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1. Introducción

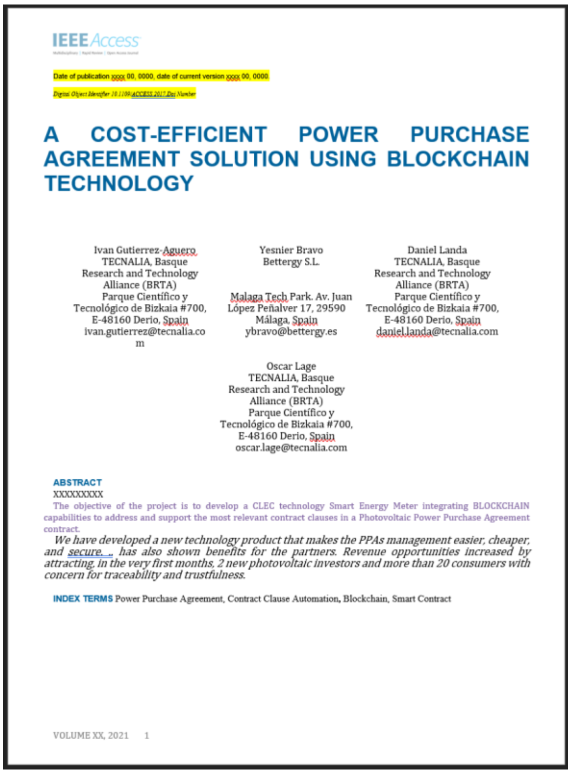
Una actividad importante en todo proyecto de investigación es la difusión y la comunicación de los resultados. en este proyecto también se incluye una actividad en esta dirección para exponer y validar en la comunidad científica los resultados obtenidos en la investigación realizada.

Concretamente se quiere validar la aplicación de la tecnología Blockchain para agregar valor a a la gestión de los contratos PPA en el marco de proyectos de energías renovables. Por un lado, los beneficios de la solución brindan mayor confianza y seguridad tanto para el inversor como el cliente en un proyecto fotovoltaico. También, desde la perspectiva ecológica, la solución sirve como mecanismo para promover el uso de energía limpia, siendo este una de las herramientas actuales que más se está impulsando para combatir el cambio climático.

Dentro del proyecto se trabajó en la elaboración de un artículo científico que se enviará para publicar en la revista *Journal of Energy Markets*[1], de referencia en el sector. A continuación mostramos extracto de contenido del artículo.

2. Artículo científico resultado de la investigación

A continuación, se muestran capturas de pantalla del artículo científico en el que se está trabajando para su publicación a corto plazo.



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A COST-EFFICIENT POWER PURCHASE AGREEMENT SOLUTION USING BLOCKCHAIN TECHNOLOGY

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ABSTRACT
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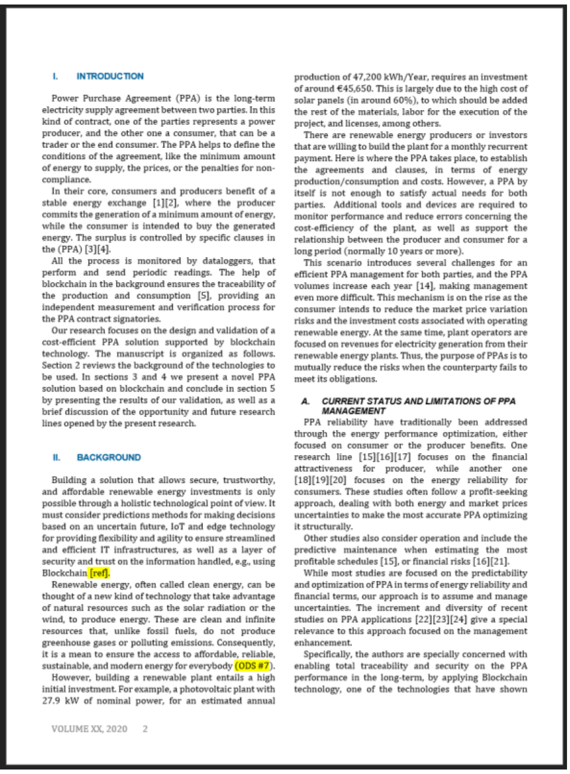
The objective of the project is to develop a CLEC technology Smart Energy Meter integrating BLOCKCHAIN capabilities to address and support the most relevant contract clauses in a Photovoltaic Power Purchase Agreement contract.

We have developed a new technology product that makes the PPAs management easier, cheaper, and secure. . has also shown benefits for the partners. Revenue opportunities increased by attracting, in the very first months, 2 new photovoltaic investors and more than 20 consumers with concern for traceability and trustfulness.

INDEX TERMS Power Purchase Agreement, Contract Clause Automation, Blockchain, Smart Contract

VOLUME XX, 2021 1



I. INTRODUCTION

Power Purchase Agreement (PPA) is the long-term electricity supply agreement between two parties. In this kind of contract, one of the parties represents a power producer, and the other one a consumer, that can be a trader or the end consumer. The PPA helps to define the conditions of the agreement, like the minimum amount of energy to supply, the prices, or the penalties for non-compliance.

