Blockchain for Energy Sharing and Trading in Distributed Prosumer Communities

Ioan Petri[a,*], Masoud Barati[b], Yacine Rezgui[a], Omer F. Rana[b]

[a]*School of Engineering, BRE Institute of Sustainable Engineering, Cardiff University, Wales, United Kingdom*
[b]*School of Computer Science & Informatics, Cardiff University, Wales, United Kingdom*

Abstract

The decentralisation of energy supply and demand can contribute decisively to protecting the environment and climate of the planet by consuming electricity in the proximity of the generation source and avoiding losses in transmission and distribution. Supporting energy transactions with emerging intelligent technologies can advance the development of energy communities and accelerate the integration of renewable sources. Distributed energy solutions play an essential role as they are explicitly designed to produce, store and deliver green energy. Profiting with these benefits is essential, especially in the context of the current debate on stopping climate change. Several technologies such as waste heat recovery with intelligent algorithms can improve the energy distribution and provide significant resource savings. On the other hand, the usage of Blockchain technology in energy markets promises to incentivise the use of renewables and provide a reliable framework to monitor real-time information of energy production and consumption. Blockchain can also enable trading between independent agents and lead to the formation of more secured energy communities.

In this paper, we demonstrate how Blockchain can be utilised to support the formation and use of energy communities. We propose a Blockchain-based energy framework as a mean to support energy exchanges in a community of prosumers. We demonstrate how smart contracts can manage energy transactions and enable a more secured trading environment between consumers and producers. We utilise data and models from a real fish processing industrial site in Milford Haven Port, South Wales, based on which we validate our research hypothesis.

Keywords: Energy communities, Blockchain, Fish industries, Smart Contracts, Cost.

*Ioan Petri
Email addresses: petrii@cardiff.ac.uk (Ioan Petri), baratim@cardiff.ac.uk (Masoud

1. Introduction

Industries in all sectors now depend heavily on the reliability and efficiency of energy infrastructure. Existing energy systems aim to improve network efficiency and boost electrical power supply access, consistency and durability. These advantages can allow companies to safeguard their processes and prepare themselves for future requirements while ensuring scalability. In general, three main issues are faced by industries, commercial areas, large buildings, towns and communities: (i) increased cost with energy, (ii) protection of energy supply and (iii) reduction of CO2 emission.

With the recent advent of modern technologies such as Blockchain, Internet-of-Things (IoT) and Artificial Intelligence (AI), decarbonisation, decentralisation and digitalisation of energy is more accessible [1]. The aim is to intelligently and sustainably produce, supply and use energy as an optimised mix of distributed energy resources (DER) such as renewable energy, combined heating and power stations, or storage systems, supported by sophisticated energy management. The outsourcing of energy excess can be realised on the basis of an energy-as-a-service model. Such solutions involve a combined analysis of data and application of intelligent technology principles to integrate consumption and production unit with renewable energy sources [2].

The decentralisation of energy production and consumption and associated energy transition have increased potential to address the multiple challenges that the energy systems face, such as rapid depletion of resources, air pollution, greenhouse gas emissions and energy poverty. This transformation is gaining increased relevance in buildings as more "consumers" of energy become independent "prosumers" that can generate electricity themselves, in particular utilising the new intelligent storage systems that can add flexibility to the overall grid. In such a scenario, regular buildings become active energy traders that can sell any electricity surpluses to the energy market and contribute with their energy capacity to the energy community [3].

Therefore, local, decentralised, and controllable production and storage solutions have advanced in capability, greatly supporting end-users to benefit from their production capacity by monetising energy surplus and achieve full independence from the grid. Such economic models identify greater benefits for grid operators that can tackle to performance gap in energy consumption by managing demand to reduce peak loads. Flexibility in energy demand and supply represents a key advantage also for large industrial sites which can reduce costs by selling the excess capacity on the market [4]. We argue that such technological advancements in the field of energy can pave the way towards a developing world driven by intelligent systems with three main benefits: environment protection, more reliable energy supply and increased economic benefits.

The emergence of sharing economies with the change in consumption models

Barati), rezguiy@Cardiff.ac.uk (Yacine Rezgui), o.f.rana@cs.cardiff.ac.uk (Omer F. Rana)

can motivate energy prosumers to participate in a leasing energy market where services are used for a shorter period and more accessible via community sharing [5, 6]. Blockchain can incentivise the participation in such a sharing economy providing greater choice for both energy consumers and providers while enabling a much greater flexibility in being able to switch between multiple market offerings. Such sharing economy has the potential to decentralise energy production but can also can balance consumption from consumers by not being restricted to energy services or price constraints from a single energy provider.

Blockchain technology can offer the mechanisms required to support energy resources decentralisation. In particular, energy companies can use intelligent contracts to transfer ownership of resources and to track energy used or purchased by consumers. Many people receive their electricity from big sources, but the rise in decentralised forms of energy production, such as wind and solar, enables more homes to generate their own energy [7, 8]. Technological advances on smart meters are also contributing to help the homeowners in using the excess energy ownership and transfer it on to others via Blockchain-based agreements [9].

This paper provides a Blockchain model to support decentralisation of energy supply and demand in prosumer communities. We devise an Ethereum environment where smart contract transactions can be processed and executed within an energy sharing market. Our proposed smart contracts also meet some requirements of General Data Protection Regulation (GDPR), aiming to protect users from privacy violations and forcing companies to upgrade their business processes to become compliant with such regulation. We test "the reliability" of our model in an Ethereum environment with data from a real industrial site. We also verify "the scalability" of our model to support an increased number of transactions and users by creating an energy community simulation environment using Peersim simulator. The work presented in this paper is part of the EU H2020 piSCES project aiming to develop smart cluster energy grid systems for fish industries.

The remainder of the paper is as follows: In Section 2, we present related works in the field of Blockchain for energy communities, in Section 3 we provide context for our research. In Section 4 we present the community case study followed by the methodology in Section 5. We provide an evaluation of the Ethereum protocol for energy exchanges in Section 6 and develop a simulation for the energy community in Section 7. We conclude our work in Section 8.

2. Related work

A secure and efficient Blockchain-based energy trading model has been proposed in [10]. The model not only enhanced privacy of users but also achieved the balance between power supply and demand. The proposed Blockchain energy trading model (BC-ETS) leverages on three main goals: (i) privacy preservation, (ii) effectiveness and credibility and (iii) security supported with verification, matching and update operations for transactions. The model is limited in terms of validation as it only explores a system overhead perspective without analysing cost implications.

A Blockchain-based energy trading scheme for secure energy trading in intelligent transportation systems has been presented in [11]. The schema utilized coins for energy trading transactions in the Blockchain network, where the miners were opted based on different factors such as energy requirements and pricing. The security of the trading scheme is ensured between the electric vehicle, the transaction server and the miner nodes. An evaluation based on communition cost and computation time is provided within an experimental testbed. The mitigation of the vehicles and storage vulnerabilities is not addressed as transactions are dependent on the reliability of the nodes rather than the actual security policies.

A power trading problem has been modelled as interactions among an admin, energy producer, and energy subscriber nodes [12]. The model has been validated by presenting a power trading scenario, which is implemented by a Blockchain platform called as Multichain. While using an admin node to manage interaction between consumers and producers, the actual validation of this study is limited as there is no evaluation for the reliability of the model. The key differentiation in our work is the data protection and privacy models that we consider to support smart contract transactions. From this perspective we are concerned to ensure a certain reliability of the Blockchain framework when executing energy transactions across a community of energy actors.

A transactive electricity marketing model has been developed with the aid of Blockchain in [13]. The model enabled local prosumers to engage in peer-to-peer energy trading. A contract theory was exploited in the model to design a smart contract providing the real-time electricity trade with minimal need of oversight. The model enables prosumers to participate in transactions based on a satisfaction index threshold with a demand driven pool of consumers. Although the work studies the relationship between demand, generation and satisfaction index, the protocol disregards the verification and attestation phases in the smart contracts.

The notions of home miner and Blockchain-based smart home was described in [14]. The authors proposed a secure and automated decentralized renewable energy trading platform in micro grid through Blockchain. The study presents a real Ethereum deployment for energy trading in smart buildings. Although a novel approach, the privacy and security aspects are neglected as transactions are not verified and users are not integrated within a reliable authentication model.

An efficient vehicle to grid (V2G) energy trading framework by using Blockchain and edge computing technologies was proposed in [15]. The former technology led to the creation of a consortium Blockchain-based secure energy trading for V2G. The latter technology improved successful probability of block creation with a view to optimise the communication channel and computational resources for the blockchain. The study focuses more on the computational infrastructures with reduced contribution around transactions and associated privacy and violation clauses.

A Blockchain-oriented approach to solve the problem of privacy breach in the energy trading within smart grid was presented in [16]. The authors propose a noise-based privacy-preserving method to conceal the trading distribution trends for Blockchain-enabled neighbouring energy trading system. The interaction between buyers and sellers is managed by a token bank that authorises energy transactions. The validation is well-elaborated with an emphasis on the cost implications but the actual scalability of the approach has not been demonstrated. As a factor of comparison, our work provides a wider community perspective by testing different scenarios where the number of consumers and providers is increased as well as the number of transactions. We thereby validate the Blockchain framework from a scalability perspective where data and observations are extracted from a real-application case study.

An effective solution for secure energy trading in the Blockchain-based Industrial Internet of Things (IIoT) was proposed in [17]. The method enabled nodes (buyers or sellers) to realize power loads by using local energy storage. The study uses the assumption that energy harvesting and power loads remain unchanged for a given time slot which reduces the applicability of the model. Also the number of nodes under which the simulation is performed is low which impacts on the scalability of the model.

