer their production assets as flexibility resources. Ideally also a DSO can exploit for itself the grid flexibility in order to improve grid stability, accessing on the grid resources and managing the flexibility of the single producer to provide flexibility-as-a-service. The DSO will be supported in decision making, the actions selected will operate on services to balance the grid and then the platform will match the requested services with prosumers offers.

MF3: Secure blockchain-based applications for DR management, control and financial settlement

Secure Energy data handling: aggregator/DSO/retailer will store data feed by smart energy metering devices using blockchain distributed ledger framework in secure way.

Smart contract for DR flexibility services: aggregators aggregate individual flexibility of prosumers via smart contract in response to the DSO flexibility request and are made aware of individual prosumer deviations from flexibility request.

Decentralized coordinated control for micro-grid: The DSO can control the assets of specific producers, in single form of in the form of a coalition, balancing the grid. As result the DSO will be enacted with the possibility of assessing and tracing the share of the contracted flexibility service has been activated in reality at the grid level.

DR Financial Settlement: The aggregator can validate the automatic financial settlement of DR transaction using blockchain. In UK, for instance, today it can take up months [21], based on the existing measurement and verification requirements from National Grid for each commercial programme, for the payments to reach the end-users. Data collected from the aggregators is reconciled against fiscal meters data via Elexon – a process that is time and resource consuming. In the smart contract scenario, each energy unit delivered by a participating site in any programme generates a token transaction that can be exchanged in real time for its monetary value.

High Level Use Case: prosumers DR flexibility aggregation via smart contract

The defined Use Case involves DSOs, aggregators and prosumers. Its main objective is to establish a mechanism for aggregating flexibility and detecting in near real time the amount of flexibility actually provided by each prosumer.

The aggregation of the flexibility potential provided by multiple prosumers and the management of the individual deviations will avoid grid level congestion points, solving potential grid issues. To do so, prosumers are enrolled with aggregators, who knows their flexibility availability through current and forecasted data from power production and load demands.

When the DSO identifies potential issues on the grid (e.g. congestion and reverse flow), a flexibility request is sent to the aggregator through the marketplace. Based on the received flexibility request, the aggregator inquires its enrolled prosumers to identify the subset which may deliver the expected flexibility, creating an offer on the marketplace. The consolidated flexibility request curves are being injected into the prosumers self-enforcing smart contracts by the aggregator, then the deviation among the prosumer actual energy consumption and the expected profile is measured. In case of significant deviations, other prosumers (from the enrolled ones) will be identified, to provide the missing amount of flexibility. The deviating prosumers (if any) will be penalized while the prosumers operating as expected will be rewarded through incentives.

Low level Use Cases

Below is detailed the action flow of the LL-UC, that represent the steps needed to accomplish the HL-UC:

1. Prosumers enrolment in demand response programmes: aggregator negotiate with its customers (prosumers) showing the benefits through interactive multi-purpose visualization tool for user interaction.

2. Contract setting: aggregator and prosumers agree on baseline and incentives for activation of flexibility through the initialization of the self-enforcing smart contract in which the prosumers provide their energy flexibility availability interval.

3. Potential energy flexibility evaluation: aggregator periodically evaluate the potential energy flexibility guaranteed by prosumers using drones for aerial surveying in combination with thermal imaging and laser scanning to assess the application of Demand Response in a specific zone.

4. Energy demand/production forecasting for day-ahead trading of flexibility: aggregator receives from each prosumer enrolled the individual energy demand/production values for the next day and create and send a forecast of the aggregated energy demand of all of their individual clients to the DSO which use it to forecast future congestion points.

5. Flexibility request: DSO creates a forecast of the total load on the critical branches of the network (i.e. parts of the grid for which a congestion is expected) and in case congestion is forecast, sends a flex request to a Flexibility Marketplace with associated incentives (intraday: step is repeated);

6. Flexibility offering: Based on the received flexibility request, the aggregator inquires its enrolled prosumers to identify the subset which may deliver the expected flexibility and injects the flexibility request curves into the prosumers self-enforcing smart contracts that measure the deviation among the prosumer actual energy consumption and the expected profile set through flexibility request curve.

   a. if there is no deviation, the aggregator responds to the flexibility request by placing a flexibility offer in a Flexibility Marketplace.

   b. if a deviation is measured at the aggregator level, the smart contract will try to identify other prosumers (from enrolled ones) to provide missing levels of flexibility in order to place a flexibility offer in a Flexibility Marketplace. If the DSO accepts the flexibility offered then the prosumer deviating will be penalized while the one taking up the missing flexibility will be rewarded using DSO provided incentives to the aggregator.

7. Flexibility acceptance: DSO accepts one or multiple flexibility offers and, if so, the DSO sends a flexibility order.

8. Flexibility provisioning: aggregator sends the flexibility orders to its prosumers (injection of demand curve via a smart contract) in order to adjusts the load of its clients to fulfil the flexibility need. The prosumers that followed the provided curve by shifting their load will receive payment from the aggregator for the flexibility provision based on their flexibility contract (settlement).

V. CONCLUSIONS

In this paper, we have proposed a system for the decentralized control of flexibility on smart energy grids. We started with the current situation of distribution grids and the advantages provided by the microgrids. To solve the potential issues deriving from grid imbalance, we proposed a decentralized control mechanism through the usage of blockchain technologies. We defined use cases and requirements involving the stakeholders, considering them as the basis for drafting the system requirements and architecture, thus to ensure the results in terms of functionality, usability and accessibility.

The proposed approach can lead to new business opportunities, providing the aggregators the possibility to operate in a “pay-per-use” model.

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