In their core, consumers and producers benefit of a stable energy exchange [1][2], where the producer commits the generation of a minimum amount of energy, while the consumer is intended to buy the generated energy. The surplus is controlled by specific clauses in the (PPA) [3][4].

All the process is monitored by dataloggers, that perform and send periodic readings. The help of blockchain in the background ensures the traceability of the production and consumption [5], providing an independent measurement and verification process for the PPA contract signatories.

Our research focuses on the design and validation of a cost-efficient PPA solution supported by blockchain technology. The manuscript is organized as follows. Section 2 reviews the background of the technologies to be used. In sections 3 and 4 we present a novel PPA solution based on blockchain and conclude in section 5 by presenting the results of our validation, as well as a brief discussion of the opportunity and future research lines opened by the present research.

II. BACKGROUND

Building a solution that allows secure, trustworthy, and affordable renewable energy investments is only possible through a holistic technological point of view. It must consider predictions methods for making decisions based on an uncertain future, IoT and edge technology for providing flexibility and agility to ensure streamlined and efficient IT infrastructures, as well as a layer of security and trust on the information handled, e.g., using Blockchain [ref].

Renewable energy, often called clean energy, can be thought of a new kind of technology that take advantage of natural resources such as the solar radiation or the wind, to produce energy. These are clean and infinite resources that, unlike fossil fuels, do not produce greenhouse gases or polluting emissions. Consequently, it is a mean to ensure the access to affordable, reliable, sustainable, and modern energy for everybody (ODS #7).

However, building a renewable plant entails a high initial investment. For example, a photovoltaic plant with 27.9 kW of nominal power, for an estimated annual production of 47,200 kWh/Year, requires an investment of around €45,650. This is largely due to the high cost of solar panels (in around 60%), to which should be added the rest of the materials, labor for the execution of the project, and licenses, among others.

There are renewable energy producers or investors that are willing to build the plant for a monthly recurrent payment. Here is where the PPA takes place, to establish the agreements and clauses, in terms of energy production/consumption and costs. However, a PPA by itself is not enough to satisfy actual needs for both parties. Additional tools and devices are required to monitor performance and reduce errors concerning the cost-efficiency of the plant, as well as support the relationship between the producer and consumer for a long period (normally 10 years or more).

This scenario introduces several challenges for an efficient PPA management for both parties, and the PPA volumes increase each year [14], making management even more difficult. This mechanism is on the rise as the consumer intends to reduce the market price variation risks and the investment costs associated with operating renewable energy. At the same time, plant operators are focused on revenues for electricity generation from their renewable energy plants. Thus, the purpose of PPAs is to mutually reduce the risks when the counterparty fails to meet its obligations.

A. CURRENT STATUS AND LIMITATIONS OF PPA MANAGEMENT

PPA reliability have traditionally been addressed through the energy performance optimization, either focused on consumer or the producer benefits. One research line [15][16][17] focuses on the financial attractiveness for producer, while another one [18][19][20] focuses on the energy reliability for consumers. These studies often follow a profit-seeking approach, dealing with both energy and market prices uncertainties to make the most accurate PPA optimizing it structurally.

Other studies also consider operation and include the predictive maintenance when estimating the most profitable schedules [15], or financial risks [16][21].

While most studies are focused on the predictability and optimization of PPA in terms of energy reliability and financial terms, our approach is to assume and manage uncertainties. The increment and diversity of recent studies on PPA applications [22][23][24] give a special relevance to this approach focused on the management enhancement.

Specifically, the authors are specially concerned with enabling total traceability and security on the PPA performance in the long-term, by applying Blockchain technology, one of the technologies that have shown

VOLUME XX, 2020 2

[1] Journal of Energy Markets - a Risk.net journal

most potential to transform climate finance and green investment [25].

As far as the authors knowledge, very few studies there exist on PPA and Blockchain, mostly focused on Certificates of Origin of green energy and energy crypto-assets or tokenization of the amount of energy [refs].

However, there is still a lack of a guarantee in the traceability of the PPA clauses, there are no systems that provide an independent and decentralized measurement and verification process for the signatories of the PPA contract. In addition, there is no reliable verification between the actual production and the corresponding invoices where the agreed price and clauses are reflected, throughout the duration of the contract.

B. COST-EFFICIENCY IN PPA MANAGEMENT

Traditional cost analysis of PPAs is based on the optimal dimensioning of the renewable installation and the predictive maintenance (e.g., [15]), thus minimizing initial costs and avoiding corrective maintenance that may be expensive and cause long downtimes, respectively.

However, there are still PPA inefficiencies related with operative costs, including the cost of the execution and data measure and verification. Significant back-office work for its signatories exists due to a lack of trust in the long-term. Participants need additional security for the PPA management while automating control of what amount of energy is produced, and consumed, or contract clauses violated, and when.

This could drive to additional operational efficiencies removing the cost of the salaries of people employed for the PPA execution. As these costs often form part of the contract price, then the new model could make renewable projects more accessible.

C. EDGE COMPUTING AND PPA

In a PPA monitorization scenario, the data gathering of the required measurements often follows an edge computing pattern [6]. Since these sensors have a natural life of thousands of sensing actions [7], sensed data is handled in a way that feasible data is generated and transmitted from the source.