A proof-of-concept system of the wireless communications infrastructure supporting Blockchain application for energy trading was introduced in [18]. The system involved a secured channel to transmit data between smart meters and cloud-based Blockchain platform. The transmission of data is identified as a key objective where transactions status depends on the security level of the sensors infrastructure and the quality of the broadcasted message.

A Blockchain-based technique for distributed energy exchanges in microgrid system was proposed in [19]. The technique synchronized the scheduling of energy resources of microgrid and accredited a fair payment mechanism without the necessity of a centralized aggregator. Two algorithms are utilised to deliver the micro-grid framework where the validation is developed around auctioning and scheduling without a comprehensive discussion of security and privacy implementation of the smart contracts.

A software defined networking (SDN-based) energy Internet trading scheme was presented in [20]. The schema exploited Blockchain to realize a secure and intelligent distributed energy trading and designed a reasonable matching algorithm for trading users in accordance with some privacy-based premises. The contract includes energy quantity, price, time, credit and location and involves one buyer and several sellers to reach an agreement. In terms of security, the protocol is under-developed with a generic evaluation that explores possible applicable Blockchain systems.

In [21], the authors by introducing a research project called as "Pebbles", developed a Blockchain-based platform to provide a transactive energy mechanism in grid environment. The platform enabled local energy markets to be directly accessible for both prosumers and grid services and it only contributes at the architectural level to support users in deploying transactions within a cloud environment with a view to achieve energy balancing within different regions.

Various software platforms can support interaction between energy actors using Blockchain. Such platforms enable Blockchain transactions between different actors such as buyers, sellers, or suppliers which can act as buyers or sellers. Elecbay [22] is a Blockchain simulation platform, where entities such as energy consumers and prosumers have the ability to sell and buy energy by scheduling the energy devices in their own premises typical for small-scale residential and commercial sites. Similarly, SunChain [23] uses Blockchain technology to execute transactions between consumers and energy producers using smart meter data for distributed ledgers. Such ledgers are then spread across the distribution network for operators and energy suppliers. PROSUME [24] represents a decentralised Blockchain platform that aggregates energy producers, consumers and utilities with a variety of applications. Pylon Network [25] is a network supporting a series of smart metering solutions powered by Blockchain technologies. The solution is developed around a Metron smart meter that integrates Blockchain to record energy production and consumtion within a network. M-PAYG [26] leverages on Blockchain technologies to monetize solar energy in developing countries with rooftop PV systems for rural households based on different membership options.

In energy communities where data is aggregated from smart meter devices, security policies and regulations may need to be checked to avoid putting users at risk and limit their ability to control their confidential data. Several works have attempted mitigate such risks by using Blockchain technology enhancing user privacy and trust in IoT-based applications [27, 28].

In this paper, we leverage on the notion of energy communities regulated through the use of smart contracts. Our Blockchain framework and associated scenarios are aiming to address the following research questions:

- how Blockchain can support the implementation of an energy sharing economy model with a view to incentivise energy trading arrangements in distributed energy networks;

- what are the implications of scaling up Blockchain for energy communities and what strategies can be adopted to unlock industries transition towards clean energy;

We devise two different experimental testbeds where Blockchain smart contracts are utilised to enable prosumers to exchange energy over a number of different scenarios. We provide an Ethereum based subsriber/supplier energy model coordinated by several contract functions “purpose”, “consent”, “payment” and “attestation” and corresponding verification and violation detection mechanisms.

3. Blockchain for energy communities

As the energy market today is transforming towards a large number of suppliers and buyers, it is important to enabling participants to exchange an increased amount of energy. The interaction between these actors and the associated processes require a high degree of standardisation which can be facilitated by a Blockchain model. The utilisation of Blockchain for energy trading can lead to the eradication of brokers, monetisation of energy excess and development of energy communities [29]. Such brokers and intermediary parties, usually are required for validating or for ensuring trustworthiness of information across parties, can be replaced by a more automated Blockchain process. As Blockchain delivers a high level of security and data protection for different applications supported by transparent ledger that records all transactions, third-party verification can be eliminated. In a Blockchain system, any user can become a trader and offer an energy product or service to a group of consumers. Blockchain technology has, therefore, the potential to leverage the benefits of decentralised energy systems and enable an environment where everyone can trade, pay, and even deliver energy to others. Blockchain can support the creation of economically attractive energy communities utilising the power of the Internet and implement the vision of a perfect energy market [30].

Blockchain identifies an online distributed database that aggregates a collection of blocks connected to each other. It is a public and decentralised ledger that stores a set of records, structured as a chain and blocks. From the multiple Blockchain solutions, smart contracts are instruments that can extend the Blockchain capabilities and have been used in a variety of industries. Smart contracts have often been used to convert business rules into codes based on which a contract code/script is stored in a Blockchain. Ethereum [31] is a recent and widely supported smart contracts platform. Ethereum is developed on the concept of "gas" payments to run a smart contract or to execute transactions that change the state of the Blockchain. Gas represents a metric that measures the amount of computational effort required to carry out smart contract operations. The transaction fees use an internal currency as *Ethereum* whereas the gas is charged in *ether* as an Ethereum token, which allows smart contracts to be executed. Although the amount of gas consumed to execute a transaction may be high, the translation into ether is cheaper. For example, if the transaction gas used is 10000, then the transaction fee will be around 0.0002 (ETH) [32]. In the context of Blockchain, Ether motivates miners to validate blocks in Ethereum because for each validation [33] a successful miner is awarded in ethers.

Smart contracts can be also utilised to promote user privacy with a view to securing the deployment of updates for IoT devices [34]. For smart energy meter devices, Blockchain can support a trace log to identify malicious objects or manufacturers information. Different privacy-preserving models have been proposed based on a Blockchain publish/subscribe model [35] by enabling subscribers and publishers to control any data access. Blockchain can also store the events associated with the life cycle of digital evidence from smart devices in a traceable, transparent, and privacy-preserving manner. Smart contracts are independent of any third party as the code/script of the contract is stored in a Blockchain. A smart contract normally contains a number of transactions, each of which may change the state of the chain as in the case of the Ethereum [36]. A recent feature has enabled smart contracts to be deployed on a Blockchain network opened for all users connected to the network [37]. Such flexibility has given smart contracts extended capabilities leading to their increased use in various industrial applications [38].

3.1. Sharing energy communities

Addressing global warming with the implementation of renewable energy strategies can decrease carbon emissions and support the green energy agenda [39]. Such renewable energy sources represent more sustainable solutions and can be a vital sustainability factor for the next decades [40]. According to the US Department of energy, the use of renewable energy sources will increase to about 18% of the total amount of energy use by 2040 [41].

According to the European Regulators Group for Electricity and Gas (ERGEG), the smart grid is an electricity network that can efficiently integrate the behaviour and actions of all providers and consumers. Such providers and consumers can become prosumers and contribute to the development of economically efficient, sustainable power systems with low losses and high levels of quality and security of supply [42]. The decentralisation of energy systems has significant benefits, primarily facilitating renewable energy resources to have integration with local energy resources and to increase the reliability of the power systems with a view to developing communities. Also, the consumption behaviour is vital in energy communities because they can use the energy system smartly to reduce power consumption in peak periods and improve the overall energy efficiency.Transmission of energy from producers to consumers with the aid of computer systems through control automation, continuous monitoring and optimisation of the distribution systems can also be facilitated in a smart grid to reduce the cost and increase the reliability [43, 45, 46, 47, 48, 49].

Recently, the sharing economy principles have been investigated via incentive models where users can provide services over a P2P network [50]. Such services can range from bartering of resources, improving the social standing of a participant within a community or obtaining a financial reward. In open markets such as distributed energy communities, it is necessary for an energy consumer to have the ability to discover suitable providers of interest and to create an added value by monetising an energy product or service.

Our community model is developed around the “sharing economy” principles and aims to unlock the energy trading arrangements for energy communities [51]. Such a P2P sharing model allows each energy node to decide with which energy node to trade (buy from or sell to) according to its own objective, e.g. minimum costs, a specific energy type, most reliable energy supply, etc. We aim to demonstrate such energy sharing scenarios by implementing a scalable Blockchain simulation environment in Peersim, that has the capability to support energy exchanges among energy nodes while also enabling the monitoring and control of the energy distribution network.

In this work, we target to explore how Blockchain can be implemented to support energy sharing in prosumer communities by exploring the performances of the system in a real use-case scenario. We explore different types of energy communities with different energy services (solar, thermal, wind, hydro) with a view to identifying how energy can be efficiently harnessed, stored and transmitted among users of the energy network. We consider that an energy community can identify specific rules in relation to the specific goals, participation policies and requirements imposed by the users of the community.

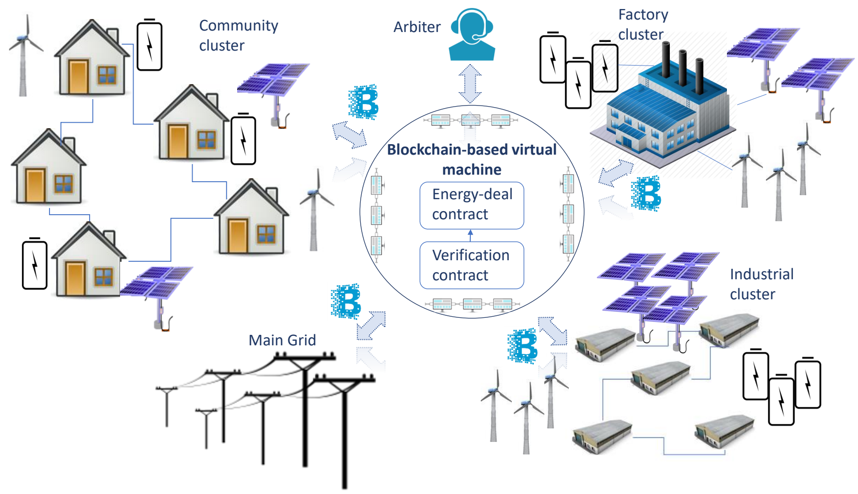


Figure 1: A representation of the energy communities with Blockchain

4. The Milford Haven Port community case study

The Milford Haven Port is the UK's and Wales's largest port [52]. The port offers a range of marine services as well as fish processing activities which are owned and also operated by tenants. The port energy community is formed of five major buildings: Packaway, K SHed, M Shed, F Shed and J Shed (see Figure 2). Each building has PV panels for energy production and several energy consuming appliances for fish processing. A 5 megawatts solar farm is also installed in the port proximity.

Packaway Building. Packaway building is the main building and contains several energy-consuming appliances: a flake ice machine, an ice store freezer, a box washing machine, lighting systems and smart meters. The building has a washing machine with a 50 kW power capacity and only operates when the fishermen clean boxes during the day. The ice flake machine is running all the time to meet the demand for fish storage with the required ice quantity. The Packaway building has installed a PV system with 50 kW panels on the building's roof which feeds the building during the daytime. With 2 DC-AC inverters, they have a total power output of 275 W per panel. The panels produce power during the day and feed it directly onto the national grid. Nonetheless, the system automatically uses the power from the main grid when the fishermen need to use energy to operate the main appliances in the building.

K Shed. K Shed is a warehouse with a large freezer unit used by tenants and with a cold room linked to the solar photovoltaic panels on the building with a capacity of 50 kW. The main hall also has about 62 double tube lighting and chiller storage systems which are connected to the lighting and cooling systems.

M Shed. The building is equipped with internal lighting and several appliances. Building units B & C are used as storage facilities whilst Unit A is used as a boat repair workshop and as an office area and store/workshop for an incident response provider.

F Shed. F Shed is a new six-unit building. The units in the ground floor are used for fish processing, and second, first-floor units are used for fish container storage.

J Shed. J Shed is considered the largest building in the port site and currently is occupied by different stakeholders. It is a complex building and has many electrical systems. The building is split into three occupied units: unit A contains a retail shop with fish processing and office space, fish processing appliances, and storage used by individuals for small processing and storage.

Solar farm. A solar farm is installed with a power capacity of approximately 5 megawatts, containing approximately 20000 panels. The site has four main cabins which convert DC to AC (32000 kV) and then link the solar farm to the national grid.

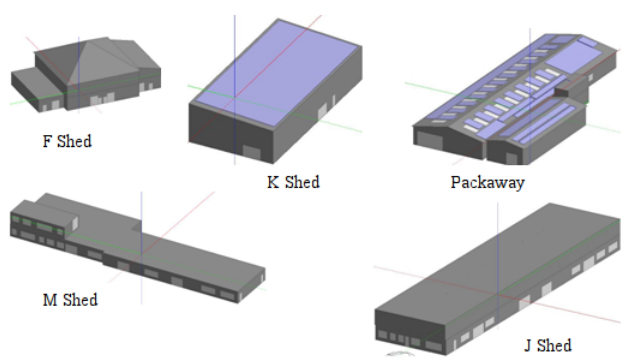


Figure 2: Five buildings community around the Milford Haven port

4.1. Energy community scenario

Each building has a set of appliances monitored by smart meters that are consuming energy from the main grid or from the local PV units. To explore the mechanisms involved in the development of a community, we consider the following consumption units:
Energy consumption units:

- *Ice Flake machine* – The ice flake system is under operation all the time during the day and consumes energy based on different operating schedules in relation of a daily fish processing demand.

- *Cold room* –The cold room is the main appliance in the building with high power consumption. The cold room has a temperature set-point and an operating schedule which have a direct impact on the energy consumed by the appliance.

- *Box washing machine* – The box washing machine has the power capacity of 50 kWh and only works on a limited daily interval, and the power consumption is low.

- *Lighting* – The lighting system in this building is about 23 double tubes lighting of 25 W each and is only used during the night. There is also four storage rooms in the Packaway building and each storage room has a double tube lighting system.

Energy production units identify (i) local PV systems with 50 kW panels for each building and (ii) a 5 megawatts solar farm containing approximately 20000 panels.
We consider the following energy community objectives:

- *Energy consumption* – The objective is to provide consumers greater efficiency and more informed use of energy in the industrial site and wider within the community.

- *Energy production* – The objective is to give energy producers more control over their energy sources and to decentralise production at the site and community level.

General objective: The scenario is applicable to energy communities to support energy exchanges between the different buildings, where each building and its production and consumption units can act as an energy producers or consumers. The overall objective is to reduce CO2 emissions at the port and community level using Blockchain for energy sharing aiming to decentralise energy use and ensure transition toward clean energy.

Consultations and an extensive energy audit process have informed our modelling which uses real site configurations with energy consumers and producers identified by a number of consumption (i.e. ice flake, cold room, etc.) and production metered units (i.e. photovoltaics). We consider the real site configuration with a number of buildings forming a community (i.e. Packaway, F Shed, etc) with their associated production and consumption behaviors. Based on requirements determined during the audit, we have also modelled several assumptions in relation the types of renewables that can be exploited by the port and daily consumption and production schedules, which have been included in the analysis. From the real site audit, we use as inputs of the smart contracts, the Blockchain addresses of both supplier and subscriber, the amount of exchanged energy and the amount of transferred energy and associated costs. These entities and their interactions have been modelled into the Blockchain framework with the objective to (i) understand energy interactions around industrial communities where various subscribers and suppliers identified by their respective units, monitored and controlled via smart meters, can share energy and (ii) provide scalability in analysis with a view to deliver a wider Blockchain based community market perspective for energy intensive industries.

5. A Blockchain-based energy community model

We consider a system formed of energy nodes as providers and consumers (p=$p_{s1}, p_{s2}, ..., p_k$), that are organised into clusters, where each producer node can generate one or multiple types of renewable energy (solar, geothermal, wind, hydro) in a specified quantity with an associated cost and each consumer node requests energy with a predefined quantity. We consider the interaction between a number of different nodes (consumers and providers), as illustrated in Figure 1, with each group of producers and consumers being represented as a community. Each community contains a number of energy nodes capable of producing or consuming energy based on their preferences and production capability. Conceptually, an energy node is a member within the community energy network and operates energy services from/to other energy consumer nodes. The assumption is that each node is equipped with a smart meter calculating the amount of used energy, as received from a particular provider. Smart meters are supposed to individually calculate energy with its associated types (i.e. solar, wind etc) for both consumers and providers.

Figure 1 shows our proposed model in which each node with the role of energy subscriber (consumer) or supplier (producer) should have a Blockchain account to connect to a Blockchain virtual machine like Ethereum to access smart contracts for purchasing/selling an energy type. During the exchange process, each supplier normally asks some personal data items (address, account details etc) from the subscriber to share energy. The assumption is that such data are stored and encrypted off chain in a local storage handled and edited by each subscriber. If a supplier should access the data, the subscriber provides the supplier a private key to decrypt and collect the data.

Our proposed smart contracts along with their functions are depicted in Fig. 3. The contracts not only provide the payment and exchange of energy between two nodes, but also promote the data privacy of subscribers. As illustrated from the figure, there are three smart contracts: *energy-deal*, *verification* and *reading* contracts, which are summarized in Section 5.1 below.

For conducting our modelling and analysis, we use the following list of terms with their associated definitions:

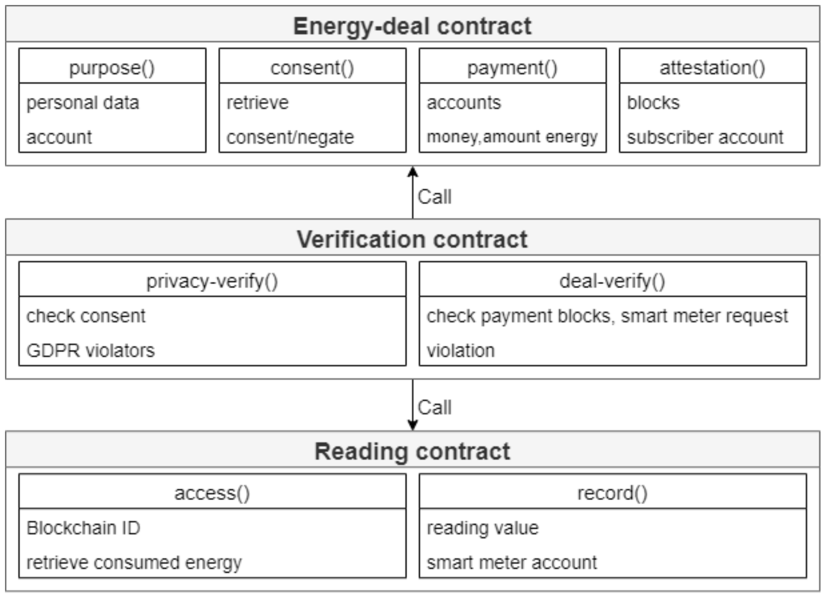


Figure 3: The smart contracts of energy community model

Term	Definition
Subscriber	A role in the Blockchain framework that is scheduled to request and consume energy services.
Supplier	A role in the Blockchain framework that is scheduled to produce and provide energy services.
Consumer	An entity that consumes energy services within the community.
Provider	An entity the produces energy within the community.
Prosumer	an entity that can consume or produce energy services within the community.
$Peer - nodes$	Entities in a Peer-to-Peer network that are involved in the market exchange as consumers, providers or prosumers.
$Energy\ nodes$	Entities in the energy network that can exchange energy as consumers, providers or prosumers.
$Group - based\ nodes$	A group of entities in the Peer-to-Peer network that exist in a network proximity such as clusters and can have common properties and objectives
Exchanges	A process of exchanging energy between a provider and a consumer.

5.1. Energy-deal contract

It contains four functions, called as *purpose*, *consent*, *payment*, and *attestation*.