In some implementations there is also the ability to update the sensor over-the-air [8], so changes can be made to the algorithms (token, thresholds, etc.) without the need for on-site visits, which may be economically unfeasible. This could be useful, for example, to remotely update the threshold for a PPA clause verification performed locally.

However, the management of the data gathered is still centralized. Issues with this approach include privacy concerns due to third party management of Cloud servers, single points of failure, a bottleneck in data flows, and others [26].

An enhancement is required to create a secure and independent data flow. This sensor could not only able to measure energy produced but also to validate PPA clauses and raise alerts in a distributed way (different from doing all validation in a centralized server).

D. BLOCKCHAIN DESIGN PRINCIPLES

There are several aspects to be considered to choose the appropriate blockchain platform when starting a project involving PPA. The same considerations can be applied for other projects relating the energy sector, because they involve specific actors like service providers, customers, and data sources, where the structure is precisely defined with respect to the business process.

An analysis of the major differences between the different blockchain technology alternatives is a critical design point [9] to determine which approach fits best for profitability and business process in the energy sector.

The first aspect to identify is if the most relevant scenarios need a permissionless network or a permissioned one instead [10]. A technology allowing both possibilities is a good option to start if there are no other initial constraints. The decision is about (i) deploying your own private network where you control who can access it, favoring the centralization and reducing attack vectors and possible data leaks. Or (ii) deploying your smart contracts into a public network where anyone knowing the address and its interface will be allowed to interact with it, maximizing the availability and the transparency. In this case, some internal logic of the smart contract may control the access to the data contained in each PPA.

Other aspect is to know if the communications are from one business to another, and all the participants in the use case shall be authorized before the network is designed and provided with credentials from a Trusted Third Party. While this case [11], covered by platforms like Hyperledger Fabric, fit better in business to business (B2B) designs, are less prone to business to consumer (B2C) designs [12].

A third aspect is the project scalability plan, to foresee if the system may have to scale in the future in terms of users, nodes, or transaction throughput.

A final aspect is the need of a token [13], whether for user rewards, funding aspects of the initiative or system, or functionalities such as contract accounting. Even though some networks have a built-in (native) token and others not, this is not a constraining aspect from the PPA point of view.

III. BLOCKCHAIN-ENABLED PPA SOLUTION MATERIALS

A. RELEVANT ACTORS

To better explain the need of a blockchain-enabled PPA solution the relevant actors taking part in a PPA contract have been identified, and their roles, requirements and obligations are explained in this section.

The main actors that take part on a PPA contract lifecycle are the energy production, the energy consumption, and the measurement registration.

This manuscript has extracted from the energy supply chain the three actors related to PPA contracts and studied them to isolate the properties that associate actions in a PPA with those anticipated to increase the cost efficiency by using blockchain (see **¡Error! No se encuentra el origen de la referencia.**).

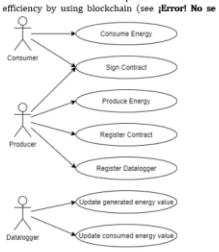


Figure 1. Blockchain-enabled PPA solution actor diagram.

a. Producer

The investor of an energy generation installation will meet the requirements established by the PPA contract for the energy production, becoming the producer actor.

The producer registers the PPA into the blockchain providing information previously agreed with a consumer about the energy generation limit values, as well as the price of the energy in each range bounded by those generation limits.

The producer will also provide the list of dataloggers authorized to update the generated and consumed energy values associated to the PPA.

The PPA will be linked to the consumer, so the energy generation and consumption balance is periodically calculated, so it can be said that the producer has closed the period for the PPA to check its clauses.

b. Consumer

The consumer actor represents the entity to which the installation that takes part in the PPA belongs to. The consumer self-manages the confirmation of its own participation. To do so, the consumer must validate the terms of the PPA and sign the agreed PPA with a blockchain transaction.

c. Datalogger

The datalogger is the only source allowed to update the generated and consumed energy values. The submitted updates are always associated to a PPA.

The datalogger periodically gathers measurement values. They pack this information and then sign it with their private key. Finally, they send it signed to blockchain.

B. RELEVANT SCENARIOS

The process proposed in this manuscript enables the definition of a list of six relevant scenarios that are enclosed in the PPA management to cover the full contract lifecycle.

In this subsection, formal methodologies [31][32][34] have been followed to name each use case and describe it in a comprehensive manner by indicating a list of steps that shall be followed to extract the most relevant information for cost-efficiency.

a. Scenario 0: PPA contract management

The initial use case (see **¡Error! No se encuentra el origen de la referencia.**) is the base for the establishment of the PPA contract.

ID	S.00
NAME	PPA contract management.
DESCRIPTION	Creation of a PPA contract.
ACTORS	Producer
TRIGGER	New energy production installation is installed.
PRE CONDITIONS	None
POST CONDITIONS	The PPA contract is created, registered and accessible.
NORMAL COURSE	1. The producer registers the PPA contract in blockchain obtaining a 'PPA Contract ID'. 2. The producer registers the PPA contract in the application using the 'PPA Contract ID'.

TABLE 1. PPA contract management

b. Scenario 1: Inventory management

This basic use case allows to register new dataloggers associated to a PPA contract (see **¡Error! No se encuentra el origen de la referencia.**).