Purpose function enables energy suppliers to share their Blockchain accounts (e.g. Ethereum wallet ID) with subscribers and to determine what personal data items must be received from subscribers in order to handle the exchange of energy. The items can be subscriber account (e.g. Ethereum wallet ID), credit card information, and the geographical address of subscriber. By activating the function, such items are recorded in a Blockchain to inform subscribers about the personal data that will be collected. In some cases a supplier may ask multiple subcontractors to supply a part of energy required for a subscriber. In such a case, the supplier through the function must inform the subscribers about the subcontractors along with their required data and addresses (Blockchain accounts). The function realizes the Art. 30(1)(b) of General Data Protection Regulation (GDPR) in which the collected personal data and the address of actor (supplier) should be announced to data subject (subscriber) before any data usage.

Consent function enables energy subscribers to retrieve the Blockchain's data (i.e. required personal data items and supplier account) already recorded by the *purpose* function. Moreover, the subscriber through the function can give a positive or negative consent to a supplier (or their subcontractors) before sharing their personal data. Note that, the process of exchanging energy is only subject to the consent of subscriber.

Payment function handles the procedure of buying and sharing of energy. It generates a hash address as a transaction ID that is related to some useful data, including the subscriber account, energy type, and the amounts of transferred money and energy. Such data are stored and encrypted off chain by the supplier. The function automatically records the hash address together with the supplier account (e.g. Ethereum wallet ID) in Blockchain to provide a basis for the audit trail of energy subscribers and suppliers to report any violation in purchasing or selling energy. Such a generated hash address can be decrypted by both the subscriber and arbiter. The latter is a trusted party verifying transactions through Blockchain (see Sect. 5.2). The function also records every access of a supplier to subscriber's personal data in Blockchain for the aim of future verification.

Attestation function provides the subscriber the permission to access the hash address recorded by the payment function to track where their personal data is processing. The subscribers, also by activating the function, can be aware of the history of possible data movement among suppliers (or their subcontractors). The presence of such a function realizes the Art. 15(2) and 20(2) of GDPR under which data subjects (subscribers) have the rights to track their personal data.

5.2. Verification contract

It involves two functions, called as *privacy-verify* and *deal-verify*. The activator of these functions is arbiter who is a trusted third party that has a Blockchain account and executes the functions to check the blocks and detect violators.

Privacy-verify function by calling the *energy-deal* contract and retrieving Blockchain records checks whether the supplier exchanging their energy has received the subscribers' consent or not. If a supplier used or accessed to a subscriber data and did not get a positive consent from the subscriber, it is reported as a GDPR violator through the function. Note that, the function tracks the blocks created by the *payment* function to verify the suppliers collecting or

processing subscriber's personal data.
Deal-verify function automatically verifies the blocks recorded through the execution of *payment* function to detect any breach in the transactions. Precisely, if the subscriber determines a violation when receiving energy (e.g., the supplier shared less amount of energy than one should be exchanged) or the supplier detects a breach from the subscriber in the payment process, each of which can ask the arbiter to examine the violation.

5.3. Reading contract

The reading smart contract provides a secure mechanism for accessing arbiter, subscriber and supplier to the amount of energy calculated by the smart meter. It is deployed in a private Blockchain. The contract contains the following functions:
Record function enables smart meter to send its calculated data (used energy) into a Blockchain.
Access function can be activated by subscriber, supplier or arbiter to retrieve the block involving the amount of consumed energy.

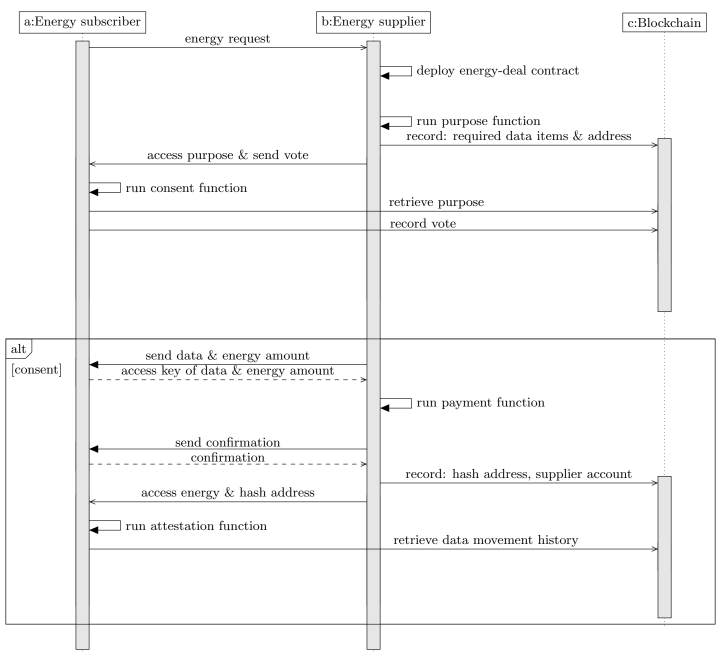


Figure 4: The protocol of selling energy via smart contract

5.4. Realization of the model

The sequence diagram depicted in Fig. 4 represents a protocol for selling/purchasing energy through the energy-deal smart contract. The actors are:

energy subscriber demanding a type of energy, energy supplier offering some types of energy, and Blockchain keeping the transactions. As seen from the diagram, upon the receipt of the energy request from a subscriber, the energy supplier deploys the smart contract to inform the subscriber about the purpose of data processing and handle the payment procedure. The supplier, by activating the *purpose* function, records the required personal data items (i.e. credit card detail, home address etc) and their address (Blockchain account of supplier) in the Blockchain to be accessed by the subscriber. Then, the supplier by sharing the deployment address of the contract waits to receive the consent of the subscriber before any data processing. The vote (consent/ negate) of the subscriber, which is given to the supplier, is sent into the Blockchain. Once a consent has been received from the subscriber, the supplier requests personal data and the amount of energy demanded by the subscriber. After providing the access key of personal data by the subscriber, the *payment* function is activated to manage the process of energy sale and to keep the access of supplier to the personal data in Blockchain. Following that, the supplier requests the subscriber to give a confirmation to complete the process of payment transaction. Through the execution of *payment* function, the supplier account along with a hash address generated as a public key/ transaction ID for referring to the off chain data involving energy type, amount of purchased energy, subscriber account address, and the amount of received money, are stored in the Blockchain to provide an immutable receipt for future verification. Finally, the supplier shares the energy and generates the hash address with the subscriber. As seen, after the exchange of energy, the subscriber by activating the *attestation* function can track their personal data hosts.

We consider that the amount of shared energy is recorded by the smart meter and can be accessible for arbiter (see Sect. 5.6). In this model, we assume that each device is behaving according to specification and identification of failures or abnormal behaviours in smart devices are known a-priori.

5.5. Violation detection protocol

If energy suppliers or subscribers feel that a breach has been committed during the process of purchasing or sharing energy, they can send their breach claim to an arbiter to verify it and detect a possible violation. The arbiter is a trusted third party connected to the Blockchain that can require the verification of a smart contract as a mean to report any breach based on the claim submitted by suppliers or subscribers. Moreover, if a supplier uses personal data while without the consent of the subscriber or its access to the personal data was not notified to the subscriber, such a supplier is detected through the arbiter as a GDPR violator.

Figure 5 illustrates the protocol of violation detection. The main entities of the diagram are: energy supplier/subscriber, arbiter, and Blockchain. The arbiter deploys the *verification* contract to initiate the verification process. As seen, the subscriber or supplier, first, sends their claim together with the hash address, referring to the payment transaction details between a subscriber and

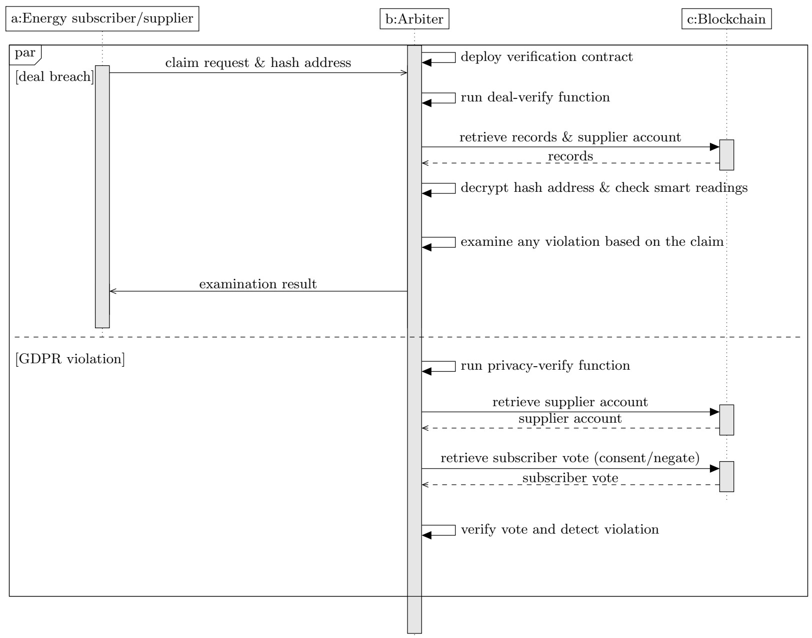


Figure 5: The protocol of detecting any violation

supplier(s) to the arbiter. Then, the *deal-verify* function is executed by the arbiter to retrieve the Blockchain records and checks the supplier and subscriber accounts. The arbiter decrypts the hash address with her private key and submits her vote to the claimer to give a report whether a breach has been detected or not. Such detection is in accordance with the money transferred by subscriber for buying energy or the amount of sold energy by the supplier. Notably, in some cases, the arbiter may also check the smart meter readings to verify the amount of exchanged energy between a supplier and its subscriber.

As seen from the diagram, the arbiter by activating the *privacy-verify* function can in parallel track the transactions recorded by suppliers in the Blockchain to check whether they have received subscriber's consent or not. In this end, the arbiter retrieves the Blockchain records already created by activating both the *payment* and *consent* functions to track the access of suppliers to the subscriber's personal data and monitor the subscriber vote in order to report violations.

5.6. Energy consumption reading

We use a private Blockchain for reading the energy consumption calculated by a smart meter. Energy subscriber, supplier, arbiter and smart meter are the parties interacting with such a Blockchain and each of which has a unique Blockchain account. The smart meter is supposed to have a private key securely stored in the device and it cannot be read out. The meter calculates energy consumption and signs it with the private key before submitting the data to the other parties in the private Blockchain. Hence, the parties are confident that the data has been signed by the meter, since it is impossible that the key has been somewhere else. We have the reading contract that allows only the subscriber, supplier and arbiter to send their requests for accessing the amount of used energy. The following figure shows the interactions of parties for reading the amount of used energy.

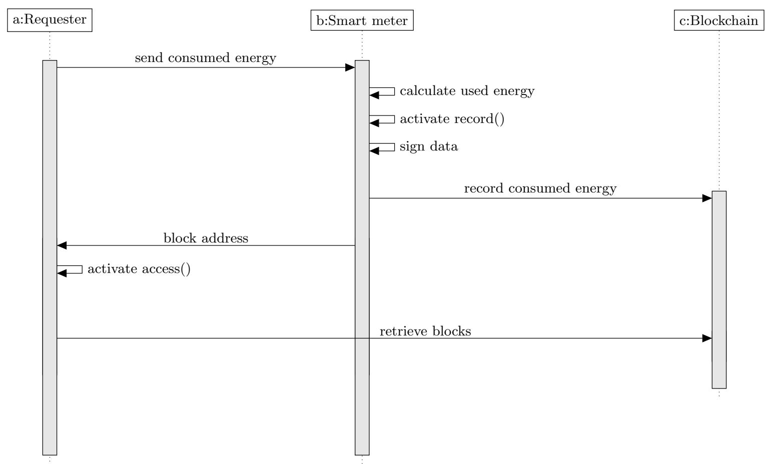


Figure 6: The protocol of reading consumed energy

As seen in Figure 6, a requester (e.g. subscriber, supplier or arbiter) sends a request to the meter for accessing the data. Once such a request has been received by the meter, it signs the calculated energy and sends it via the record function into the Blockchain. Moreover, the meter provides the requester the block address containing the data. Following that, the requester executes the access function to retrieve the calculated energy from the Blockchain. The use of a private Blockchain in such a protocol can promote the level of privacy for meter reading. We deployed the reading smart contract in a private Ethereum Blockchain and the amount of gas consumed for its deployment was 324232wei.

6. Experimental results

An initial prototype was constructed using Ropsten [53], a public test network for Blockchain. We used Solidity [54] to implement our proposed smart contracts on Ethereum. The smart contracts were written per transaction with the objective of minimum gas consumption. They have been tested using Remix, which is an online solidity IDE that runs deployed contracts. In Ropsten the proposed smart contracts, namely *energy-deal contract* and*verification contract*, were deployed. The former enables buyers and sellers to purchase and share energy resources, including wind, solar, geothermal, and hydro. The latter contract provides an audit trail mechanism for tracking the deals between buyers and sellers in order to detect any violation. According to the results showing the

Table 1: The relationship between the number of requests and transaction cost

Energy type	Wind energy	Solar energy	Geo energy	Hydro energy
Energy requests	5	10	15	20
Average consumed gas	247,556	498,995	862,422	999,213
Gas price	1	3	8	13
Average gas cost (Gwei)	247,556	1,496,985	6,899,376	12,989,769
Average gas price (USD)	\$0.05	\$0.19	\$1.2	\$2.43
Average transaction delay (s)	99	45	31	26

amount of used gas for deploying these contracts in Ropsten, the gas consumption was 1297246 *wei* and 364847 *wei* for *energy-deal contract* and *verification contract*, respectively. The amount of used gas for the energy transactions inside such contracts can vary based on several factors, namely the number of energy requests, energy suppliers, and claimers. In this end, the following evaluations show how such factors can affect on time and the amount of gas used for running transactions.

We deployed the *reading* smart contract in a private Ethereum Blockchain and the amount of gas consumed for its deployment was 324232 *wei*.

6.1. The effects of number of energy requests on transaction cost

This experiment evaluates the relationship between the number of energy requests and the cost that should be paid for executing the transaction (*payment* function) implemented for exchanging money and energy between energy subscribers and suppliers. The assumption is that there are four groups of suppliers, each of which offers a particular type of energy that can be: wind, solar, geo, or hydro. The number of energy requests varies from 5 to 20, and each request is sent by an individual subscriber. Moreover, the subscribers of each type of energy determine an amount of gas price, ranging from 1 to 13, for the execution of the transaction. Both subscribers and suppliers have connected to Ethereum virtual machine and received valid accounts in the Blockchain network. Table 1 represents the data that resulted from the experiment. The data involves average transaction delay and consumed gas in both Gwei and USD units. We used ETH gas station[1] for estimating price and time based on the last 1500 blocks created each time. The gas cost in Gwei unit is calculated as: *consumed gas* $\times$ *gas price*. The *payment* function was deployed in Ropsten test network and was activated ten times with different parameters or inputs to calculate the average results, since the function manages the exchange of energy. As seen from the table, increasing the number of requests leads to a significant increase in the amount of consumed gas. This is due to the fact that more cost should be paid for storing and processing more requests. Furthermore, the average delay in seconds obtained for the execution of transactions in each community shows

[1] https://ethgasstation.info

that when the rate of gas price rises, the deployment time of transactions in the Blockchain network decreases remarkably. In fact, higher gas prices encourage miners to validate transactions and create blocks in a shorter period of time.

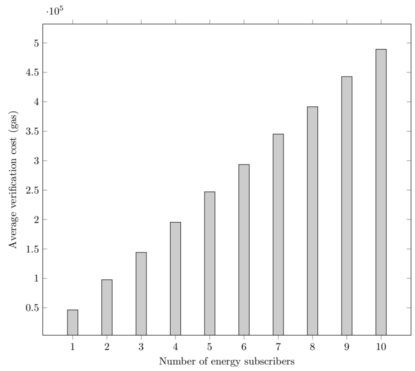


Figure 7: The relationship between the number of subscribers and the verification cost (gas)

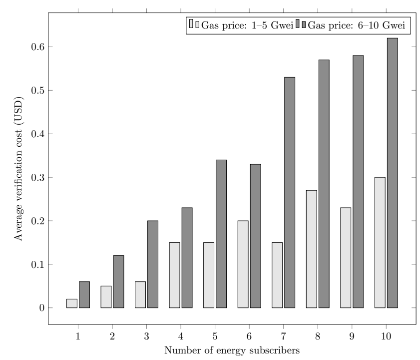


Figure 8: The relationship between the number of subscribers and cost under different gas price

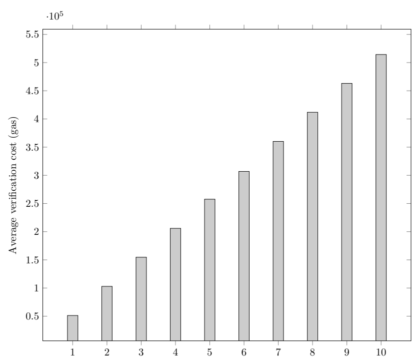


Figure 9: The relationship between the number of suppliers and the verification cost (gas)

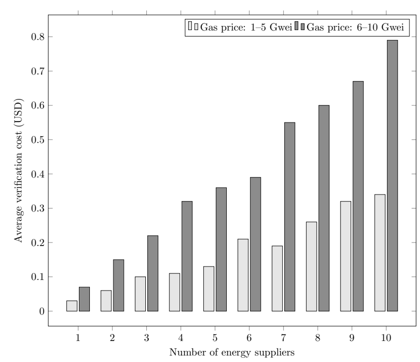


Figure 10: The relationship between the number of suppliers and cost under different gas price

6.2. The evaluation of verification cost

This experiment provides two different scenarios: (i) one for verifying the claim of energy suppliers to detect whether an energy subscriber committed a breach for transferring payment or not; and (ii) the other for checking the claim of subscribers to detect if any violation was committed by suppliers for offering their energy resources. Given the first scenario, the assumption is that each supplier is selling an energy type (i.e., wind, solar and so on). The number of subscribers of the supplier varies from 1 to 10. Each subscriber determines a rate of gas price, ranging from 1 to 10 Gwei. Moreover, it is supposed that there is a violation committed by a subscriber for paying the energy cost. The *deal-verify* function implemented for checking such kind of violation was deployed in Ropsten test network. Figures 7 and 8 provide the experimental results of this scenario. To calculate the average results, the *deal-verify* function was activated 10 times. The supplier determined two different ranges of gas prices for evaluating the verification costs: one evaluation with gas prices between 1 and 5; the other evaluation with gas prices between 6 and 10 for deploying the contract. For each time of transaction execution, the rate of gas was randomly selected based on its range. As comprehended from the figures, when the number of subscribers increases, the verification cost increases steadily. The fluctuations in the increasing trend of the verification cost, in USD unit, depicted in Fig. 8 is due to the random selection of gas prices. The calculation of transaction (verification) cost per each execution is calculated as consumed gas * gas price. When we activated the deal-verify function, the average consumed gas for n and n+1 subscribers did not have significant impact. Given the random selection of gas price per each times of execution, the rate of gas price could effect on the trend of the verification cost and there were some fluctuations in the trend. Furthermore, the average transaction delay for gas price between 1 and 5 Gwei was calculated 77 seconds, and it was around 36 seconds when gas prices were between 6 and 10 Gwei.