ID	S.01
NAME	Inventory request.
DESCRIPTION	The consumer registers a new datalogger.
ACTORS	Consumer
TRIGGER	New datalogger is installed.
PRE CONDITIONS	S.00 is executed.
POST CONDITIONS	The datalogger is registered and bonded to the PPA contract.
NORMAL COURSE	3. The consumer registers a datalogger in blockchain associated to the 'PPA Contract ID'.

TABLE 2. Inventory request

c. Scenario 2: Generated and consumed energy update

This use case covers the path of updating the energy data collected by the dataloggers (see **¡Error! No se encuentra el origen de la referencia.**). In the scenario defined for the experiments, the dataloggers communicate directly with the blockchain. This direct channel guarantees the integrity and no repudiation of the data from the source to its management in the smart contract.

ID	S.02
NAME	Generated and consumed energy update.
DESCRIPTION	The dataloggers must register in blockchain all the generated and consumed energy.
ACTORS	Datalogger
TRIGGER	Datalogger collects new generated or consumed energy.
PRE-CONDITIONS	S.00 is executed. S.01 is executed. Each energy production installation has one or more dataloggers capable of being blockchain users.
POST CONDITIONS	The generated and consumed energy balances are updated.
NORMAL COURSE	1. The datalogger collects the generated and consumed energy data. 2. The datalogger sign the collected data. 3. The datalogger sends to blockchain the collected data associated with the 'PPA Contract ID'.

TABLE 3. Generated and consumed energy update

d. Scenario 3: Energy balance recover

This use case (see **¡Error! No se encuentra el origen de la referencia.**) lets the consumer to totalize the energy balance, specified by the sum of generated and consumed energy ($\sum_0^{t-1} energy\_value$).

The cost value is the aggregated value from the last balance recovered. Its formula is defined by **¡Error! No se encuentra el origen de la referencia.**, being b the current energy balance read by the dataloggers in the last period and p the PPA contract energy price agreed for that moment.

ID	S.03
NAME	Energy balance recover.
DESCRIPTION	The consumer totalizes the current total energy cost related to their PPA contract.
ACTORS	Producer
TRIGGER	The producer requests the totalization of the current total energy cost value related to a 'PPA Contract ID'.
PRE CONDITIONS	S.00 is executed.
POST CONDITIONS	The current total energy cost is reset for a consumer.
NORMAL COURSE	1. The smart contract calculates the current total energy cost value. 2. The smart contract updates the last total energy cost value. 3. The smart contract resets the current total energy cost value.

TABLE 4. Energy balance recover

Algorithm Energy balance calculation

```
procedure Consumption(balance, price)
  let total_balance ← 0
  while read(balance) ≠ 0 do
    total_balance += balance
  end while
  balance ← 0
  return total_balance * price
end procedure
```

Algorithm 1. Energy balance calculation

e. Scenario 4: Maintenance activities

In this scenario (see **¡Error! No se encuentra el origen de la referencia.**), maintenance activities are performed for a specific inventory component using the provided management form from the application. Warranties shall be checked (see **¡Error! No se encuentra el origen de la referencia.**).

ID	S.04
NAME	Maintenance activity.
DESCRIPTION	The producer performs maintenance activities for a given energy production installation.
ACTORS	Producer
TRIGGER	The producer registers a maintenance activity.
PRE CONDITIONS	None
POST CONDITIONS	The list of maintenance activities is available.
NORMAL COURSE	1. The producer registers a maintenance activity for a specific datalogger. 2. The smart contract checks for warranty violations. 3. The smart contract returns the maintenance activities.
ALTERNATIVE COURSE	1. The smart contract returns a warranty violation alert.

TABLE 5. Maintenance activity

Algorithm Check for warranty violations

```
procedure CheckWarranty(ppa_contract_id, activity_type)
  let expiration ← find(ppa_contract_id).end_date
  if activity_type ≠ "component replacement" do
    return find(ppa_contract_id).maintenance
  else if expiration ≥ time.now
    return find(ppa_contract_id).maintenance
  end if
  return error
end procedure
```

Algorithm 2. Check for warranty violations

f. Scenario 5: Monitoring alerts

In this scenario (see **¡Error! No se encuentra el origen de la referencia.**), PPA contract clauses are being continuously monitored to raise alerts when any 'clause violation' is detected (see **¡Error! No se encuentra el origen de la referencia.**).

The possible types of 'clause violation alert' defined for the experiment are:

- Daily generated energy below threshold.
- Daily generated energy over threshold.
- Monthly generated energy below threshold.
- Monthly generated energy over threshold.
- Daily consumed energy below threshold.
- Daily consumed energy over threshold.
- Monthly consumed energy below threshold.
- Monthly consumed energy over threshold.

ID	S.05
NAME	Monitoring alerts
DESCRIPTION	The PPA contract are monitored to raise an event in case of clause violations.
ACTORS	Producer Consumer
TRIGGER	S.02 is executed.
PRE CONDITIONS	S.00 is executed. S.01 is executed.
POST CONDITIONS	The list of clause violations is available.
NORMAL COURSE	2. The smart contract checks the clauses violations for a PPA contract.
ALTERNATIVE COURSE	3. The smart contract raises an event.