The second scenario has used similar aforementioned assumptions for deploying transactions in the first scenario. We have a subscriber, requesting energy from different suppliers varying from 1 to 10. The subscriber also determined two different ranges of gas prices such as those described in the first scenario to evaluate the verification costs. The assumption is that there exists a violation committed by a supplier for selling energy (e.g., energy resource has not been shared with subscriber). Figures 9 and 10 represent the results of this evaluation. Similarly, as seen from the figures, there is a direct relation between the number of suppliers and the verification cost. Moreover, the average time taken for executing the *deal-verify* function was around 74 seconds for gas prices between 1 and 5 Gwei, whereas it reached 32 seconds when the gas prices were between 6 and 10 Gwei.

6.3. The evaluation of verification cost on violation detection rate

This experiment investigates the relationship between the cost paid for verifying a violation and the average rate of violation detection under different number of energy suppliers and subscribers. Figures 11 and 12 represent the results of the experiments, where they were obtained under different scales of energy subscribers and suppliers, respectively. The verification contract along with its *deal-verify* were deployed in Ropsten test network. The assumptions in both experiments are: (i) there is a violation committed by a supplier or subscriber; (ii) the number of suppliers/subscribers vary from 20 to 40; (iii) the amount of gas price is randomly selected between 1 and 10. The x-axes indicate

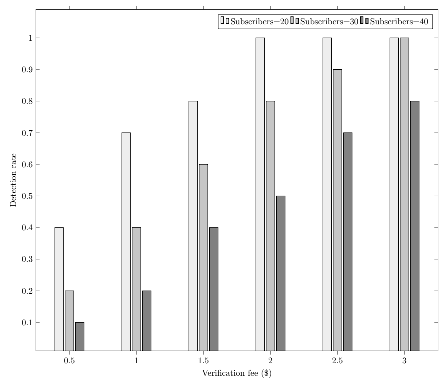


Figure 11: The relationship between the verification cost and violation detection rate under different number of subscribers

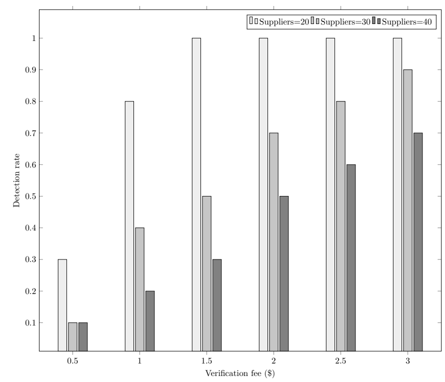


Figure 12: The relationship between the verification cost and violation detection rate under different number of suppliers

the verification fee changing from 0.5 to 3 USD and y-axes show the average rate of violation detection obtained after ten times execution of verification contract. As seen from the bar charts, there is a direct relationship between the fee paid by the subscriber or supplier for verifying a claimed breach and the rate of violation detection. Moreover, for a given price, when the number of energy subscribers or suppliers increases, the violation detection rate decreases gradually. For instance in Fig. 11, when the number of subscribers is 30 and the cost paid by the energy supplier for checking a violation is merely $0.5, the violation can be detected with a chance of 20 per cent. The evaluation indicates that such a chance rises when a supplier or subscriber requests the minimum gas price for the execution of the verification contract.

6.3.1. The evaluation of verifying consent and number of suppliers

The experiment evaluates the cost paid for verifying whether the suppliers processing personal data have received subscriber's consent or not. The assumption is that we have one subscriber and the number of suppliers varies from one to ten. The *privacy-verify* function is executed in the Ropsten test network with the gas price rate of 1 Gwei. The function was executed five times to calculate the average consumed gas. Per each execution, there was a violation committed by a supplier (i.e. access to data without getting the subscriber's consent). Figure 13 shows the results of this experiment. As seen, by increasing the number of suppliers, the verification cost rises steadily. Such a trend is due to the fact that the complexity of processing which requires additional memory when the number of suppliers increases.

7. Community evaluation

To extend our analysis, we simulate an energy community with associated dynamics for energy service exchanges using PeerSim [55] simulator. PeerSim

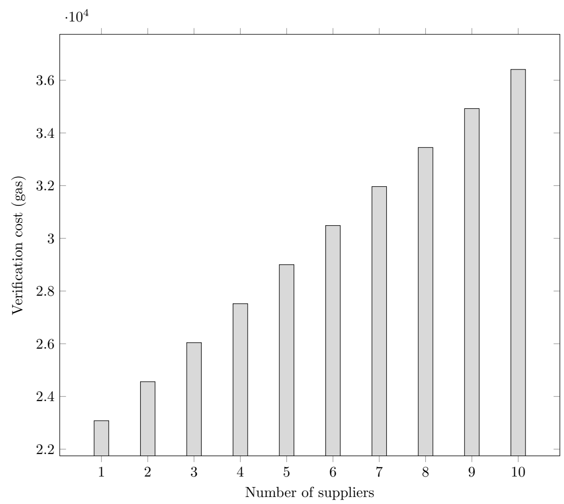


Figure 13: The relationship between the number of suppliers and verification cost

is a Peer-to-Peer simulator with components that are flexible and can provide two important advantages for the energy clusters simulation: (i) scalability in testing an increasing number of nodes and exchanges and (ii) dynamism in adding and removing energy nodes during a simulation. PeerSim has modules and corresponding implementations for the simulation of energy communities to support a variety of different system configurations, where the community is modelled as a collection of peer-nodes (i.e energy nodes), where each node has a list of associated protocols. A simulation starts in the initialisation phase where energy nodes and exchanges are programmed through the mean of initialisers and controls – facilitating a sequential simulation where energy nodes can have different roles (energy producers and consumers), and exchanges are facilitated via the mechanism of "event scheduling". We assume that energy nodes in the network belong to an energy community such that nodes belonging to the same community are connected directly or by a few hops in an underlying Peer-to-Peer graph. Energy nodes would, therefore, tend to share energy within a network unless other parameters (such as lack of group-based nodes, economic benefit, efficiency, etc.) become more important. The action of various community prosumers is modelled using a PeerSim framework that organises the network into a stable, artificial social network (ASN) with small-world features [56]. The protocol enables the creation of energy communities to combine their various types of energy with a view to improving the overall economic efficiency.

7.1. Configuration

The simulation model has been tested with different functional scenarios where parameters such as the connectivity of the energy network, the number

of energy producers and energy consumers, and the set of energy types have been varied. The Peersim simulation system has imported the Newscast protocol [57] in order to manage the overlay network topology. We have divided a simulation process into cycles with an energy network formed of 1000 nodes. The simulation begins at cycle 0, where 25% of the nodes are scheduled to broadcast energy requests. A remaining percentage of 75% are nodes are energy providers nodes which can respond to the incoming energy requests. In the system, there are different types of energy services allocated to different producers nodes. In the set of energy transactions, one transaction t_i is marked in a smart contract and configured with a set of parameters:$[energy.type, quantity, price]$. The execution of the energy transactions is programmed based on a predefined request where an exchange e_i involves a price to be paid by the consumer and a payoff to be received by the provider. The coordination of the transaction for a cluster C_i is performed by the energy community manager $Cluster_{manager}$, which manages the interactions of all energy nodes in the community. In the initialization phase, each community manager registers the energy capability of each node and coordinates the entire exchange process. We assume that during the simulation, every energy node can deliver a limited energy capability (type and quantity). For the community simulation, we consider three metrics:
(i) Cost with smart contracts:

$$Cost_{contracts} = \sum_{j=1}^{n}(cost.energy_j + cost.contract_j + cost.verify_j) \qquad (1)$$

where *cost.energy* is the cost of energy per tariff, *cost.contract* is the cost of running the Blockchain contract and $cost.verify$ is the verification cost.

(ii) Cost per transaction:

$$Cost_{transaction} = \frac{1}{m}\sum_{j=1}^{m}(cost.transactions) \qquad (2)$$

(iii) Cost per energy type:

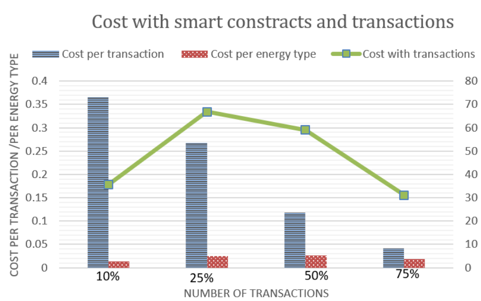
$$Cost_{type} = \frac{1}{p}\sum_{j=1}^{p}(cost.types) \qquad (3)$$

The configuration we adopted in the experiments is the following: (i) The size of the energy system nodes (N): 1000; (ii) the energy nodes degree: $d \in \{3, 5, 10, 20\}$;(iii) the energy community network topology: random; (iv) energy types allocation: trading nodes are configured to have random energy types such as ($S_i \in \{1, 2, 3, 4, 5\}$)(wind, solar, hydro, geothermal, etc); (v) gas cost and verification cost; (vi) payoffs: for each energy exchange, a node receives a payoff of 1.

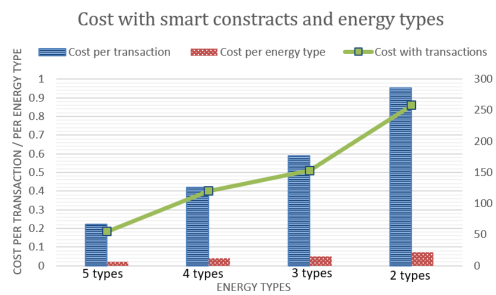
The community evaluation investigates how various factors such as energy types, cluster size and payoffs can induce fluctuation in the transaction costs. The transaction costs associated with smart contracts can be aggregated across the entire energy community, or a subset of energy nodes, and reflects the status of the system during the simulation. In particular, we investigate how Blockchain can support the energy transactions by measuring the reaction of the community when different energy market factors change. Observing the community when the number of energy agents with associated energy types is increased helps us to understand how a local energy market reacts to variation around competing energy consumers and providers.