TABLE 6. Monitoring alerts

Algorithm Check for clause violations

```
procedure CheckClauses(ppa_contract_id, balance, period)
  let min← min(find(ppa_contract_id).clause,period)
  let max
     ← max(find(ppa_contract_id). clause, period)
  if min ≤ balance(period ) && max ≥ balance(period) do
    return
  end if
  return error
end procedure
```

Algorithm 3. Check for clause violations

A. PPA CONTRACT DESIGN

The PPA contracts are defined by standardized parameters and clauses that must be agreed between the producer and the consumer specifically for each signed PPA contract. A comprehensive work on the definition and parameters of a PPA can be found in [32].

In this section, we summarize the key parameters of a PPA, which are tentative to be managed in a decentralized and secure way. Typical parameters concerning personal information of the signatories are not considered, due to privacy concerns. Instead, a unique identified is taken in both cases.

i. General Data

The "General Data" parameters state the basic information to be included in every PPA contract. It sets the relationship between actors.

- *PPA contract reference*: A unique string value that identify the agreement.
- *Type of PPA*[34]: Category. The default value is "Direct PPA".
- *Consumer*: The facility owner's unique identifier. This actor will consume the energy generated by the energy production installation.
- *Producer*: The producer's unique identifier. This actor will build and operate the energy production installation.

ii. Contract Duration

The "Contract Duration" parameters state the information relating to the periods of the PPA contract and how often the "Energy balance recover" operation shall be called.

- *Start date*: The date on which the PPA contract comes into value.
- *Contract duration*: Natural number, greater than 0, meaning the number of months until the PPA contract expires.
- *Suspensive condition*: Allow to set the date from what the plant must be already producing energy.
- *Frequency of payment*: Natural number, greater than 0. The frequency with which the totalization is called. The default value is "1".

iii. Energy Data

The "Energy Data" parameters define the information used for the "Energy balance recover" and "Monitoring alerts" calculation operations.

- *Installed power*: Float number, greater than 0. The sum of the nominal power installed.
- *Minimum yearly generation*: The minimum amount of energy to generate in a year.

iv. Economic Data

The "Economic Data" parameters listed below vary depending on the generation and consumption thresholds. The solution allows three different values for these parameters: (i) standard conditions, (ii) underperformance and (iii) overgeneration.

-
- *Energy pricing*: Float number, greater than 0. The energy price for the produced unit of energy.
- *Energy purchase low threshold*: Float number, greater than 0. The percentage of energy that is mandatory to purchase, even not used.

v. Set of PPA contract violations

According with the above mentioned parameters, there is a set of PPA contract clauses that must be respected. Otherwise, it entails a *PPA CONTRACT VIOLATION* alert should be raised somehow. The authors have selected four cases of anomalous behavior which help the actors to manage the PPA operation correctly:

1. Generated energy abnormally low, with the code LOW_PRODUCTION_ALERT. This is launched when incidents in the installation require corrective maintenance.
2. Consumed energy abnormally low, with the code LOW_CONSUMPTION_ALERT. This is launched when there is a greater feed to the grid than the consumption.
3. The energy production installation did not start operating on the date expressed in the PPA contract, with the code SUSPENSIVE_CONDITION_ALERT. This is launched when the value of the parameter "Duration of suspensive condition" is not being respected.
4. PPA contract end date is approaching, with the code CONTRACT_FINALIZATION_ALERT. This is launched when the current date is near the addition of "Contract duration" (y) to the "Start date" ($t0$) parameter, as represented in **Error! Reference source not found.** By default, the backup period is a 10%.

Algorithm Check for PPA contract finalization

```
procedure CheckEndAlert(ppa_contract_id)
  let t0 ← find(ppa_contract_id).start_date
  let y ← find(ppa_contract_id).contract_duration
  let backup ← contract_duration * 0.1
  if t0 + y ≥ now() + reserve
    return CONTRACT_FINALIZATION_ALERT
  end if
  return 0
end procedure
```

Algorithm 4. Check for PPA contract finalization

IV. METHOD AND PROCEDURE

The blockchain-enabled PPA solution offers a secure communication flow, where data gathered from dataloggers is sent directly to blockchain. The dataloggers periodically collect information and send it signed through an agent running a blockchain decentralized application (DApp).

Once the data arrives to blockchain network, the related contractual clauses of the PPA are verified. This action is possible because the verification operations are implemented in the smart contracts and customized with each PPA's clauses that have been previously accepted by the contract signatories.

An alert will be raised if a clause is violated. The alerts are received by the authorized actors correctly subscribed to the topic of an event channel. As an alert means that there's a contract disturbance, the mediator business can intervene when needed, restoring the normal execution, and saving time and money for the signatories.

A. ADRESSING THE CHALLENGES IN THE PPA MANAGEMENT

PPAs can be very different as they must be adapted to the specific application. This occurs because of its bilateral agreement nature. The producer and the consumer must agree point by point on the contract.

This manuscript presents reliable ways to manage prices and the clauses from PPA contracts that respond to the traditional challenges in the PPA management [28]. A relevant scenario has been modelled considering the different scenarios where PPA contracts can be presented. This scenario must have per energy production installation, at least:

1. One PPA contract: The PPA includes actions derived from measures and contract clauses.
2. Datalogger: This device is in charge measuring the amount of energy produced by the renewable plant and energy consumed by the facility sending this information to the Blockchain.