7.2. Experiments

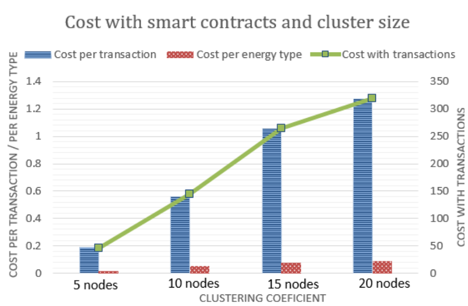
We test four different scenarios by evaluating the cost with smart contracts, cost per energy type and cost per transaction ($ [USD]), when (i) the number of transactions increases, (ii) the set of energy types changes, (ii) the cluster size increases and (iv) payoff levels are increased.



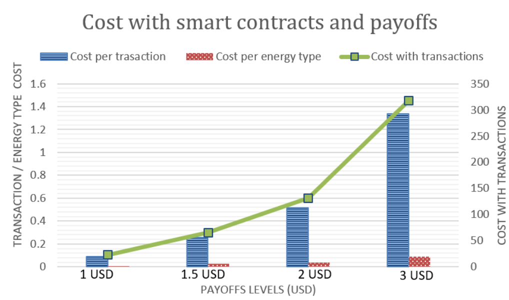
(a) Experiment 1: Cost with energy requests



(b) Experiment 2: Cost with energy types



(c) Experiment 3:Cost with cluster size



(d) Experiment 4: Cost with transaction payoffs

Figure 14: Cost of smart contracts with requests and energy types

Experiment 1: Cost of smart contracts and transactions. In this experiment we simulate community events and exchanges based on different transaction probabilities (10%, 25%, 50% and 75%, measuring the percentage of energy transactions in the system) in order to determine the impact of energy demand on the total amount of service exchanges. As presented in Figure 14a, the cost with smart contracts (transactions) increases proportionally with the probability of transactions, whereas the cost per transaction decreases based on the transaction probability. It is observed that an optimum in terms of cost with transactions is reached when the system circulates 25% of transactions, respectively 50%. Cost per transaction decreases with the number of energy transactions whereas the cost per energy type increases up to 50% and then decreases. This experiment shows that energy communities can support a certain number of energy transactions until reaching saturation as the number of transactions has a direct impact on cost per transaction and cost per energy type. This is also influenced by the structure of the energy community network where energy nodes have a limited number of trading paths and a limited energy capability during a simulation.

Experiment 2: Cost of smart contracts and energy types. In this experiment, we investigate the total cost with smart contracts when using different energy types. Each transaction is mapped into a smart contract, and an energy type refers to a renewable energy resource (solar, wind, geothermal, hydro, etc.). In Figure 14b, we present the distribution of cost with smart contracts when utilising different energy types. The highest cost is identified when the system utilise only two energy types for all the transactions. When the number of energy types is increased, the total cost with smart contract decreases, including the average cost per transaction and per energy type. We observe, therefore, that in communities where fewer energy types are used, the total cost with transactions is higher whereas for communities with 3, 4, 5 energy types the cost is lower. This is applicable also to the cost per transaction and per energy types and demonstrates that communities with 3 to 4 energy types can reach an optimum of cost with energy transactions. A higher number of energy types represents a diversity in energy demand, which gives consumers an increased number of purchasing options (i.e. types) which optimises the overall cost with transactions. This re-emphasizes the importance of having distribution in energy sources and variation of services across a community.

Experiment 3: Cost of smart contracts and cluster size. This experiment shows how the number of neighbours in a node view (direct links to other energy nodes – cluster size) can impact the cost per transaction and cost per energy type. The cluster size refers to a number of connected neighbours and also has a direct impact on the total cost with transactions as it primarily identifies potential energy traders for an energy node. From Figure 14c can be observed the correlation between the cluster size and total cost with transactions where the increase in cost is more significant when changing from a community of 10 energy nodes in cluster to 15 energy nodes. When the community is formed by clusters with increased number of energy consumers and providers, more transactions can be executed hence the cost with transactions increases. This experiment demonstrates that energy communities with a large number of consumers and providers in clusters have higher costs per transaction and higher cost per energy type and consequently a higher cost with transactions. This reflects the impact of different levels of community decentralization where communities with less decentralisation (higher number of energy providers and consumers per cluster) identify a higher level of costs.

Experiment 4: Cost of smart contracts and payoffs. In this experiment, we test the impact of payoffs in the overall cost distribution, where payoffs is a financial incentive for energy nodes to participate in energy transactions. We change payoffs from 1 USD to 3 USD for all nodes participating in the transaction flow and observe how the payoffs level influence the cost per transaction, cost per type and total cost with smart contracts. As presented in Figure 14d, the cost per transaction and cost per energy type increase proportionally with the payoffs threshold whereas the total cost with smart contracts is directly related to the level of payoffs in the system. When the payoffs level increases, the acceptance rate of transactions increases as consumers and providers are incentivised to participate in the energy community market. This experiment demonstrates that energy community formation and use is significantly related to the level of payoffs within the community. Such payoffs also have an impact of the total cost with smart contracts and in a certain proportion is justified by the economic consumption and production laws where an incentive to buy will increase the level of transactions in a system and also the total income. The experiments demonstrate that energy communities can be influenced by different financial or non-financial incentives, and the actual enactment of such Blockchain supported energy markets is related to several key factors that can be decisive in the overall realisation of such marked decentralisation and transition towards clear energy.

8. Conclusions

This paper aims to contribute to the ongoing research around energy communities by proposing a Blockchain model to support energy sharing and trading. We have developed an Ethereum-Blockchain framework with an application scenario from the fish industry to demonstrate how energy transactions can be coordinated through the use of smart contracts. Our goal was to understand the formation and use of energy communities and to explore the mechanisms on decentralisation of energy in prosumer communities. We have implemented an Ethereum based subsriber/supplier energy model with associated purpose, consent, payment and attestation functions, in different energy scenarios, where energy actors such as buyers and sellers can purchase and share energy resources using smart contracts. We have also addressed the verification and violation detection aspects with a view to enable a more secured energy trading environment. We have scaled up our analysis and deployed energy exchanges with an increased number of consumers and providers. We have analysed the cost impact of different numbers of transactions to observe how the size of an energy community and number of exchanges can influence the cost across the community.

The utilisation of Blockchain for energy communities has proved beneficial with energy transactions are recorded in an immutable and complete record which facilitates a more secure and efficient way of monitoring the community interactions and prosumers activities. Blockchain can also enable energy prosumers to monetise any surplus of energy and register its ownership by supporting their integration into a more competitive energy market. In the future, we want to explore the use of Blockchain for the development of the industrial edges, where several smart devices are coordinated by the use of private Blockchains such as hyper-ledger fabric. The use of private Blockchains can support the anonymisation of energy communities in an attempt to facilitate security and privacy policies for energy actors. Such deployment can advance the digitalisation of industries and accelerate integration with renewable energy sources.

In future work, we will investigate the trustworthiness of smart meters with methods for behaviour modelling and prediction for appliances and controllers. Such trustworthiness can be undertaken by using trust and reputation techniques to evaluate the level of trust/reliability of smart devices/meters and associated risks.

Acknowledgment

This work was supported by the EU INTERREG piSCES Project: "Smart Cluster Energy Grid Systems for Fish Processing Industries", grant number: 504460, funded via the European Regional Development Fund through the Ireland Wales Cooperation Program.

References

[1] Su, Zhou, et al. "A secure charging scheme for electric vehicles with smart communities in energy Blockchain." IEEE Internet of Things Journal (2018).

[2] Becker, Sren, and Matthias Naumann. "Energy democracy: Mapping the debate on energy alternatives." Geography Compass 11.8 (2017): e12321.

[3] Moroni, Stefano, et al. "Energy communities in the transition to a low-carbon future: A taxonomical approach and some policy dilemmas." Journal of environmental management 236 (2019): 45-53.

[4] Gui, Emi Minghui, and Iain MacGill. "Typology of future clean energy communities: An exploratory structure, opportunities, and challenges." Energy research & social science 35 (2018): 94-107.

[5] Zukin, Sharon and Jennifer Smith Maguire, Consumers and Consumption, Annual Review of Sociology, 30, 173 197, 2008

[6] Belk, Russell W.., Why Not Share Rather Than Own?, The ANNALS of the American Academy of Political and Social Science, 611, 126 140, 2007

[7] Ioannis, Kounelis, et al. ”Blockchain in energy communities.” , Technical report, European Commission, Retrieved from Centro Comum de Investigao da Comisso Europeia: http://publications.jrc.ec.europa.eu/repository/bitstream/JRC110298/del 344003 (2017): v09.

[8] Andoni, Merlinda, Robu, Valentin, Flynn - David, Crypto-control your own energy supply, Nature, 2017/08/09/online, 548, 158, http://dx.doi.org/10.1038/548158b, Correspondence.

[9] Plaza, Caroline, et al. “Distributed solar self-consumption and Blockchain solar energy exchanges on the public grid within an energy community.” 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe. IEEE, 2018.

[10] Z. Guan, X. Lu, N. Wang, J. Wu, X. Du, and M. Guizani, Towards secure and efficient energy trading in IoT-enabled energy internet: A Blockchain approach, Future Generation Computer Systems, 2019. doi: 10.1016/j.future.2019.09.027.

[11] R. Chaudhary, A. Jindal, G. S. Aujla, S. Aggarwal, N. Kumar, and K. R. Choo, BEST: Blockchain-based secure energy trading in SDN-enabled intelligent transportation system, Computers and Security, vol. 85, 2019, pp. 288–299. doi: 10.1016/j.cose.2019.05.006.