A key innovation in the energy transactions is the ability to get automatic balances based on the amount of energy generated by the energy production installation [29][30].

Moreover, to mutually reduce the risks and conflicts between parties, it is mandatory to monitor the violation of the agreed contract clauses. When a violation occurs during the life of a PPA, an automated and decentralized alert event registration ensures the execution of the contract agreements. Naturally, these alert events should be created from trusted and certified energy readings, needing dataloggers capable of ensuring the data origin. This way, the producer can provide evidence of the origin.

The consumers need a way of getting direct access to a reliable source of information without intermediaries. This specific challenge is susceptible to be met by the usage of blockchain, following the line of decentralization.

In summary, the PPA management challenges tackled by this manuscript are:

3. Monitoring the violation of contract clauses.
4. Automating the billing process.
5. Certifying green energy origin.
6. Granting self-management to consumers.

B. PROCEDURE

To provide a solution on the CURRENT STATUS AND LIMITATIONS OF PPA MANAGEMENT explained on section II.A, a new operational design is presented. The proposed solution enables a blockchain-based scenario, where the consumers become autonomous, and the producers reduce management costs thanks to automatically settled agreements written in smart contracts.

Thanks to the blockchain network, a digital record of measures allows to calculate the clauses of the PPA and back it at the distributed ledger. All the information is

handled cryptographically to minimize the attack vectors.

The flow of the operation (see Figure 2) begins with some offline negotiations between the producer and the consumer to agree on the PPA contract's clauses.

As later will be shown in the Figure 3, the producer uses a DApp to communicate with the smart contract and register the PPA (createPPA). Among other information the producer provides the generation limit values as well as the prices of the generated energy in each range bounded by those limits and registers the dataloggers (linkMeterToPPA) that are authorized to send their measures into the PPA by providing their credentials. This is an in independent task from the creation of the PPA due to the possibility that the dataloggers change during the life of the PPA.

After a successful PPA creation the consumer receives informative event and proceeds to query the PPA details (getMyPPAs, getPPADetails) and, once validated, sign it to confirm the participation in the PPA (signPPA). The consumer uses a DApp to perform these actions in the smart contract.

Once the contract is registered, it is ready to accumulate measures from the dataloggers. The dataloggers connected to the consumer's installations periodically collect measures about the energy generation and consumption values. Then the dataloggers use a DApp to communicate with the smart contract and deliver the measures (saveEnergy). The dataloggers have no information about the relationship of the dataloggers to the specific PPA. The smart contract gets that relation from the credentials used by the datalogger to sign the measures sent.

Once the PPA has received the measures belonging to a full balance period, the balance is closed by the producer (closeBalancePeriod). At this stage, the smart contract will calculate the generation costs, notify the consumer by means of an informative event, and reset the balance period.

The producer can also validate the clauses established in the PPA by requesting the closing of a validation period (closeValidationPeriod). When requested, the smart contract will validate the clauses and issue clause violation alerts when applicable with specific clause details.

C. SOLUTION COMPONENTS

Figure 3 shows the architecture designed for the blockchain-enabled PPA solution that facilitates the operation process of the PPA. Its purpose is to build and manage the identification of actors and the functionality. This functionality is driven by production and consumption capabilities, specified by the consumer and certified in a secure way by the clauses agreed in each PPA.

Every involved actor will need a DApp to exchange certified information between them over the blockchain network to which they are all connected.

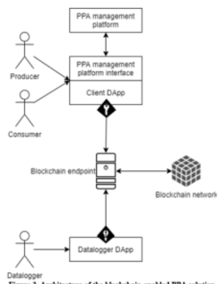


Figure 3. Architecture of the blockchain-enabled PPA solution.

a. Blockchain endpoint

The blockchain endpoint is the server (commonly called node) connected to a blockchain network. This blockchain endpoint will be reachable by the actors using their associated DApps to complete the process detailed in the PROCEDURE section.

The process is implemented by the functionality developed in a smart contract that is deployed in all the blockchain network nodes. This model covers all the needs from the relevant scenarios, be grouped in the following categories:

7. PPA contract registration
8. Measure registration
9. PPA clause compliance monitoring
10. Cost of generation calculation
11. Data query

b. PPA management platform

The proposed blockchain-enabled PPA solution does not remove PPA management platforms. Instead, it adds value by means of a trustful software layer.

This platform is connected to the plant by means of standard communication protocols and provide to the consumers different information to that managed by blockchain.

The PPA management platform will provide the font-end support to the users that allow them to interact with blockchain using the Client DApp. This platform nor its operator can interact with the blockchain network, access to the PPA contract data or see the user credentials. This is achieved because blockchain needs that the user confirms each transaction from a DApp.

c. Client DApp

The DApp for producers and consumers is a client application that allows these actors to interact with the blockchain network and access this functionality of the smart contract as stated in the relevant scenarios.

In the proposed solution, producers and consumers access to the system from the PPA management platform interface, offered by the PPA management platform. Access to the functionality is granted by the Client DApp, so it can manage the interaction with blockchain and the user credential storage.

Every input to the blockchain ledger must be signed by a private key, that in this case, corresponds to a user defined in the referred PPA contract.

d. Datalogger DApp

The datalogger performs periodic measurements on the produced and consumed energy of the installation where it has been connected.