[12] S. Oh, M. Kim, Y. Park, G. Roh and C. Lee, Implementation of Blockchain-based energy trading system, Asia Pacific Journal of Innovation and Entrepreneurship, vol. 11, no. 3, 2017, pp. 322–334. doi: 10.1108/APJIE-12-2017-037.

[13] M. Sabounchi and J. Wei, Towards Resilient Networked Microgrids: Blockchain-Enabled Peer-to-Peer Electricity Trading Mechanism, IEEE Conference on Energy Internet and Energy System Integration, Beijing, China, 2017.

[14] E. S. Kang, S. J. Pee, J. G. Song, and J. W. Jang, A Blockchain-Based Energy Trading Platform for Smart Homes in a Microgrid, 3rd International Conference on Computer and Communication Systems, Nagoya, Japan, 2018, pp. 472–476.

[15] Z. Zhou, L. Tan, and G. Xu, Blockchain and Edge Computing Based Vehicle-to-Grid Energy Trading in Energy Internet, 2nd IEEE Conference on Energy Internet and Energy System Integration, Beijing, China, 2018.

[16] K. Gai, Y. Wu, L. Zhu, M. Qiu, and M. Shen, Privacy-Preserving Energy Trading Using Consortium Blockchain in Smart Grid, IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS, vol. 15, no. 6, 2019, pp. 3548–3558.

[17] W. Hou, L. Guo, and Z. Ning, Local Electricity Storage for Blockchain-Based Energy Trading in Industrial Internet of Things, IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS, vol. 15, no. 6, 2019, pp. 3610–3619.

[18] Z. Huang, K. Suankaewmanee, J. Kang, D. Niyato, and N. P. Sin, Development of Reliable Wireless Communication System for Secure Blockchain-based Energy Trading, 16th International Joint Conference on Computer Science and Software Engineering, Chonburi, Thailand, 2019, pp. 126–130.

[19] A. Salian, S. Shah, J. Shah, and K. Samdani, Review of Blockchain Enabled Decentralized Energy Trading Mechanisms, IEEE International Conference on System, Computation, Automation and Networking (ICSCAN), Pondicherry, India, 2019.

[20] X. Lu, L. Shi, Z. Chen, X. Fan, Z. Guan, X. Du, and M. Guizani, Blockchain-Based Distributed Energy Trading in Energy Internet: An SDN Approach, IEEE ACCESS, vol. 7, 2019, pp. 173817–173826.

[21] M. Vasconcelos, W. Cramer S. Jessenberger, A. Amthor, C. Ziegler, C. Schmitt, F. Heringer, and A. Armstorfer, The Pebbles Project-Enabling Blockchain-Based Transactive Energy Trading Of Energy & Flexibility Within a Regional Market, 25th International Conference on Electricity Distribution, Madrid, Spain, 2019.

[22] Zhang, Chenghua, et al. "Peer-to-Peer energy trading in a Microgrid." Applied Energy 220 (2018): 1-12.

[23] SunChain, Sunchain, http://www.sunchain.fr/, [accessed 2 May 2020],

[24] PROSUME, Prosume decentralising power White paper, https://prosume.io/white-paper/, [accessed 2 May 2020].

[25] Pylon Network, Pylon Network, https://pylon-network.org/, [accessed 2 May 2020].

[26] MPAYG, Join us in democratizing access to energy, http://www.mpayg.com/,[accessed 2 May 2020].

[27] Aymen Boudguiga, Nabil Bouzerna, Louis Granboulan, and Alexis Olivereau. 2017. Towards better availability and accountability for IoT updates by means of a blockchain. In Proceedings of the European Symposium on Security and Privacy Workshops. IEEE, Paris, France, 5058.

[28] Fran Casino, Thomas K. Dasaklis, and Constantinos Patsakis. 2019. A systematic literature review of blockchain-based applications: current status, classification and open issues. Telematics and Informatics 36 (2019), 5581

[29] Kouveliotis-Lysikatos, Iasonas, et al. "Blockchain-Powered Applications for Smart Transactive Grids." 2019 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe). IEEE.

[30] van Leeuwen, Gijs, et al. ”An integrated blockchain-based energy management platform with bilateral trading for microgrid communities.” Applied Energy 263 (2020): 114613.

[31] “Ethereum.” https://www.ethereum.org/, 2020. [Online].

[32] “ETH Gas Station.” https://ethgasstation.info/, 2020. [Online].

[33] G. Wood, Ethereum: A secure decentralised generalised transaction ledger, Ethereum Project Yellow Paper, 2014.

[34] Duc-Phong Le, Huasong Meng, Le Su, Sze Ling Yeo, and Vrizlynn Thing. 2018. BIFF: A blockchain-based IoT forensics framework with identity privacy. In Proceedings of the TENCON, IEEE Region 10 International Conference. IEEE, Jeju, South Korea, 2372-2377

[35] Pin Lv, Licheng Wang, Huijun Zhu, Wenbo Deng, and Lize Gu. 2019. An IoToriented privacy-preserving publish/subscribe model over blockchains. IEEE Access 7 (2019), 4130941314

[36] Zibin Zheng, Shaoan Xie, Hongning Dai, Xiangping Chen, and Huaimin Wang. 2017. An overview of blockchain technology: architecture, consensus, and future trends. In Proceedings of the 6th International Congress on Big Data. IEEE, Honolulu, USA, 557564.

[37] Tara Salman, Maede Zolanvari, Aiman Erbad, Raj Jain, and Mohammed Samaka. 2019. Security Services Using Blockchains: A State of the Art Survey. IEEE Communications Surveys & Tutorials 21, 1 (2019), 858880.

[38] Petri, I., Yama, A. and Rezgui, Y. 2019. Agent-based appliance scheduling for energy management in industry 4.0., International Conference on the Economics of Grids, Clouds, Systems, and Services, Leeds, UK, 17-19 Sep 2019, Switzerland: Springer Verlag pp. 199-207.

[39] Brundtland, G. H. 1985. World commission on environment and development. Environmental policy and law 14(1), pp. 26-30.

[40] Abdelaziz, E. et al. 2011. A review on energy saving strategies in industrial sector. Renewable and sustainable energy reviews 15(1), pp. 150-168.

[41] Conti, J. et al. 2016. International Energy Outlook 2016 With Projections to 2040. USDOE Energy Information Administration (EIA), Washington, DC (United States). Office of Energy Analysis.

[42] Yoldas, Y. et al. 2017. Enhancing smart grid with microgrids: Challenges and opportunities. Renewable and Sustainable Energy Reviews 72, pp. 205-214.

[43] Phuangpornpitak, N. and Tia, S. 2013. Opportunities and challenges of integrating renewable energy in smart grid system. Energy Procedia 34, pp. 282-290.

[44] Granade, H.C., Creyts, J., Derkach, A., Farese, P., Nyquist, S. and Ostrowski, K., 2009. Unlocking energy efficiency in the US economy. McKinsey & Company.

[45] A. T. Rezvan, N. S. Gharneh, G. Gharehpetian, Optimization of distributed generation capacities in buildings under uncertainty in load demand, Energy and Buildings 57 (0) (2013) 58 64. doi:http://dx.doi.org/10.1016/j.enbuild.2012.10.031.

[46] L. Magnier, F. Haghighat, Multiobjective optimization of building design using TRNSYS simulations, genetic algorithm, and artificial neural network, Building and Environment 45 (3) (2010) 739 746. doi:http://dx.doi.org/10.1016/j.buildenv.2009.08.016.

[47] T. Hong, S. Chou, T. Bong, Building simulation: an overview of developments and information sources, Building and Environment 35 (4) (2000),347 361. doi:http://dx.doi.org/10.1016/S0360-1323(99)00023-2.

[48] Giotitsas, Chris, Alex Pazaitis, and Vasilis Kostakis. "A peer-to-peer approach to energy production." Technology in Society 42 (2015): 28-38.

[49] T. Liu, X. Tan, B. Sun, Y. Wu, X. Guan and D. H. K. Tsang, "Energy management of cooperative microgrids with P2P energy sharing in distribution networks," 2015 IEEE International Conference on Smart Grid Communications (SmartGridComm), Miami, FL, 2015, pp. 410-415. doi: 10.1109/SmartGridComm.2015.7436335.

[50] Ioan Petri, Magdalena Punceva, Omer F. Rana, George TheodorakopoulosYacine Rezgui "A broker based consumption mechanism for social clouds" , International Journal of Cloud Computing (IJCC), 2(1), 2014, pp. 45-57.

[51] Lombardi, P., and F. Schwabe. "Sharing economy as a new business model for energy storage systems." Applied energy 188 (2017): 485-496.

[52] Alzahrani, A., Petri, I. and Rezgui, Y. 2019. Analysis and simulation of smart energy clusters and energy value chain for fish processing industries. Energy Reports (10.1016/j.egyr.2019.09.022)

[53] Ropsten 2019. Ropsten testnet pow chain. Retrieved Sep 5, 2019 from https://github.com/ethereum/ropsten

[54] Solidity 2019. Solidity v0.5.3. Retrieved Sep 5, 2019 from https://solidity.readthedocs.io/en/v0.5.3/

[55] A. Montresor and M. Jelasity, "PeerSim: A scalable P2P simulator", *Proceedings of the 9th Int. Conference on Peer-to-Peer (P2P'09)*, pp. 99–100. Seattle, WA, September 2009.

[56] Hales, David, Stefano Arteconi, and Ozalp Babaoglu. "SLACER: randomness to cooperation in peer-to-peer networks." 2005 International Conference on Collaborative Computing: Networking, Applications and Worksharing. IEEE, 2005.

[57] Jelasity, M. and M. van Steen (2002), Large-Scale Newscast Computing on the Internet". Internal Report IR-503, Vrije Universiteit Amsterdam.