Then it packs this information into a transaction and signs it by means of a python library called web3py and a blockchain credential previously set in the smart contract. There is no explicit information sent to the smart contract about the PPA contract associated with the datalogger. The smart contract will deduce it by the identity of the datalogger.

V. RESULTS

The purpose of this manuscript is to propose a new solution for the management of the PPA contracts with a cost-efficient perspective based on the digitalization allowed by the usage of blockchain.

The cost efficiency comes mainly from the trusted automation of the operations and the self-management that is a novelty from the user point of view.

The software components and the functionality are key points for this solution, since they help to cover the blind points existing on the PPA management [36][37]. This section explains those materials that helped to give shape to this coverage, defining the stages where a consumer can become autonomous on its own management; designing the event broadcasting for the most important energy production installation alerts; and studying the main formulas of a PPA contract and selecting those where the automation with blockchain could give better results. Finally, a case study has been proposed to help materializing this procedure.

A. SELF-MANAGED CONSUMERS GRANTED

The proposal of enhancing the management of the PPA contracts by using blockchain proves a new concept of interactions between actors.

The producers can digitalize the settlement of the PPA contracts and give autonomy to their dataloggers. And the dataloggers can recollect measures and deliver them in a direct way, without the need of trusting in a centralized platform which would work as a black box.

Due to the nature and the tecnologies used in the blockchain platform, every participant actor has full confidence of the integritiy and non-repudiation of any information exchanged.

Granting self-management to consumers means that they manage their own account instead of trusting in a third party.

From the perspective of this proposal, every user account is independent from the PPA management platform, protected by a password and recoverable with a unique set of words, called mnemonic. This way, blockchain ensures the uniqueness and independency of the consumers.

B. A DISTRIBUTED SOLUTION

Given the nature of the described procedure, blockchain data will be directly managed by the corresponding actor. To this extent, the actors need to trust in the smart contracts deployed in each network node to manage the PPA contract lifecycle.

Ethereum, for instance, provides a trust-minimized platform where no trusted third party is needed and nevertheless, the whole system is trusted. So, this could be a good starting point for the development of a fully distributed solution.

The authors considered the data minimization principle, by including on-chain on the procedure only the PPA information required to verify the clauses and to do energy balances, while the personal information is kept off-chain in the PPA management platform, also complying with current privacy regulations. In addition, the authors recommend sending to blockchain only aggregated data and hashes instead of the production data, also taking care of scalability and performance of the solution.

Comparing the costs of the solution maintenance, the use of a public network has a cost attached to the transactions executed, whereas using a private network has the cost of the maintenance of the servers that host the network itself. Which kind of network to use is dependent to the needs of the platform involved and the relevant actors.

C. FORMULAS ADDRESSED BY BLOCKCHAIN

The way to find a cost-efficient solution is to pick up the advantages of the automation provided by blockchain. The interactions performed between the relevant actors during the PPA contract lifecycle have some operation points where the smart contracts are a trusted source for the results needed.

To this extent, there are some PPA contract parameters that blockchain must manage to automate the calculations needed to leverage the power of the technology in benefit of the cost-efficiency. These parameters are:

1. PPA contract reference
2. Installed power
3. Energy pricing
4. Energy generation low threshold
5. Energy generation high threshold
6. Energy consumption low threshold
7. Energy consumption high threshold
8. Warranty expiration

This solution provides four strategic operations that allow the actors to be autonomous, solving the issue of depending on a trusted third party

a. Energy Cost

The energy cost is the first element for which calculation can be automatized. The cost at a specific moment ($C(\omega)_{\square}$) can be defined as the current energy balance ($\sum_{i=0}^{n} e(\omega)_i$), given by the summation of all readings ($g(\omega)_i - c(\omega)_i$) made by the dataloggers registered in an installation belonging to a consumer, adjusted to the energy price (p). This brings Equation 1 and Equation 2 as a result.

$$e(\omega)_i = g(\omega)_i - c(\omega)_i$$

Equation 1. Balance given by generation and consumption readings.

$$C(\omega)_{\square} = p * \sum_{i=0}^{n} e(\omega)_{i_{\square}}$$

Equation 2. Energy cost.

b. Mandatory energy purchase

The energy purchase is intended to have a mandatory amount of energy ($M(\omega)_{\square}$) that is the low threshold established by the PPA contract to be purchased by the consumer for each period. This value is bound to the energy consumed ($c(\omega)_i$) and the energy price (p) for the considered period. This is mathematically described by Equation 3.

$$M(\omega)_{\square} = p * \sum_{i=0}^{n} c(\omega)_{i_{\square}}$$

Equation 3. Mandatory energy purchase.

c. Purchase of energy over the Minimum energy purchase value

Purchase of energy over the minimum = (Energy generated – Energy committed) * Energy price

d. Total energy

Based on the calculations made to get the mandatory energy purchase ($M(\omega)_{\square}$) and the c. Purchase of energy over the Minimum energy purchase value ($O(\omega)_{\square}$) established by the PPA contract, the smart contract can obtain the total energy ($T(\omega)_{\square}$) for an installation belonging to a consumer.

$$T(\omega) = M(\omega) + O(\omega)$$

Equation 4. Total energy cost.

D. CASE STUDY: USE OF THE SOLUTION IN A WORKING PLATFORM

This section presents how does the proposed solution work with a current system and what happens to the lifecycle when the flow is intervened by the blockchain solution.

When two parties (the producer and the consumer) reach an agreement on how the energy is going to be produced and consumed, they create and sign a PPA contract. The basic elements and considerations of the contract are commonly digitalized and managed by a platform provided as a service to the final consumer.

The producer, helped by a DApp, registers a new PPA contract proposal sending the needed elements from all the PPA contract elements. This is the first interaction with blockchain, and it is in a proposal state. Now, the consumer can accept the contract request by the producer, creating the full-working PPA contract in blockchain. As both the producer and consumer operations are signed with their private key, they can't repudiate this signature, and anyone could verify this contract (not only the platform as in the state-of-the-art solutions).

Each datalogger will be represented by a blockchain identifier, although more than one identifier can be attached to one energy production installation. The dataloggers registered per energy production installation are defined by the PPA contract. So, only the allowed dataloggers can send measures to blockchain referencing one PPA contract. The measures they send are also digitally signed, guaranteeing the origin of the energy, and avoiding disputes between actors.

Once a period is ended, the smart contract can calculate the cost and deviations, given the clauses and the sum of dataloggers' measures.

For the case study, the authors have chosen dataloggers with the same characteristics as a Raspberry Pi Model 3B. This allowed to cut costs and demonstrates that common and cheap market-available elements can accomplish the needs of the proposed scenarios. Chosen dataloggers allowed to run Python code, as the security and the blockchain DApp they use are written in Python. A local display to show per datalogger (i) single measure values and (ii) green/red verification status icons is also desirable, although it's not mandatory to cover this paper needs.

A centralized view of this scenario is both a bottleneck for the consumers' self-management and it lacks trust to perform peer-to-peer operations in the producer-to-consumer relationship.

On its side, the proposed solution makes autonomous users on the accomplishment of the PPA contract clauses and guarantees the origin of the measurements performed by the dataloggers.

VI. CONCLUSIONS

A. ENHANCEMENTS IN PPA MANAGEMENT

The solution proposed by this manuscript presents some (7) enhancements to the autonomy of the actors. In the state-of-the-art solutions, the actors are forced to trust in a third party providing the service, the agreements, and the numbers. In addition, these services mean a bottleneck in PPA contract management, that is freed with this solution, adding smart contracts to provide automatic PPA executions.

The challenges that this proposal overcomes are listed below these lines:

- To find a reliable way to manage prices and clauses from PPA contracts.
- To get balances automatically based on the amount of energy generated by the energy production installations.
- To control the violation of the PPA contract clauses, registering alert events in a decentralized way.
- To decentralize the management of information and cost calculations, solving the issue of depending on a trusted third party.
- To decentralize the access of users to the information. Now, they can be autonomous.
- To get an origin certification report from the energy readings.

B. DATA OWNERSHIP

Assuming that is important that certain parts of the data contained in a PPA contract can only be visualized by specific kinds of actor, this cost-efficient solution is built on the basis that the operations performed by some functions on the smart contract are only callable by specific roles (e.g., the owner of the contract, or a registered datalogger).

Each blockchain address (representing the user identifier) shall be assigned to one or more roles. When a user (origin) makes a call to a smart contract function generating a new transaction, the access allowance is

validated by taking advantage of one of the major benefits offered by blockchain, that is non-repudiation.

To improve the user data protection, the authors recommend using a DApp to manage one's own data while interacting with blockchain to operate PPA contract. Using cloud-hosted wallets from third party servers could incur on data and money loss [38][39].

C. ENHANCEMENTS IN COST-EFFICIENCY

Added to the enhancements to the autonomy of the actors, this manuscript presents demonstrable enhancements in cost-efficiency.

The use of Blockchain reduce PPA management costs due to eliminating, for example, personnel for operating the PPA. Common PPA operation tasks include periodic on-site monitoring, energy billing, contract clauses verification, and detection of anomalies. On the one hand, the proposed solution allows to manage PPA contracts even within trustless relationships. All the information is saved in an immutable, reliable, and decentralized registry that can be verified at any time in the future.

Also, smart contracts are implemented to automate frequent billing and clauses verification. In summary, we can manage a PPA contract with less personnel and resources in comparison with the conventional way.

A renewable installation of 1 MWp can cost about 700,000 €, considering 0.7 €/Wp, with 20 years of operation. Normally it requires 1 person for the operation, assuming a salary of 25,000 € per year, it represents an additional cost of 17.86 % (125,000 €) over the project cost. The Blockchain enabled solution saves that significant amount thus making renewable projects more affordable.

D. MARKET OPORTUNITY

This solution has a high market impact. Major market segment are solar producers looking at monitorization tools for maximizing security and minimizing maintenance costs to achieve the highest profitability.

Revenue opportunities are increased with this solution, by attracting new renewable energy producers and consumers with concern for traceability and trustfulness, as the PPA are contractual relationships that takes many years (20 year or more). It provides them with an easy-to-install and security, what is particularly appropriate for long-term agreements.

In addition, it allows addressing small projects (< 1 MWp) that were normally not considered because they did not pay out due to the additional operational costs.

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